DESIGN FOR MANAGING OBSOLESCENCE

A Design Methodology for Preserving Product Integrity in a Circular Economy

Dissertation by

MARCEL DEN HOLLANDER

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A Design Methodology for Preserving Product Integrity in a Circular Economy

Dissertation
for the purpose of obtaining the degree of doctor at Delft University of Technology
by the authority of the Rector Magnificus, prof. dr. ir. T. H. J. J. van der Hagen
chair of the Board for Doctorates
to be defended publicly
on Friday 15 June at 12:30 o'clock

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This research has been funded by the Innovation-Oriented Research Program 'Integrated Product Creation and Realization (IOP-IPCR) of the Netherlands Ministry of Economic Affairs, facilitated by the Netherlands Enterprise Agency (RVO) and the ResCoM (Resource Conservative Manufacturing) project, a European Commission co-funded project working to develop an innovative methodology and software platform for the industrial implementation of closed-loop manufacturing systems by 2017.

Title: DESIGN FOR MANAGING OBSOLESCENCE
A Design Methodology for Preserving Product Integrity in a Circular Economy
ISBN 9789082873603 Design by Yvo Zijlstra
Published by Marcel den Hollander IDCR
Printed by ProefschriftMaken || www.proefschriftmaken.nl

Doctoral dissertation, Delft University of Technology, Delft, the Netherlands

Over 10,000 years humans have been remarkably successful at envisioning and instigating change in an attempt to improve the human condition. However, it seems that in the last century or so, we have become too skilled at these activities for our own good.

To my family, with immense gratitude for the past and present and with hope and anticipation for the future.

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PREFACE

Much of the literature on sustainability and sustainable product design seems permeated by the belief that it is Mother Earth who needs saving. This widespread misconception presents a major barrier to the transition to a circular economy. Mother Earth might at some point in the future no longer look the way we want her to, and for a cosmic blink appear to have lost her ability to sustain human life, but she will continue to live on long after the last human has walked the face of the planet. As a matter of fact, some might even say she is better off without us.

Blessed with a sufficiently large brain and opposable thumbs, we humans, as a playful, curious and tool wielding species, have for over 10,000 years been remarkably successful at envisioning and instigating change in an attempt to improve the human condition. However, it seems that in the last century or so, we have become too skilled at these activities for our own good. Recklessly leveraging the power of fossil fuels and fanning the flames of human desire, we are currently using up natural resources and polluting our world at such a dazzling rate that the same processes that were originally meant to enhance our chances of survival have instead become a threat to it. The challenge we are currently facing is therefore not how to save Mother Earth, but rather how to bring the industrial and economic processes we have unleashed under control and make them work again for *our* long-term survival, preferably in such a way that it doesn't require us to renounce our innate desire for new experiences and our love for toys and tools that makes us so human.

As an industrial designer, I have always worked from the belief that well-designed products can help enhance the quality of our lives and give expression to who we are (or want to be). Material artefacts have always been and will always be an integral part of human culture. But to keep our products from destroying us, especially in light of the expected growth in world population and demand, I also think we need to learn to contain their – what in our present throwaway society often seems – all-consuming power over us, just as we have learned to contain the all-consuming power of fire thousands of years ago.

In my more than 20 years as a practicing industrial designer, I have learnt that many, potentially promising, ideas for sustainable design end up unused – or are not even considered in the first place – if they are not accompanied and supported by a business rationale for adopting such an idea. The circular economy concept in that respect seems promising, as it aims to limit the flows of materials and energy into and out of the economic system at levels that in principle can be tolerated and sustained indefinitely by nature whilst protecting the capacity of the economic system to create wealth. I hope that the concept of managing obsolescence and the new design methodology for managing obsolescence in a circular economy that are presented in this thesis will inspire industrial designers (and other business professionals) to explore and discover new ways to contribute in doing so[1].

1. *In the remainder of this thesis, I will use the pronoun "we" instead of "I" when describing specific research activities. The first reason for this is to reflect that, although the thesis is the result of my own work, my supervisors and others have helped me throughout the study to achieve this result. The second reason is that the pronoun "we", in my opinion, makes for more pleasant reading.*

What design methodology can help industrial designers to design products that are tailored to match business model types for creating, delivering and capturing value from long and extended product lifetimes in a circular economy?

SUMMARY

This thesis is about the development of a design methodology that can help industrial designers to design products with a long or extended lifetime in support of a circular economy. The research is presented from an industrial design perspective.

CHAPTER 1: INTRODUCTION

Material resources are the lifeblood of the industrial economy. Since the start of the Industrial Revolution, the rate at which the economy uses up natural resources and produces waste through the production and consumption of products has been steadily increasing to the point of becoming critical from an environmental (pollution) and economic (supply) point of view. Many options to reduce the consumption of resources and the production of waste have been conceived and tried with varying levels of success. These range from policy and legal to market incentives and attempts to influence consumer behaviour. The most promising option, both from an environmental and from an economic perspective, to limit the rate at which we use up natural resources, is to reduce – and preferable minimize – the flux of non-renewable energy and (natural) resources into and out of our economic system. This can be done by preserving as much of the economic value embedded in our products as possible, in a systematic manner and preferably many times over. It is this notion that lies at the heart of the circular economy concept, an idea that has in recent years been embraced by the European Commission and is rapidly gaining momentum in the scientific community and wider society. The aim of a circular economy is to limit the flows of materials and energy into and out of the economic system at levels that in principle can be tolerated and sustained indefinitely by nature whilst protecting the capacity of the economic system to create wealth. In a circular economy, the economic and environmental value of materials is preserved by keeping them in the economic system for as long as possible, preferably by lengthening the useful lifetimes of products formed from them and, when lifetime extension at product level is no longer possible for environmental or economic reasons, by looping products back into the manufacturing process so their constituent materials can be reused. The notion of *waste* no longer exists in a circular economy because products and materials are, in principle, reused and cycled indefinitely. It follows that product lifetime extension – not instead of but in addition to materials recycling – and the ability to create, deliver and capture economic value from long or extended product lifetimes are essential to a circular economy. Industrial design has the potential to contribute significantly to achieving the goals of a circular economy because the design of a product directly affects the characteristics of the physical product as well as the structure of the entire value chain.

The thesis belongs to the scientific discipline of design research and, within this larger discipline, focuses on the domain of sustainable design, i.e., that segment of industrial design that in the creation of products and systems intentionally takes on the additional responsibility of *"balancing economic, environmental and social aspects"* (Charter & Tischner, 2001, p. 121) with the end goal of fostering and safeguarding lasting human well-being.

The field of sustainable design originated in eco-design. Eco-design is the systematic integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life cycle. As the field of sustainable design evolved, its scope gradually enlarged. Where eco-design is primarily con-

cerned with resource flows, sustainable design has also come to include aspects such as social sustainability, for instance. As the thesis takes a material flows perspective on the circular economy, it compares product design for a circular economy with eco-design (but not with sustainable product design). As part of the domain of sustainable product design, the discipline of eco-design is well developed and recognized. It provides product designers with a design methodology, i.e., a range of guiding principles, eco-design strategies, and methods, for systematically integrating environmental aspects into product design with the aim to improve the environmental performance of the product throughout its whole life cycle. The thesis argues, however, that there is a fundamental distinction to be made between eco-design and product design for a circular economy, i.e., circular product design, and that this means that circular product design requires a new, or at least an adapted, design methodology.

The most important difference between eco-design and circular product design is of a methodological nature. The current design methodology (i.e., guiding principles, strategies, and methods) for product lifetime extension as proposed by eco-design is rooted in the here and now (which is the linear economy). It is aimed at mitigating the effects of current problems (e.g., waste as a by-product of creating wealth) and as such is an example of what is known in the literature as a *relative* approach to sustainability. But how can industrial designers come up with truly sustainable or circular innovations if the current methods only lead them to optimize what is already there? By contrast, circular product design starts from *"an idealised end state"* (Faber, Jorna & Van Engelen, 2005, p. 3) (i.e., creating wealth without creating waste) and systematically works back and forth to close the gap between there and here. As such, it is an example of what is known in the literature as an *absolute* approach to sustainability. Although absolute approaches have been viewed by many as utopian, impractical, and unnecessarily normative, they could prove advantageous over and complementary to relative approaches to sustainability for two reasons. The first is that because absolute approaches imply notions of an ideal state (i.e., a circular economy without waste as an ideal state), they can challenge industrial designers to strive for such an ideal state, thus opening up a wider solution space and an increased likelihood of finding innovative solutions. This could lead to new solutions that may not be evident or considered viable when the problem is viewed from a relative, in this instance linear economy, perspective but which emerge only when the problem is allowed to be considered in a different and wider (socio-economic) context. The second reason is that, because of its widened perspective, an absolute approach can help industrial designers avoid unintended adverse effects of their interventions that could occur if underlying, and often more systematic, problems are left unaddressed.

Over the past six decades, the field of eco-design has for example framed product lifetime extension mainly from a resource efficiency perspective, largely ignoring the business implications ushered in by the circular economy concept. Notwithstanding its usefulness for reducing the environmental impact of products, the eco-design approach has left largely unexplored the interaction between (the design of) long-life tangible products and their business-economic context. As a consequence of this rather narrow way of framing product lifetime extension – i.e., focused on tangible products and resource efficiency – limited attention has been given to the development of a design methodology explicitly aimed at leveraging the interactions between (the design of) physical products and their business-economic context to systematically increase, let alone optimize, product lifetimes. With the recent increase in attention paid to the circular economy concept and its adoption by the EU, the resulting knowledge gap has gained significance and needs to be addressed, as the economic and environmental success of the circular economy concept hinges on its ability to leverage the above interactions.

Taking an absolute perspective on sustainability to the circular economy concept, this thesis therefore sets out to develop a design methodology for designing products with a long and/or extended product lifetime in a circular economy with the intention to help fill this knowledge gap. Accordingly, the main research question of the thesis is:

"What design methodology can help industrial designers to design products that are tailored to match business model types for creating, delivering and capturing value from long and extended product lifetimes in a circular economy?"

To arrive at an answer to the above research question, the thesis is divided in two main parts in which a number of sub-research questions are subsequently addressed. The first part, chapter 2 through chapter 4, aims to establish a theoretical framework for the development of a new design methodology that is presented in the second part, chapter 5 through chapter 6. (As the thesis, due to its cross-disciplinary nature of its subject, reviews literature from multiple scientific domains, a set of appendices is furthermore included after the main text to provide background information for those readers who may be familiar with concepts from some of these domains but less so with concepts from others.)

PART ONE

CHAPTER 2: PRESERVING PRODUCT INTEGRITY aims to provide an answer to sub-research question A: "How can product lifetime extension in a circular economy be defined within the context of industrial design?" The chapter reviews the literature on resource states and interventions for product lifetime extension and creates a comprehensive overview of the key concepts and terms that are considered relevant for industrial designers when designing for long and extended product lifetimes in a circular economy. This chapter defines product lifetime in terms of obsolescence, thereby making it clear that product lifetime is not merely an engineering quality that can be designed into products but is also affected by intangible factors like user behaviour and wider socio-cultural influences. Given these many factors potentially affecting product lifetime, chapter 2 argues that industrial designers cannot design products with a long or extended lifetime but can only design *a potential for* a long or extended lifetime into products. The degree to which this potential is actually realized is determined to a large extent by factors *other* than the design of the physical products or systems, such as the socio-economic context of the product (e.g., the business model that the product is embedded in).

In addition, chapter 2 presents new definitions of interventions for product lifetime extension and introduced the concepts of *presource*, *recovery horizon* and *leakage* to accommodate the absence of the concept of waste in a circular economy. Adopting the order indicated by Stahel's (2010) Inertia Principle allows the chapter to develop a new typology for interventions for preserving product integrity. Based on this typology for interventions for preserving product integrity, chapter 2 concludes its proposed answer to sub-research question A with the presentation of a typology for eight design approaches for preserving product integrity. This typology is shown in figure S.1 and forms the starting point for chapter 3.

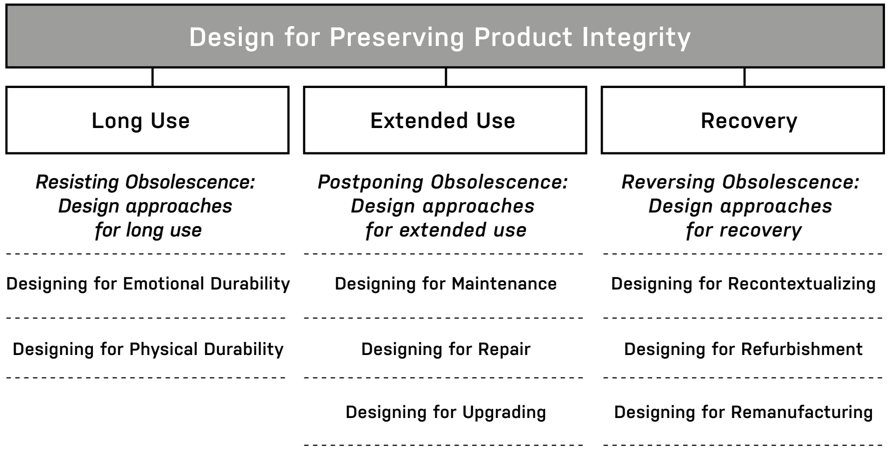

Figure S.1: A typology for design approaches for preserving product integrity in a circular economy.

CHAPTER 3: DESIGNING FOR PRESERVING PRODUCT INTEGRITY aims to provide an answer to sub-research question B: "What guiding principles and design interventions can industrial designers use when designing for long and extended product lifetimes in a circular economy?" The chapter takes the typology of approaches of design for preserving product integrity presented at the end of chapter 2 as a starting point and sets out to develop the abstract design approaches into practical and actionable design strategies for preserving product integrity by reviewing the literature in search of design interventions that industrial designers can select and apply to support the various design approaches for preserving product integrity. This chapter introduces the distinction between design directions (e.g., resisting obsolescence, postponing obsolescence and reversing obsolescence), design approaches (e.g., designing for physical durability, designing for emotional durability, designing for maintenance, etc.), design principles (e.g., material selection, dis- and reassembly, modularization, identification) and design strategies (e.g., design for physical durability, design for emotional durability, design for maintenance, etc.). The distinction between design approaches and design strategies is necessary as the chapter finds that virtually all of the design approaches for preserving product integrity from the typology developed in chapter 2 are supported by the same set of underlying design principles. This leads to two important insights. The first insight is that the design principles selected by industrial designers in support of a particular design approach will also affect other design approaches. To make industrial designers aware of the notion that the design principles selected in support of a particular design approach more often than not also affect other design approaches, chapter 3 introduces the concept of a three-dimensional design space for preserving product integrity, as shown in figure S.2.

By plotting existing products in this design space based on an assessment of the relative importance of the three design directions for preserving product integrity in the overall design intention of a product, industrial designers can use the design space for preserving product integrity as a tool to compare product designs and increase their understanding of what it means to design for different design directions and intentions for preserving product integrity.

The second insight is that the application of the design approaches (and underlying design principles) is heavily dependent on business context, i.e., the particular business objec-

Figure S.2: Example products plotted in the three-dimensional design space for preserving product integrity. The three dimensions are formed by the three design directions for preserving product integrity: resisting obsolescence, postponing obsolescence and reversing obsolescence.

tive(s) the design approaches are intended to help achieve. Chapter 3 finds that the business context (e.g., business and product strategy) of a product to a large extent determines how a particular design approach should be materialized. For instance, the requirements for, and the desired end result of, design for repair are different for a company that wants to retain control and have repairs exclusively performed by qualified service personnel than for a company that wants to promote repair by the users of their products. Design principles such as accessibility need to be interpreted differently by industrial designers in each of these examples depending on the particular business context (e.g., restricting access in the former and facilitating access in the latter instance). Building on this insight, chapter 3 concludes that the eight design approaches only provide practical guidance to industrial designers, i.e., only become actionable design strategies, when they are considered in conjunction with the business context of the product. For this reason, the chapter proposes to make the business context an integral part of the definition of the eight design strategies (i.e., design for emotional durability, design for physical durability, design for maintenance, design for repair, design for upgrading, design for recontextualizing, design for refurbishment and design for remanufacturing) that are presented in chapter 3.

CHAPTER 4: CREATING AND CAPTURING VALUE FROM PRODUCT INTEGRITY aims to provide an answer to sub-research question C: "What business model types can companies use to create, deliver and capture value from long and extended product lifetimes in a circular economy?" The chapter reviews the literature with the aim of creating a typology of circular business models for preserving product integrity in a circular economy. The chapter introduces the concept of a circular business model for preserving product integrity and establishes three criteria that business models have to meet in order to qualify as such: 1) They must be built around tangible products, 2) preserving product Integrity must be essential to their continuity, revenue and profit and 3) they must be circular.

Chapter 4 develops a new typology for circular business models for preserving product integrity, consisting of three product-service based business model types: The Classic Long Life Model, the Access Model and the Performance Model. In addition, the chapter identifies three additional business model types that create and capture value from preserving product integrity but do not qualify as circular business model types for preserving product integrity. Strictly speaking, the Hybrid Classic Long Life Model, and the Hybrid Access Model do not qualify as circular business model types for preserving product integrity as their main revenue streams rely on short-lived consumables rather than long-lived durables. However, depending on how the resource loops for the consumables are set up in specific instances, they could qualify as circular business models and as such play an important role in (the transition towards) a circular economy. Business models of the third type, i.e., Gap Exploiters, not only fail to qualify as a circular business model type for preserving product integrity but can also never qualify as a circular business model at the instance level as they (by definition) have no control over the design of the products whose lives they extend. The Gap Exploiter Model is included in the chapter as it can play an important role in the transition to an absolute circular economy.

PART TWO

Using data and insights gathered from the literature and company interviews and visits, Part Two brings together the separate elements from the theoretical framework established in Part One with the end-goal of developing a new methodology for designing products with a long or extended lifetime in a circular economy.

CHAPTER 5: MANAGING OBSOLESCENCE aims to provide an answer to sub-research question D: "What guiding principles and management strategies can businesses use when creating, delivering and capturing value from long and extended product lifetimes in a circular economy?" The objective of chapter 5 is to identify or develop guiding principles and management strategies for circular business models for preserving product integrity as these determine the objectives that design strategies for preserving product integrity should help achieve. Based on the current literature, chapter 5 identifies maximizing business model circularity as the unique additional business goal that sets circular business model types for preserving product integrity apart from business model types for long and extended lifetimes in a linear economy. The chapter identifies two key barriers to maximizing business model circularity: 1) Random fluctuations in the flow of obsolete products, and 2) a mismatch between the actions required for achieving environmental and economic business objectives. Next, the chapter focuses on how circular business models for preserving product integrity could surmount the first key barrier, i.e., how circular business models for preserving product integrity could maximize their level of control over the flow of obsolete products. As the current literature contains only approaches for *affecting* the flow of obsolete products but none for *controlling* the flow of obsolete products, chapter 5 introduces the concept of *managing obsolescence* as a new management and design approach for supporting the creation, delivery and capture of value from long and extended product lifetimes in a circular economy. During the development of the concept of managing obsolescence, a gap is identified in the current literature: it does not provide insight into the factors within companies that play a role in successfully manufacturing and marketing long-life products – other than the design of the tangible product – that could potentially be leveraged by industrial designers (and other business professionals) to control the flow of obsolete products. To gain insight into the workings (and challenges) of companies currently marketing and manufacturing long-life products and (partly) fill this gap, five company interviews and two, multi-day, company visits are conducted. The outcomes of the interviews and company visits make clear that, apart from the design of the tangible product, many other factors – such as the type of right to the product traded, brand identity, company culture, contractual agreements, (relationships with) suppliers, (relationships with) employees, (relationships) with customers, level and type of service, channels, rules and regulations, internal organizational structure, i.e., elements from virtually the entire structure of the business model – affect the feasibility and success of manufacturing and marketing products with a long or extended lifetime and should therefore be taken into consideration when planning for managing obsolescence. The essence of managing obsolescence lies in the fact that successfully preserving product integrity is not achieved by preserving functionality over time (i.e., a tangible product design and engineering task) alone but instead relies on preserving perceived value over time (i.e., a combined task of tangible product design and engineering and the marketing function).

CHAPTER 6: A DESIGN METHODOLOGY FOR MANAGING OBSOLESCENCE, building and expanding on the answer to sub-research question D presented in chapter 5, develops a methodology for design for managing obsolescence and, as part of the process, provides an answer to sub-research question E: "To what extent are some combinations of design interventions and business model types more likely to be successful in creating, delivering and capturing value from long and extended product lifetimes in a circular economy than others?"

The new design methodology for managing obsolescence consists of five new design methods and is intended to enable industrial designers to tailor their product designs to circular business model instances for preserving product integrity that strive to maximize the circularity of their business model. It is different from – and adds to – existing design methodology for (sustainable) product design for products with a long and/or extended lifetime in that it takes into account the design of the tangible product as well as the design of the overall value proposition(s) and the business model(s) supporting said value proposition(s) over the entire lifetime of the product time. In addition to (and making use of) the design method of the three-dimensional design space for preserving product integrity introduced already in chapter 3, chapter 6 introduces four new design methods in support of design for managing obsolescence: (the development of) an *obsolescence profile*, (the development of) a *longitudinal value proposition*, the development of a *longitudinal business model* and the *heuristic framework for design for managing obsolescence*. The obsolescence profile for a product describes the predetermined sequence covering the entire lifetime of a product that lists the point(s) in time when, and the way(s) in which, a product will be prevented from becoming obsolete and/or will become obsolete and subsequently will be recovered. As such, it captures the predetermined series of use cycles (e.g., number and duration) of a product that would enable a circular business model for preserving product integrity to maximize business model circularity (defined by the thesis as the fraction of economic value added to (p)resources that is preserved over time) for this product. As the properties of the product can, however, vary between use cycles (e.g., a refurbished product is different from a new product), the contribution of the tangible product to the overall value proposition it is embedded in is likely to differ accordingly. For example, whereas a new smartphone can be offered as part of a premium priced service plan, a refurbished phone would most likely require a service plan with discounted rates to result in an attractive and viable value proposition.

The longitudinal value proposition describes the predetermined set of value propositions in which changes in the properties of the tangible product along the obsolescence profile are compensated by, for example, changes in pricing and/or service levels as required over a product's entire lifetime, i.e., along its obsolescence profile.

The longitudinal business model describes the predetermined set of business models that matches the longitudinal value proposition along the obsolescence profile, as in some instances the different value propositions need different business models to support them (e.g., different channels, different key partners). The heuristic framework for design for managing obsolescence is intended to aid industrial designers in meeting the new challenges posed by designing for managing obsolescence in a circular economy (i.e., designing in the *temporal* dimension as well as in the spatial dimension and selecting design directions in conjunction with circular business models for preserving product integrity) by providing guidance to industrial designers (and other business professionals) in selecting design directions and circular business model types for preserving product integrity when developing obsolescence profiles, longitudinal value propositions and longitudinal business models. For lack of theoretical and empirically validated data in the extant literature as to which particular combinations of design directions and PSS-based (circular) business model types are successful, the heuristic framework is constructed from inferences. Although these inferences are the result of careful reflection in the light of the secondary data and the authors' 20 years industry knowledge, they are made on the basis of incomplete (e.g. not taking into account the effects of product type) and non-validated information. Therefore, the heuristic framework as shown in figure S.3 is presented in chapter 6 as a conceptual proposition. As a consequence, the version of the heuristic framework as currently presented should be considered generic and recognized as having limited predictive value. A comparison between the predictions for successful combinations of design directions and circular business models from the heuristic framework and those found in twelve existing products for example, yields perfect and close matches as well as some discrepancies. The predictive value of the heuristic framework as presented in chapter 6, however, is secondary. The primary purpose of the heuristic framework for design for managing obsolescence as presented in chapter 6 is twofold: Firstly, it serves to illustrate how the author envisions a method for design for managing obsolescence that integrally captures and communicates the varying extent to which different combinations of design directions and circular business model types can be expected to be successful as a result of different product types, life cycle stages and circular business model types, with the aim of providing guidance to industrial designers (and other business professionals) in selecting design directions and circular business model types when designing for managing obsolescence. Secondly, it highlights a gap in the literature with regard to the extent to which a combination of design directions and circular business models can be expected to be successful and, as such, indicates the need for further research should there be a desire to make concept of managing obsolescence and the design methodology for managing obsolescence operational as part of (the transition to) an absolute circular economy.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS presents the main conclusions of the study which are summarized here.

In answer to the main research question – "what design methodology can help industrial designers to design products that are tailored to match business model types for creating, delivering and capturing value from long and extended product lifetimes in a circular economy?" – the thesis argues that in order to increase the likelihood that product lifetime extension in a circular economy will be successful from both an environmental and an economic perspective, industrial designers need to be able to control not only the spatial dimension (materialization and geometry) of products, but also the *temporal* dimension. This temporal dimension is related

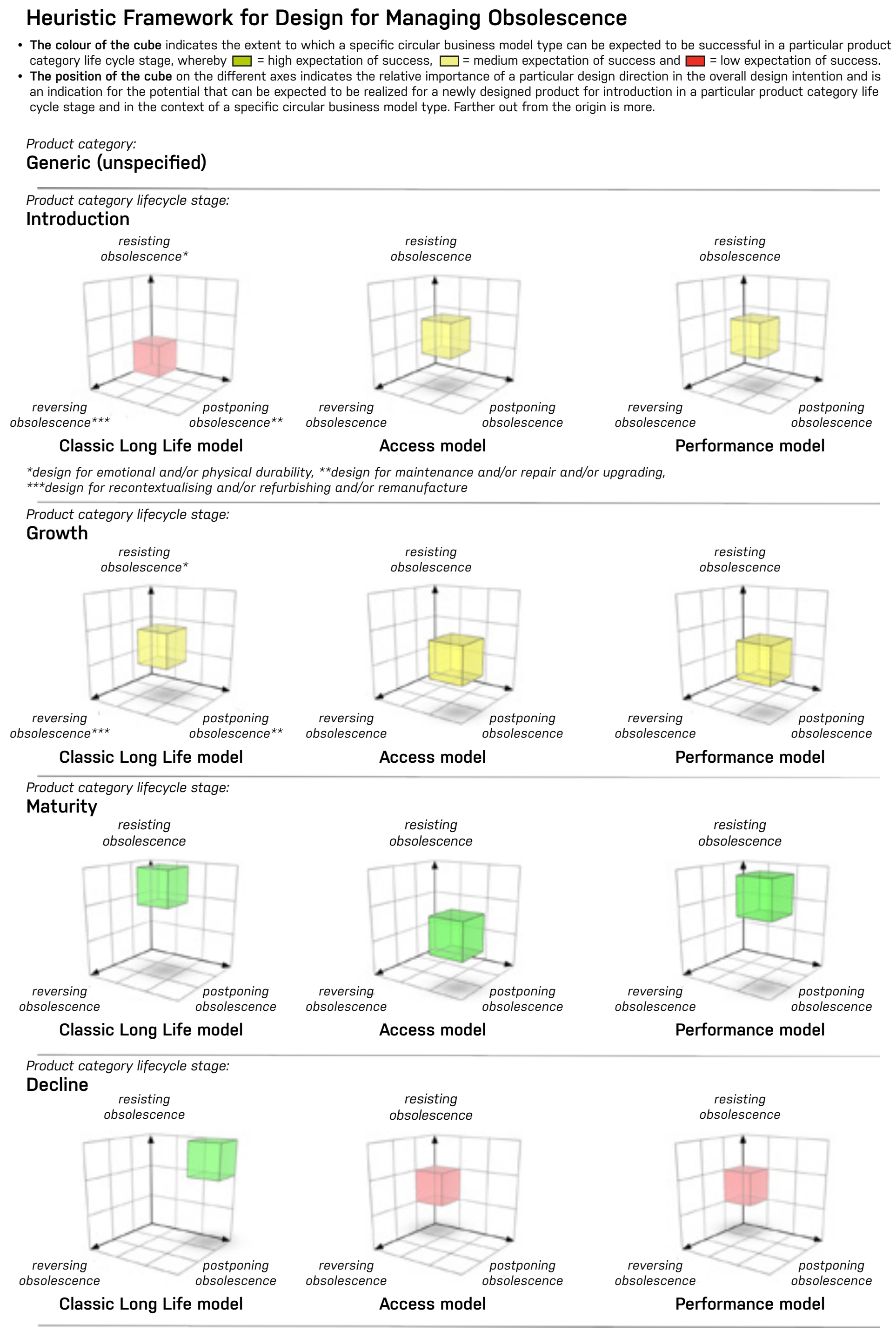

Figure S.3: A heuristic framework for design for managing obsolescence based on the inferences presented in sub-section 6.4.2.

to the number and duration of product use cycles and the duration of total product lifetime. To enable industrial designers to capture this temporal dimension, the thesis presents:

- a new design methodology: design for managing obsolescence;
- five new design methods and two typologies in support of managing obsolescence;
- insight into (the factors determining) how and when to best apply these methods;
- insight into where and in collaboration with whom to apply these methods in the product innovation process.

One of the most important insights gained from the development of the design methodology for managing obsolescence is that managing obsolescence should not be considered a *one-size-fits-all* approach, but that (design for) managing obsolescence instead requires the careful crafting of *tailor-made* solutions that, in order to be successful, must take into account factors like product type, product (sub-)category lifecycle stage, circular business model types and cultural preferences and managerial (e.g., strategic) considerations over the entire product lifetime. The design methodology for managing obsolescence as presented in this thesis offers (conceptual propositions for) methods to industrial designers that are intended to help them work with the above factors and to get a better grip on their effects on requirements for the design of the tangible product when developing such *tailor-made* solutions.

As (the design methodology of) managing obsolescence implies that tangible products are iteratively co-designed in conjunction with obsolescence profiles, longitudinal value propositions and longitudinal business models, the role of industrial designers will change from a predominantly operational to a more business strategic one. This will require industrial designers to work together more closely with professionals from other, presently already more strategically inclined, business functions such as marketing and familiarize themselves with some aspects of the theory and terminology from the business sciences. The latter may seem a daunting prospect at first but will ultimately increase the importance of the industrial designer's role and skills.

For (design) researchers, the design methodology of managing obsolescence offers a structure to interpret, re-evaluate and/or leverage the results of past and current research on product lifetimes and product lifetime extension as well as an outline of opportunities for future research, for example increasing the predictive capacities of the heuristic framework for design managing obsolescence by refining it and/or creating different versions for specific product categories or industries or deepening insights into the application of individual design principles specifically from a product lifetime perspective. As product lifetime extension or preserving product integrity has only limited relevance in a linear economy as compared to in a circular economy, there are many aspects of product lifetime extension that have been researched in the past, but never evaluated in the context of managing obsolescence, such as research on reliability, maintenance and dis- and reassembly.

The same can be said for insights acquired from decades of design and marketing research. In a linear economy, many of these insights have mainly been used to motivate consumers to swiftly acquire new or quickly replace their old products. When re-evaluated in the context of managing obsolescence, these insights could perhaps provide new information on how consumers could be motivated to hold on to their products longer, potentially complementing extant work on this topic.

For business professionals involved with manufacturing and marketing tangible, and durable, products, managing obsolescence means that they need to rethink their current business models, as these – most probably – are based on repeated product sales and not designed to profit from preserving product integrity.

The design methodology for managing obsolescence presented in the thesis was developed *based upon theory* and has not been tested or validated empirically. As such, it is in need of future validation before it could be made operational. However, these tasks are considered to lie outside the scope of the present thesis.

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1

INTRODUCTION

Product lifetime extension – not instead of but in addition to materials recycling – and the ability to create, deliver and capture economic value from long or extended product lifetimes are essential to a circular economy.

1.1 INTRODUCTION

This thesis is about the development of a design methodology that can help industrial designers to design products with a long or extended lifetime in support of a circular economy. The research is presented from an industrial design perspective.

The aim of a circular economy is to limit the flows of materials and energy into and out of the economic system at levels that in principle can be tolerated and sustained indefinitely by nature whilst protecting the capacity of the economic system to create wealth (Korhonen, Honkasalo & Seppälä, 2018). In a circular economy, the economic and environmental value of materials is preserved by keeping them in the economic system for as long as possible, preferably by lengthening the useful lifetimes of products formed from them and, when lifetime extension at product level is no longer possible for environmental or economic reasons, by looping products back into the manufacturing process so their constituent materials can be reused. The notion of *waste* no longer exists in a circular economy because products and materials are, in principle, reused and cycled indefinitely. It follows that product lifetime extension – not instead of but in addition to materials recycling – and the ability to create, deliver and capture economic value from long or extended product lifetimes are essential to a circular economy. Industrial design has the potential to contribute significantly to achieving the goals of a circular economy (SER, 2016; EC, 2015a; EPEA, 2004) because the design of a product directly affects the characteristics of the physical product as well as the structure of the entire value chain (De los Rios & Charnley, 2016). The thesis belongs to the discipline of design research (Faste & Faste, 2012):

> [Design research] includes the study of how designers work and think, the establishment of appropriate structurers for the design process, the development and application of new design methods, techniques and procedures, and the reflection on the nature and extent of design knowledge and its application to design problems (Cross, 1984 as cited in Kuijer, 2014, p. 1).

Within this larger discipline, the thesis focuses on the domain of sustainable design, i.e., that segment of industrial design that in the creation of products and systems intentionally takes on the additional responsibility of *"balancing economic, environmental and social aspects"* (Charter & Tischner, 2001, p. 121) with the end goal of fostering and safeguarding lasting human well-being.

The field of sustainable design originated in eco-design (Wever & Vogtländer, 2015). Eco-design is the systematic integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life cycle (EC, 2009a, Tischner, Schminke, Rubik & Prösler, 2000). As the field of sustainable design evolved, its scope gradually enlarged. Where eco-design is primarily concerned with resource flows, sustainable design has also come to include aspects such as social sustainability, for instance. As the thesis takes a material flows perspective on the circular economy, it will compare product design for a circular economy with eco-design (but not with sustainable product design).

Over the past six decades, the field of eco-design has framed product lifetime extension mainly from a resource efficiency perspective (De Pauw, 2015; Bjørn & Hauschild, 2012), largely ignoring the business implications ushered in by the circular economy concept. The development of design methodologies in the field of sustainable design (Pigosso, McAloone & Rozenfeld, 2015, Bovea & Pérez-Belis, 2012, Luttropp & Lagerstedt, 2006), including those aimed at product lifetime extension, has focused on interventions for improving the design of tangible products in order to reduce the environmental impact generated by these products over their entire lifecycle (De Pauw, 2015; Bjørn & Hauschild, 2012; Stevels, 2007). Notwithstanding its usefulness for reducing the environmental impact of products (De Pauw, 2015), the eco-design approach has left largely unexplored the interaction between (the design of) long-life tangible products and their business-economic context. As a consequence of this rather narrow way of framing product lifetime extension – i.e., focused on tangible products and resource efficiency – limited attention has been given to the development of a design methodology explicitly aimed at leveraging the interactions between (the design of) physical products and their business-economic context to systematically increase, let alone optimize, product lifetimes.

With the recent increase in attention paid to the circular economy concept (Korhonen et al., 2018; Geisendorf & Pietrulla, 2017) and its adoption by the EU (Korhonen et al., 2018; Geisendorf & Pietrulla, 2017; EC, 2015b), the resulting knowledge gap has gained significance and needs to be addressed, as the economic and environmental success of the circular economy concept hinges on its ability to leverage the above interactions.

This thesis sets out to develop a design methodology with the intention to help fill this knowledge gap. Daalhuizen (2014) defined a design method as *"a description of a design activity which has been rationalized and abstracted from observations or imagined based upon theory with the purpose of helping designers to see the structure of that activity (so that they can learn or teach it, extend their capabilities, communicate it or reflect on their own or other's* [*sic*] *actions"* (p. 34). As a circular economy is not (yet) a reality, the development of design methods in this thesis will be of the above "imagined based on theory" variety.

To create new knowledge in the form of a design methodology (Faste & Faste, 2012) on how the interaction between (the design of) products with a long or extended product lifetime and their specific business-economic context can be leveraged to systematically increase product lifetimes, the thesis will begin in chapters 2 and 3 by reviewing the literature from the domains of sustainability and eco-design to identify and develop a comprehensive terminology and a coherent set of guiding principles and design strategies for product design for a circular economy. It will then in chapter 4 venture into the literature from the business sciences to explore the relationship between business models and long and extended product lifetimes, resulting in a typology of circular business model types able to create, deliver and capture value from long or extended product lifetimes in a circular economy.

Next, the thesis will in chapter 5 take inventory of potential barriers to creating, delivering and capturing value from long or extended product lifetimes in a circular economy and existing approaches to surmounting these barriers by means of a further review of the literature and seven company interviews. Based on the results from the literature review and the findings from these company interviews, the thesis will then in chapter 5 propose a new business management and design approach, i.e., managing obsolescence to help these circular business models for long and extended product lifetimes achieve their environmental and economic goals. Lastly, the thesis will in chapter 6 present a new design methodology for managing obsolescence. This new methodology is intended to support and provide guidance to industrial designers when designing long-life products in support of (a transition to) a circular economy. It provides new design methods and typologies in support of managing obsolescence, insight into how and when to best apply these methods and insight into where and in collaboration with whom to apply these methods in the product innovation process.

Conclusions and recommendations for further research will be presented in chapter 7.

1.2 INDUSTRIAL DESIGN, SUSTAINABLE DESIGN, CIRCULAR ECONOMY AND PRODUCT LIFETIME EXTENSION

The literature offers many different definitions for and descriptions of the concept of industrial design (e.g., IDSA, 2017; Van Boeijen, Daalhuizen, Zijlstra & Van der Schoor, 2013; Roozenburg & Eekels, 1995; Heskett, 1987). Historically, the addition of the adjective "industrial" to the concept of design served to highlight the separation of the act of designing a product from the act of making the actual tangible product that sets industrial design apart from *"traditional crafts"* (Heskett, 1987, p. 10) and makes it suitable for use in an industrial context (Heskett, 1987). Since its introduction over half a century ago, however, the meaning of the term "industrial design" has expanded from its more narrow, tangible product-based interpretation (e.g., Heskett, 1987) to also incorporate the conception and development of systems, services and experiences that include, support or surround tangible products, as can be seen from the following extended definition of industrial design proposed by the World Design Organization (2017), which is adopted by the thesis:

> Industrial Design is a strategic problem-solving process that drives innovation, builds business success, and leads to a better quality of life through innovative products, systems, services, and experiences. Industrial Design bridges the gap between what is and what's possible. It is a transdisciplinary profession that harnesses creativity to resolve problems and co-create solutions with the intent of making a product, system, service, experience or a business, better. At its heart, Industrial Design provides a more optimistic way of looking at the future by reframing problems as opportunities. It links innovation, technology, research, business, and customers to provide new value and competitive advantage across economic, social, and environmental spheres.

In most companies built around tangible products, the process of designing the actual tangible product is but one part of a larger, ongoing, product innovation process (Van Boeijen et al., 2013; Buijs, 2012; Roozenburg & Eekels, 1995) (See also Appendix A: The Product Innovation Process). This larger product innovation process loops back onto itself in a continuously repeating sequence of steps, i.e., *"product use, strategy formulation, design brief formulation, product development and market introduction"* (Van Boeijen et al., 2013, p. 23), whereby product use is often taken as the beginning of the continuously repeating sequence to stress that new products are always conceived, designed, developed and introduced in the context of - and often in response to the shortcomings or success of - existing products. Because larger organisations typically have more than one product in their product portfolio at any given time, their larger product innovation process often involves (strategic) planning for, and managing the development of, multiple products (e.g., products with a different function or products intended for different markets and customer segments) in parallel: *"a product mix"*

(Van Boeijen et al., 2013, p.21). However, in order to not let the complexity from developing multiple products cloud the core of the argument presented in the thesis, the remainder of the thesis will consider the product innovation process for a single new product. The business function of industrial design is guided by overall business objectives and does not set its own design goals, nor is it completely free in deciding how to achieve them: In our highly competitive markets, the specifications for the functionality and styling of new products, as well as the timing of their introductions and the extent to which technical information and spare parts will be made available have all become strategic business decisions (Freedman, 2013; Rainey, 2005; Roozenburg & Eekels, 1995; Mayo, 1993; Porter, 1980).

At present, the role of most industrial designers is limited to generating and proposing design solutions in the form of concepts and designs for tangible products that support the strategic objectives of a company that have already been set out in conjunction with, or are often determined by, the capabilities, limitations and plans of other functions within the larger company, such as production and marketing.

More elaborate discussions of the product innovation process, strategy (development) and (the roles of) marketing can be found in Appendix A: The Product Innovation Process, Appendix C: The Strategy Concept: Definition, Evolution and Ontology and Appendix D: The Marketing Concept: Definition, Evolution and Roles.

As part of the domain of sustainable product design, the discipline of eco-design is well developed and recognized. It provides product designers with a design methodology, i.e., a range of guiding principles, eco-design strategies, and methods, for systematically integrating environmental aspects into product design with the aim to improve the environmental performance of the product throughout its whole life cycle (Pigosso et al., 2015; Bovea & Pérez-Belis, 2012; EC, 2009a; Luttropp & Lagerstedt, 2006; Tischner et al., 2000; Brezet & Van Hemel, 1997).

The thesis argues, however, that there is a fundamental distinction to be made between eco-design and product design for a circular economy, i.e., circular product design, and that this means that circular product design requires a new, or at least an adapted, design methodology.

Relative vs. Absolute Perspective on Sustainability

The most important difference between eco-design and circular product design is of a methodological nature. The current design methodology (i.e., guiding principles, strategies, and methods) for product lifetime extension as proposed by eco-design is rooted in the here and now (which is the linear economy). One important guiding principle in eco-design is the European waste hierarchy (EC, 2009b), which assumes that all products at a certain time inevitably will become waste. Eco-design is what Faber, Jorna & Van Engelen (2005) and De Pauw (2015) refer to as a *relative* approach. It *"starts with the present state of affairs and identifies existing problems, which people subsequently attempt to solve. Improvements take place incrementally … In contrast to the absolute approach, the focus of this relative approach is not the good, but the less worse or better"* (Faber et al. 2005, p. 8). It is precisely this focus on existing problems that was critiqued (e.g., De Pauw 2015), because how can designers come up with truly sustainable or circular innovations if the current methods only lead them to optimize what is already there? This led design thinkers such as McDonough and Braungart (2002), Benyus (1997), and Webster (2015) to propose more absolute approaches. In contrast to relative approaches, absolute approaches to sustainability (Faber et al., 2005) start with *"an idealised end state"* (Faber et al., 2005, p. 3) or "the good" instead of "the less worse or better" (De Pauw, 2015; Faber et al., 2005). Systematically working back and forth to close the gap between there and here, absolute approaches to sustainability aim to mimic a closed loop, type III ecology (Graedel & Allenby, 2003; Lifset & Graedel, 2002) (see figure 1.2.1) as closely as possible. In such a cyclic, type III ecology, *"resources and waste are undefined, because waste to one component of the eco-system represents resources to another"* (Graedel & Allenby, 2003, p. 50). With its end-goal of realizing an envisioned future socio-economic system that is inherently sustainable (De Pauw, 2015) and its dismissal of the concept of waste, the thesis considers the circular economy concept to be such an *absolute* approach to sustainability.

1

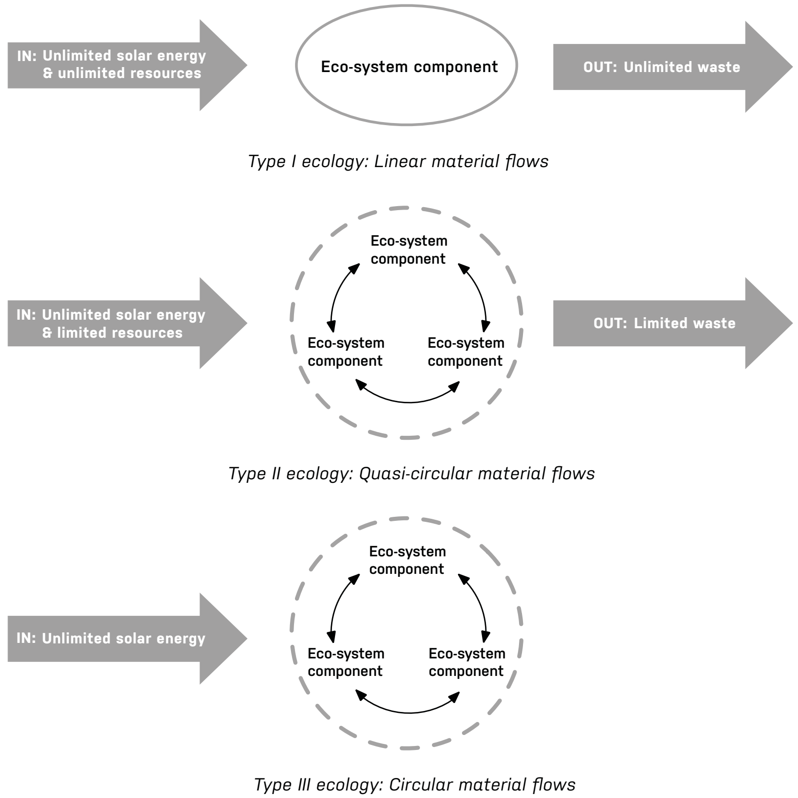

Figure 1.2.1: Ecosystems vary according to the circularity of their resource flows, ranging from a type I ecology that is the least circular and most reliant on external resources and sinks, to a type III ecology that has the greatest degree of circularity and least reliance on external resources and sinks (Lifset & Graedel, 2002). Adapted from Lifset and Graedel, 2002 and Graedel and Allenby, 2003.

So far, absolute approaches have been viewed by many as utopian, impractical, and unnecessarily normative. Some researchers have argued that the end result of both types of approaches in practice will largely be the same, as *"an envisioned ideal may need to be watered down to make it achievable in the short run"* (Wever & Vogtländer, 2015, p. 517). This however does not necessarily have to be so. Absolute approaches to sustainability, not being constrained to solving problems in the limited context of the here and now, could prove advantageous over and complementary to relative approaches to sustainability for two reasons. The first is that because absolute approaches imply notions of an ideal state (i.e., the circular economy as an ideal state), they can challenge industrial designers to strive for such an ideal state, thus opening up a wider solution space and an increased likelihood of finding innovative solutions (De Pauw, 2015). This could lead to new solutions that may not be evident or considered viable when the problem is viewed from a relative, in this instance linear economy, perspective (Maxwell & Van der Vorst, 2002; De Pauw, 2015), but which emerge only when the problem is allowed to be considered in a different (socio-economic) context. The second reason is that, because of its widened perspective, an absolute approach can help industrial designers avoid what Ehrenfeld (2008) and Braungart, McDonough and Bollinger (2007) saw as one of the dangers inherent to a relative approach to sustainability, namely that interventions aimed at increasing eco-efficiency might unintentionally *"have adverse effects if the underlying problems are not addressed"* (De Pauw, 2015).

Reducing Environmental Impact vs. Preserving Added Economic Value

The second ground for distinction flows from the fundamental methodological difference mentioned above. Eco-design and the circular economy concept can both be traced back to industrial ecology and environmental management. In theory, they have by and large the same goals, i.e., *"dematerialization"* (Heiskanen, 1996, p. 2) and *"detoxification"* (Heiskanen, 1996, p. 2), and use similar approaches. In practice, however, eco-design and circular product design differ as a result of the relative emphasis they put on the different approaches to achieve those goals, e.g., through *"resource efficiency"* (Heiskanen, 1996, p. 2) or *"narrowing"* (Bocken, De Pauw, Bakker & Van der Grinten, 2016, p. 309) resource flows, *"product life extension"* (Heiskanen, 1996, p. 2) or *"slowing"* (Bocken et al., 2016, p. 309) resource flows and *"product recyclability"* (Heiskanen, 1996, p. 2) or *"closing"* (Bocken et al., 2016, p. 309) resource flows or creating *"resource loops"* (Bocken et al., 2016, p. 309). This is most visible in those instances where these particular approaches work against each other. For example, making a product lighter to reduce resource consumption may decrease its durability if taken too far (Heiskanen, 1996). As a relative approach to sustainability, eco-design is focused on reducing the environmental impact across a single product life cycle, whereas the circular economy concept and circular product design by virtue of their absolute end-goal of no waste must focus on preserving added economic value during and across multiple product use cycles, i.e., keeping products and materials in the economic system for as long as possible, hence their emphasis on product lifetime extension. In the above light weighting example, eco-design would opt for interventions promoting resource efficiency and materials recycling. Product design for a circular economy would put more emphasis on interventions for slowing resource flows through lifetime extension at product level, such as product reuse, maintenance, upgrading, repair, refurbishment and remanufacturing (WRAP, 2017; EMF, 2015; 2014; 2013; 2012).

Limited Consideration of Business-Economic Context

The third difference between eco-design and circular product design pertains to the extent to which they take the business-economic context of products into consideration. From the perspective of a relative approach to sustainability like eco-design, companies can decide to limit interventions for reducing the environmental impact once they become too costly and can decide to expel materials that cannot profitably be recycled from the economic system as waste. This has allowed eco-design to work within the boundaries of conventional business models based on transfer of product ownership and largely ignore business-economic implications beyond that of cost. In an absolute approach to sustainability, such as the one taken in the circular economy concept, however, companies must strive to limit the environmental impact of their products to a level that can be tolerated and sustained indefinitely by nature. They are no longer allowed to expel materials that cannot profitably be recycled as waste and must keep products and materials in the economic system for as long as possible. In order to protect their capacity to generate wealth in the face of these environmental requirements, these companies (and thus circular product design) must focus on preserving added economic value, i.e., extending product lifetimes. However, because most purchases in saturated markets (as most of our markets for products currently are (Bayus, 1991)) are replacement purchases, long and extended product lifetimes do not go well with the transfer of product ownership-based business model types that are currently prevalent in companies built around products (Malone et al., 2006)). Contrary to eco-design, circular product design must therefore challenge these conventional, transfer of product ownership based, business model types and take into account (changes to) the wider business-economic context, such as the introduction of alternative business model types (e.g., Antikainen, Lammi, Paloheimo, Rüppel, & Valkokari (2015)) for the products to be designed.

Product lifetime extension is widely considered one of the most promising options for effectively reducing the rate at which our economy uses up natural resources and produces waste (e.g., Den Hollander et al., 2017; SER, 2016; EMF, 2015, 2014; 2013; Tukker, 2015; Stahel, 2010; Cooper, 2010; Vezzoli & Manzini, 2008; Heiskanen, 1996), provided it is applied sensibly and selectively as *"extended product lifetime is not per definition an environmental improvement"* (Van Nes & Cramer, 2005, p. 287). It is recognized in the literature (e.g., Bakker, Wang, Huisman & Den Hollander, 2014; Burns, 2010; Van Nes & Cramer, 2005) that it sometimes is preferable to shorten the lifetime of a product. Some academics (e.g., Charter & Tischner, 2001; Tischner et al., 2000; Van Hemel, 1998) therefore prefer to speak of product *"lifetime optimisation"* (Van Nes & Cramer, 2005, p. 287), maximizing a product's *"utilization time"* (Sirkin & Ten Houten, 1994, p. 229), or of striving for *"appropriate longevity"* (Burns, 2010, p. 51) of a product instead, referring to the process of altering (i.e., either shortening or lengthening) the lifetime of a product to minimize or reduce its environmental impact over its life cycle. In most instances, however, with the notable exception of cases where an existing product is significantly less energy efficient than a newer, replacement product, extending the lifetime of a product is the desired option from an environmental point of view (Van Nes & Cramer, 2005).

1.3 Research Gap, Aim, Questions, Approach and Scope

1.3.1 Research Gap

With the growing interest in the circular economy (Korhonen et al., 2018; Bressanelli, Peronoa & Saccani, 2017; Linder & Williander, 2017; Prendeville & Bocken, 2017; Geissdoerfer, Savaget, Bocken & Hultink, 2016; Lewandowski, 2016; Rizos et al., 2016), product lifetime extension (and its potential implications for industrial designers and industry) have been put firmly back on the agenda: *"CE highlights the importance of high value and high quality material cycles in a new manner"* (Korhonen et al., 2018, p. 45).

The thesis argues that the field of eco-design has not explored product lifetime extension in sufficient detail (see section 1.2). In spite of the sizeable body of literature in support of the potential environmental and economic benefits of extended product lifetimes and the increasing recognition of the role of business models as vehicles for promoting environmental and social sustainability (Bocken, Short, Rana & Evans, 2014; Boons & Lüdeke-Freund, 2013), the literature (both scientific and grey) that focuses on the industrial design implications of business model types for extended product lifetimes in a circular economy is sparse (e.g. Den Hollander et al., 2017; Bocken et al., 2016; Bakker, Den Hollander, Van Hinte & Zijlstra, 2014). The effect of the business-economic context of products on their lifetime, for example, has repeatedly been reported in both the business and sustainability-oriented literature (e.g., Reim, Parida & Örtqvist, 2015; Tukker, 2015; Tukker & Tischner, 2006; Tukker, 2004; Mont, Dalhammer & Jacobsson, 2006; Mont, 2004, 2002; Swan, 1970; Levhari & Srinivaran, 1969). Research on extending product lifetimes within eco-design, however, has so far mainly been focused on developing strategies and approaches for safeguarding the technical functionality of tangible products over time, for example prevention engineering (Stahel, 1994), design for repair, design for maintenance and design for upgradability (Van Nes, 2003), and for enabling products to, at least in theory, evoke a lasting emotional response from their individual users, for example design for emotional durability (Chapman, 2009), design for product attachment (Mugge, 2007) or design for mindfulness (Grosse-Hering, Mason, Aliakseyeu, Bakker & Desmet, 2013).

In the literature of the business sciences, research into business model types for extended product lifetime is almost non-existent. Existing research on product lifetime and product lifetime extension has so far mainly focused on operational, e.g., process and management, aspects relating to different modes of product life extension and closed-loop supply chains (e.g., Govindan, Soleimani & Kannan, 2014; Guide Jr. & Van Wassenhove, 2009; Linton & Jayaraman, 2005; Guide Jr., Harrison & Van Wassenhove, 2003). Other business sciences research into product lifetime extension is concerned mainly with reducing costs and risks associated with product lifetime in business-to-business processes like reducing downtime, for example in manufacturing, or with the mitigation of operational risks and/or reduction of operational cost in obsolescence-sensitive industries such as aviation and defence (e.g., Zheng, Terpenny & Sandborn, 2016; Bartels, Ermel, Sandborn & Pecht, 2012; Rojo, Roy & Shebab, 2010).

As a result of this limited attention paid to, and the narrow and relative perspective on, product lifetime extension in the fields of sustainable design and the business sciences, there currently are three problems from a research perspective with regard to design for product lifetime extension in a circular economy. First, the current literature uses ambiguous and confusing terminology with regard to product end-of-life (Gharfalkar, Ali & Hillier, 2016; Butti, 2012) and interventions for product lifetime extension (Gharfalkar et al., 2016; Oakdene Hollins Ltd., 2007). Secondly, the current literature lacks information on the relationships between strategies for product design for a circular economy and business-economic context when designing for product lifetime extension in a circular economy. Thirdly, there is a lack of guiding principles, strategies and methods to help industrial designers implement design for product lifetime extension in a circular economy.

1.3.2 Research Aim, Questions and Approach

Nobody knows what the real form of a truly circular economy is and whether or not it could work. Nevertheless, designers should be expected to explore new avenues and promising directions. The urgency of this was expressed by the CEO of design consultancy IDEO, Tim Brown (Brown & Katz, 2011): *"It is hard to imagine a time when the challenges we faced so vastly exceeded the creative resources we have brought to bear on them"* (p. 3). To meet these challenges, however, industrial designers need an up-to-date set of principles, strategies, and methods to guide the conceptualization and embodiment of their designs.

Therefore, the aim of this thesis is to identify guiding principles, design strategies and design methods that could underpin product design for the circular economy from an absolute perspective, taking as a starting point the notion that eco-design (i.e., a relative approach to sustainability) and circular product design (i.e., an absolute approach to sustainability) differ on a fundamental level. The thesis asks the question: If we accept the *absolute* idea of a circular economy as described earlier (i.e., a circular economy as an ideal end-state (Faber et al., 2005) that mimics a cyclic, type III ecology (Graedel & Allenby, 2003; Lifset & Graedel, 2002) as closely as possible), how would this affect the way we design products in a circular economy and what design methodology could industrial designers use to help them design products for a circular economy?

The main research question of the thesis is:
"What design methodology can help industrial designers to design products that are tailored to match business model types for creating, delivering and capturing value from long and extended product lifetimes in a circular economy?"

The above question seeks to identify guiding principles, strategies and methods for a suitable design methodology, and adds the fit with specific business model types to reflect that industrial design is guided by business strategy and objectives (Van Boeijen et al., 2013; Adamson, 2003; Heiskanen, 1996; Roozenburg & Eekels, 1995)
To be able to provide an answer to the main research question of the thesis, a number of sub-research questions have been formulated that will need to be answered first:

A: "How can product lifetime extension in a circular economy be defined within the context of industrial design?"

Question A addresses the problem of the ambiguous and confusing terminology in the current literature with regard to product end-of-life (Gharfalkar et al., 2016; Butti, 2012) and interventions for product lifetime extension (Gharfalkar et al., 2016; Oakdene Hollins Ltd., 2007). The aim of question A is to establish comprehensive and unambiguous terminology for product end-of-life states and interventions for product lifetime extension, in terms that are intended for use by industrial designers, including an overview of possible design approaches to product lifetime extension at an abstract level, which can provide a basis for the development of guiding principles, design strategies and methods that could underpin circular product design.

B: "What guiding principles and design interventions can industrial designers use when designing for long and extended product lifetimes in a circular economy?"

Question B goes deeper into how industrial designers can best support the abstract design approaches to product lifetime extension resulting from question A with actual design interventions at the level of the tangible product. The aim of question B is to arrive at an overview of the options available to industrial designers and gain insight into the factors affecting and guiding how industrial designers make a selection from these options.

C: "What business model types can companies use to create, deliver and capture value from long and extended product lifetimes in a circular economy?"
Question C is intended to establish the different business contexts that industrial designers can expect to encounter and design for in a circular economy. The business model type that is currently most used by companies producing tangible products (Malone et al., 2006) thrives on replacement purchases. As in saturated markets (as most of our Western markets currently are (Bayus, 1991)) the frequency of replacement purchases tends to increase with shortened product lifetimes and decrease with extended product lifetimes; it follows that business models based on that particular type do not work well with extended product lifetimes and are therefore of little use in a circular economy. The aim of question C is to identify those business model types that can create, deliver and capture value from extended product lifetimes, as their particular business strategies and objectives will provide the business context for the work of industrial designers in a circular economy.

D: "What guiding principles and management strategies can businesses use when creating, delivering and capturing value from long and extended product lifetimes in a circular economy?"

Question D goes deeper into the specific economic and environmental business goals, objectives and barriers of business models that can capture, deliver and create value from long and extended product lifetimes. The aim of question D is to identify guiding principles and management strategies that can be used by these business model types to achieve those goals and surmount those barriers, as these are the principles and strategies that industrial designers would need to support with their design interventions.

E: "To what extent can some combinations of design interventions and business model types be expected to be more successful in creating, delivering and capturing value from long and extended product lifetimes in a circular economy than others?"

With the business context for circular product design and the spectrum of design interventions now established by the answers to questions A, B, C and D, the question that remains for industrial designers is which design intervention(s) to best apply when designing for a particular business model type. The aim of question E is to determine whether some combinations of design interventions and business model types are more likely to be successful than others and, if so, to identify the factors that are responsible for these differences.

1.3.3 Scope
The question of whether product lifetimes should or should not be extended from an environmental point of view is out of the scope of this thesis. The body of literature relevant to this question in the field of Sustainable Product Design is vast (e.g., Bakker & Schuit, 2017; Pérez-Belis, Bakker, Juan & Bovea, 2017; Prakash, Dehoust, Gsell, Schleicher & Stamminger, 2016; Bakker, Wang et al., 2014; Tasaki, Motoshita, Uchida & Suzuki, 2013; Yu et al., 2010; Kiatkittipong, Wongsuchoto, Meevasane & Pavasant, 2008; Kim, Keoleian & Yuhta, 2006). As of yet, however, the literature does not provide a simple answer (Bakker & Schuit, 2017). What it does make clear, however, is that answering the question is extremely complex and depends on the parameters of the particular scenario that is considered, for example product type (e.g., energy consuming or not), type of use and user (e.g., frequent or occasional use), method of measurement, geographical location and local infrastructure. The thesis works from the premise that creating economic value through extended product lifetime leads to a net reduction in environmental impact when the total environmental impact, associated with providing a certain perceived use value (Bowman & Ambrosini, 2000) over a certain period time, is lower for a single product with an extended product lifetime than it is for a product and one or more replacement products. Total environmental impact in this instance includes the environmental impact resulting from manufacture, use and interventions for product lifetime extension (Heiskanen, 1996). The concept of perceived use value is employed as the basis for comparison between products instead of the more commonly used functionality, as it reflects that product lifetime is defined in this thesis in terms of obsolescence, e.g., loss of perceived use value, instead of mere loss of function. Furthermore, while aware of its potential limitations (Korhonen et al., 2018), this thesis assumes that an absolute circular economy contributes to global net sustainability.

As mentioned in section 1.2, industrial design is driven by business objectives (e.g., Van Boeijen et al., 2013; Adamson, 2003; Roozenburg & Eekels, 1995). With regard to business objectives, the thesis adopts the literature-based premise that the purpose of any for-profit business is to make a profit (Tukker, Van den Berg & Tischner, 2006; Heiskanen, 1996) whilst at the same time serving the long-term interests of the company (Tukker et al., 2006) and its stakeholders (Stout, 2017).

The form of business ownership, e.g., whether a business is privately owned or publicly listed, often also has an influence on product lifetime, as private and public shareholder demands can differ. Privately owned companies can autonomously and for reasons of their own choose to make it their strategy to manufacture and market high grade, high quality products with a long product lifetime potential, and accept the financial consequences of their decision with no responsibilities to holders of publicly listed shares. For publicly listed companies, matters are different. Many investors in publicly traded shares are first and foremost interested in the highest, and preferably short term, return on their investment (Graham, 2006). This can limit the options available to the management of such businesses and affect their decisions with regard to sustainability issues, such as product longevity (e.g., Financial Times, 2017). Although the effect of business ownership on product lifetime decisions is acknowledged, it will not be pursued further here as the thesis adopts an absolute perspective on a circular economy and takes the presence of a business interest in product longevity as a starting point. Swan (1970) and others, e.g., Levhari & Srinivaran (1969), also have recognized the effects of market structure (e.g., pure competition, monopolistic competition, oligopoly or pure monopoly) on product lifetime decisions. Changing the structure of a market, however, is generally beyond the power of single businesses and industrial designers. The topic is therefore also considered to fall outside the scope of this thesis and will not be explored further here.

Lastly, the focus of the thesis is limited to the interaction of design strategies and business model types that concern durable consumer products, i.e., *"tangible* [consumer] *goods that normally survive many uses"* (Kotler, 1984, p. 465) and that may or may not be accompanied by intangible services. This is in line with Heiskanen (1996) who in "Conditions for product lifetime extension" stated that *"non-durables"* (p. 9), or "consumables", i.e., tangible single-use consumer goods such as foods, packaging or toilet paper (Heiskanen, 1996; Kotler, 1984), are *"mostly not relevant for PLE* [Product Lifetime Extension]*"* as they have their *"chief* [environmental] *impacts at* [the] *production/disposal stage"* (Heiskanen, 1996, p. 9).

Knowledge about the potential effects of the interactions mentioned above can be used throughout the entire product development process, from formulating goals and strategies to realization. Although they may apply and prove useful in select instances, the terminology and typologies for interventions for product lifetime extension and business models for extended product lifetimes, as well as the design approaches, design strategies and framework for product lifetime extension presented in the thesis are not intended to be applied to consumables.

1.4 RESEARCH POSITIONING, SCIENTIFIC RELEVANCE AND SOCIETAL RELEVANCE

1.4.1 Research Positioning and Scientific Relevance

The newness and scientific relevance of the research reside in that the thesis explores (design for) product lifetime extension in a circular economy from an *absolute* perspective on sustainability (De Pauw, 2015; Faber et al., 2005). This has not been done before as the sustainable design field has in the past almost exclusively looked at (design for) product lifetime extension from a *relative* perspective on sustainability (De Pauw, 2015; Faber et al., 2005). By defining product lifetime in terms of obsolescence instead of in terms of (loss of) functionality, the research furthermore highlights both the need for and the option of addressing subjective and intangible factors in coordinated conjunction with objective or engineering factors when designing for long and extended product lifetimes in a circular economy in order to (re)create and deliver lasting perceived use value. The (results from) the seven company interviews add to the extant literature by providing new insights into how factors other than the tangible product affect the manufacture and marketing of products intended to have a long or extended product lifetime. As such, the research presented in the thesis informs the discussion on the role of industrial designers in a circular economy and contributes to the body of scientific knowledge on industrial product design for a circular economy. By presenting a new terminology for product design for product lifetime extension in a circular economy and new typologies for interventions, design strategies and circular business models for preserving product integrity, the research additionally helps further design research into design for the circular economy and provides both industrial design students and practitioners with an expanded and more precise vocabulary for entering into (discussions concerning) the field of industrial product design for a circular economy.

The research contributes to (sustainable) design methodology by proposing a new methodology, i.e., design for managing obsolescence, consisting of a set of new methods that can support industrial design education and practice. In a wider context, the research also contributes to a much-needed (Korhonen et al., 2018; Bocken et al., 2014) deeper understanding of the circular economy as an absolute concept and of its potential and limitations.

A consequence of the thesis taking an absolute perspective to the circular economy concept and (design for) product lifetime extension is that a normative, prescriptive component is introduced to – and underlies all of – the work.

1.4.2 Societal Relevance

The need for effective and scalable solutions that can help to bring down the rates at which our economy uses up natural resources and produces waste to sustainable levels has at present become perhaps more pressing than ever before (Geissdoerfer et al., 2016; Markard, Raven & Truffer, 2012; Seiffert & Loch, 2005; WBCSD, 2010; Meadows, Randers & Meadows, 2004). Since the beginning of the Industrial Revolution, the rates at which we use up natural resources and produce waste through the production and consumption of products have increased exponentially (Bressanelli et al., 2017) to the extent that they have now become critical from an environmental (e.g., depletion and pollution) and economic (e.g., supply) point of view (Graedel, Harper, Nassar & Reck, 2015; Huisman et al., 2012; Köhler, 2012; Allwood, Ashby, Gutowski, Worrell, 2011; McKinsey Global Institute, 2011; UNEP, 2010). The current literature provides no indications that this pace will relent or decline in the foreseeable future (Krausmann et al., 2009). Rather, it contains indications that the pace will most likely increase. On a global level, the literature on resource consumption for example shows some evidence of relative decoupling over the past decades but – as a result of continuing economic growth – virtually none of absolute decoupling (Jackson, 2009). When these trends are extrapolated, they indicate ongoing net growth in resource consumption (Jackson, 2009). This is in line with Hoornweg & Bhada-Tata (2012) who predicted that the amount of waste that is generated globally on a daily basis will double by 2025 (as compared to 2012 levels) to a staggering total of 6.5 million tons.

The research presented in the thesis is timely and has societal relevance because the European Commission has in recent years adopted the circular economy concept as a promising solution (Geisendorf & Pietrulla, 2017; Korhonen et al., 2018; EC, 2015b) for promoting sustainability and solving, or at least mitigating, future problems caused by increasing resource use and waste production. In 2015, the European Commission presented its Circular Economy Package – including Closing the Loop, an EU action plan for the circular economy (EC, 2015b, 2017a) – to facilitate and speed up the transition to a circular economy. In 2017, the European Parliament underlined the importance of (design for) long and extended product lifetimes to a circular economy by adopting resolution 2016/2272(INI), A longer lifetime for products: benefits for consumers and companies (EC, 2017b). The provisional text of this resolution explicitly calls for *"designing robust, durable and high-quality products"* (EC, 2017b, p. 5), *"promoting repairability and longevity"* (EC, 2017b, p. 6), "*operating a usage-oriented economic model"* (EC, 2017b, p. 7) and *"measures on planned obsolescence"* (EC, 2017b, p. 9). These topics are at the heart of the research presented in this thesis, which, for the first time in the literature, explores the implications of absolute decoupling from an industrial design perspective in the context of a circular economy. In addition to contributing to a deeper understanding of the role of the industrial designer in a circular economy and of the circular economy as an absolute concept, the thesis translates these findings into a new design methodology that is intended to help practicing industrial designers (and businesses) make design decisions that will facilitate and support the transition from a linear economy and its problems, as sketched out above, to a circular economy, in line with the goals set by the European Commission.

1.5 RESEARCH DESIGN

The research in the thesis makes use of both theoretical and empirical data.

Gathering and Processing Theoretical Data

As far as the theoretical data is concerned, the thesis uses literature review as a research methodology in its own right in order to develop a vocabulary to address product lifetime extension from an industrial design and business perspective and to develop classifications (i.e., typologies) that subsequently can be used as a basis for the development of design methodology. This use of literature review differs from how literature review is more commonly used in preparation for, and contextualization of, subsequent empirical research: When literature review is used in conjunction with empirical research, the data for the empirical research is gathered from a sample taken from a population of people or objects. When literature review is employed as a methodology in its own right, however, the actual research data to be analysed is obtained from sampling the literature itself (Comerasamy, 2017).

Literature reviews can be performed in a number of different ways, ranging from what Hagen-Zanker & Mallet (2013) termed *"orthodox literature reviews"* (p. 3) to *"systematic* [literature] *reviews"* (p. 1), each with their own advantages and drawbacks (Hagen-Zanker & Mallet, 2013)

As the research presented in this thesis is explorative and needs to look for – and even depends on – connections across disciplinary boundaries, the ability to capture additional, potentially relevant information, knowledge and context by being allowed to cast a wide net is essential. For this reason, the thesis follows a variety of the systematic review approach that *"adheres to the core principles of 'full' systematic reviews but allows for greater flexibility and reflexivity in the process"* (Hagen-Zanker and Mallet, 2013, p. 5). The aim of the alternative approach as developed by Hagen-Zanker and Mallet (2013) is to mitigate some of the disadvantages of conventional systematic literature reviews whilst maintaining most of their advantages over orthodox reviews.

The process for an alternative systematic literature review as proposed by Hagen-Zanker & Mallet (2013) consists of eight main stages as pictured in figure 1.5.1. The differences between this methodology and the more conventional systematic literature review are explained in more detail below.

As can be seen from figure 1.5.1, the stages making up the alternative systematic literature review are largely in line with those of a conventional systemic literature review. The difference between the two methodologies resides in stage 5, retrieval. Instead of limiting the retrieval stage to search results based on strictly specified search strings and an exclusive focus on academic literature (e.g., *"Track I: Academic literature search"* (Hagen-Zanker and Mallet, 2013, p. 10) in figure 1.5.1), the alternative methodology allows for two additional tracks. The first of these is what is known in the literature as snowballing (e.g., *"Track II: Snowballing"* (Hagen-Zanker and Mallet, 2013, p. 10) in figure 1.5.1).

The process of snowballing allows for taking on board and examining relevant publications that did not necessarily surface in track I, based on the experience and advice of experts in the field, and also allows for working backward and forward from the references in those publications. Although this approach does introduce a degree of subjectivity into the research, due to the selection of both the experts and the publications, it also is *"extremely useful to get a sense of which literature has been important and influential in the field – which may not necessarily be the high-quality peer-reviewed journal articles"* (Hagen-Zanker and Mallet, 2013, p. 10). The second additional track (e.g., *"Track III: Grey literature capture"* (Hagen-Zanker and Mallet, 2013, p. 10) in figure 1.5.1) is intended to capture relevant materials that are located outside the realm of scientific literature, such as books, working papers or reports from industry, policy makers or other institutions. It may be evident that allowing these additional tracks to enter the systematic literature review process will sacrifice some of the rigour and objectivity associated with conventional systematic literature reviews. However, allowing them in can also help to *"increase the breadth, relevance, topicality and ultimate utility"* (Hagen-Zanker & Mallet, 2013, p. 11) of the review.

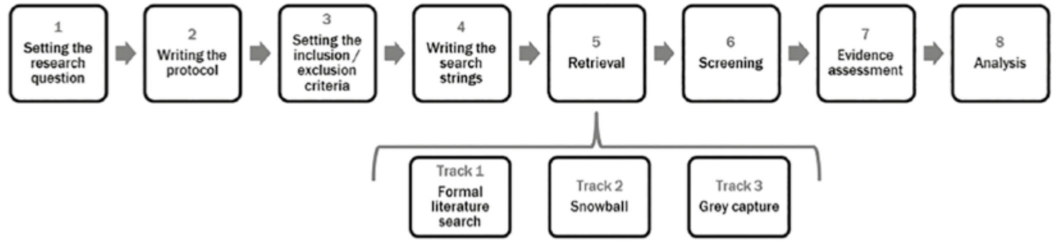

Figure 1.5.1: Literature review process as proposed by Hagen-Zanker & Mallet (2013) (from Hagen-Zanker-Mallet, 2013, p. 6)

The research presented in the thesis is explorative and intended not as an end-point but rather as a starting point for further (empirical) research and academic and societal discussion. The loss of some rigour and objectivity inherent in the chosen methodology for literature review is therefore deemed to be outweighed by the potential benefits of creating a broader base and therefore is accepted for this thesis.

The thesis applies the literature review-based research methodology as discussed above in a slightly different manner in each of the following chapters. A more detailed discussion of the particular research methodology used (e.g., search strings and inclusion/exclusion criteria) is therefore presented at the start of each chapter.

Papers 3 for Mac (Labtiva, 2016) software was used for managing documentary sources throughout the entire research project.

APA style (APA, 2013) citations are used throughout the thesis.

Gathering and Processing Empirical Data

The empirical data that is used in the thesis was collected through seven semi-structured interviews (DiCicco-Bloom & Crabtree, 2006) with representatives from companies that currently manufacture and market long-life products. A semi-structured approach was chosen for a number of reasons. The first is that the research presented in this thesis is explorative and the semi-structured interview approach allows for capturing additional information that might prove relevant, potentially contributing to new and unexpected insights. The second reason is that, as all interviewees are business professionals in managerial positions, the opportunities to go deeper into particular remarks during follow-up interviews at a later time were limited. Lastly, as the author has over 20 years of hands-on experience in commercial industrial design, the semi-structured interview approach allowed for the quick creation of rapport (DiCicco-Bloom & Crabtree, 2006) and instant exploration of emerging, but related, topics.

The interviews took place at the respective companies and were recorded using a voice recorder (after asking for and obtaining permission from the participants).

The data from the interviews was analysed and compared through repetitive, reflective immersion (DiCicco-Bloom & Crabtree, 2006) in the recordings, transcriptions and summaries, whereby the author's experience in commercial industrial design mentioned earlier provided the *"strong theoretical background"* (DiCicco-Bloom & Crabtree, 2006, p. 40) that is a prerequisite when applying this *"immersion/ crystallisation"* (DiCicco-Bloom & Crabtree, p. 40) approach. A more detailed discussion of the research methodology used for the interviews is presented in section 5.2 Methodology.

F5transkript software for Mac (Audiotranskription, 2017) software was used for transcribing the interviews.

1.6 THESIS OUTLINE

The basic structure of the thesis is presented in figure 1.6.1. As can be seen from figure 1.6.1, the thesis is divided in two main parts and a number of appendices. The first part, chapter 2 through chapter 4, aims to establish a theoretical framework for the second part of the thesis, chapter 5 through chapter 6.

PART ONE

Chapter 2 aims to provide an answer to sub-research question A: "How can product lifetime extension in a circular economy be defined within the context of industrial design?" The chapter reviews the literature on resource states and interventions for product lifetime extension and creates a comprehensive overview of the key concepts and terms that are considered relevant for industrial designers when designing for long and extended product lifetimes in a circular economy, culminating in a typology of approaches for design for preserving product integrity.

Chapter 3 aims to provide an answer to sub-research question B: "What guiding principles and design interventions can industrial designers use when designing for long and extended product lifetimes in a circular economy?" The chapter takes the typology of approaches of design for preserving product integrity presented at the end of chapter 2 as a starting point and sets out to develop the abstract design approaches into practical and actionable design strategies for preserving product integrity by reviewing the literature in search of design interventions that industrial designers can select and apply to support the various design approaches for preserving product integrity.

Chapter 4 aims to provide an answer to sub-research question C: "What business model types can companies use to create, deliver and capture value from long and extended product lifetimes in a circular economy?" The chapter reviews the literature with the aim of creating a typology of circular business models for preserving product integrity in a circular economy.

PART TWO

Using data and insights gathered from the literature and company interviews, part two brings together the separate elements from the theoretical framework established in part one with the end-goal of developing a new methodology for designing products with a long or extended lifetime in a circular economy.

Chapter 5 aims to provide an answer to sub-research question D: "What guiding principles and management strategies can businesses use when creating, delivering and capturing value from long and extended product lifetimes in a circular economy?" The objective of chapter 5 is to identify or develop guiding principles and management strategies for circular business models for preserving product integrity as these determine the objectives that design strategies for preserving product integrity should help achieve. Chapter 5 identifies maximizing business model circularity as a guiding principle and introduces managing obsolescence as a management strategy for circular business models for preserving product integrity.

Chapter 6 presents the development of a design methodology for managing obsolescence. The design methodology for managing obsolescence is intended to enable industrial designers to tailor their product designs to circular business models for preserving product integrity that strive to maximize business model circularity. The objective of chapter 6 is to create a design methodology for managing obsolescence, including a heuristic framework that expresses which combinations of design interventions for preserving product integrity and circular business model types for preserving product integrity can be expected to be successful when managing obsolescence. As such, chapter 6 aims to provide an answer to sub-research question E: "To what extent are some combinations of design interventions and business model types more likely to be successful in creating, delivering and capturing value from long and extended product lifetimes in a circular economy than others?"

Appendices
Due to the cross-disciplinary nature of its subject, the thesis reviews literature from multiple scientific domains. To provide background information for those readers who may be familiar with concepts from some of these domains but less so with concepts from others, references to the appendices are made throughout the thesis. The various appendices discuss a number of key concepts from the different scientific domains used in the thesis in a more elaborate manner. The aim of structuring the thesis in this way is to preserve the continuity of the main argument as much as possible, whilst still providing information at appropriate moments on concepts that might be less familiar to some readers.

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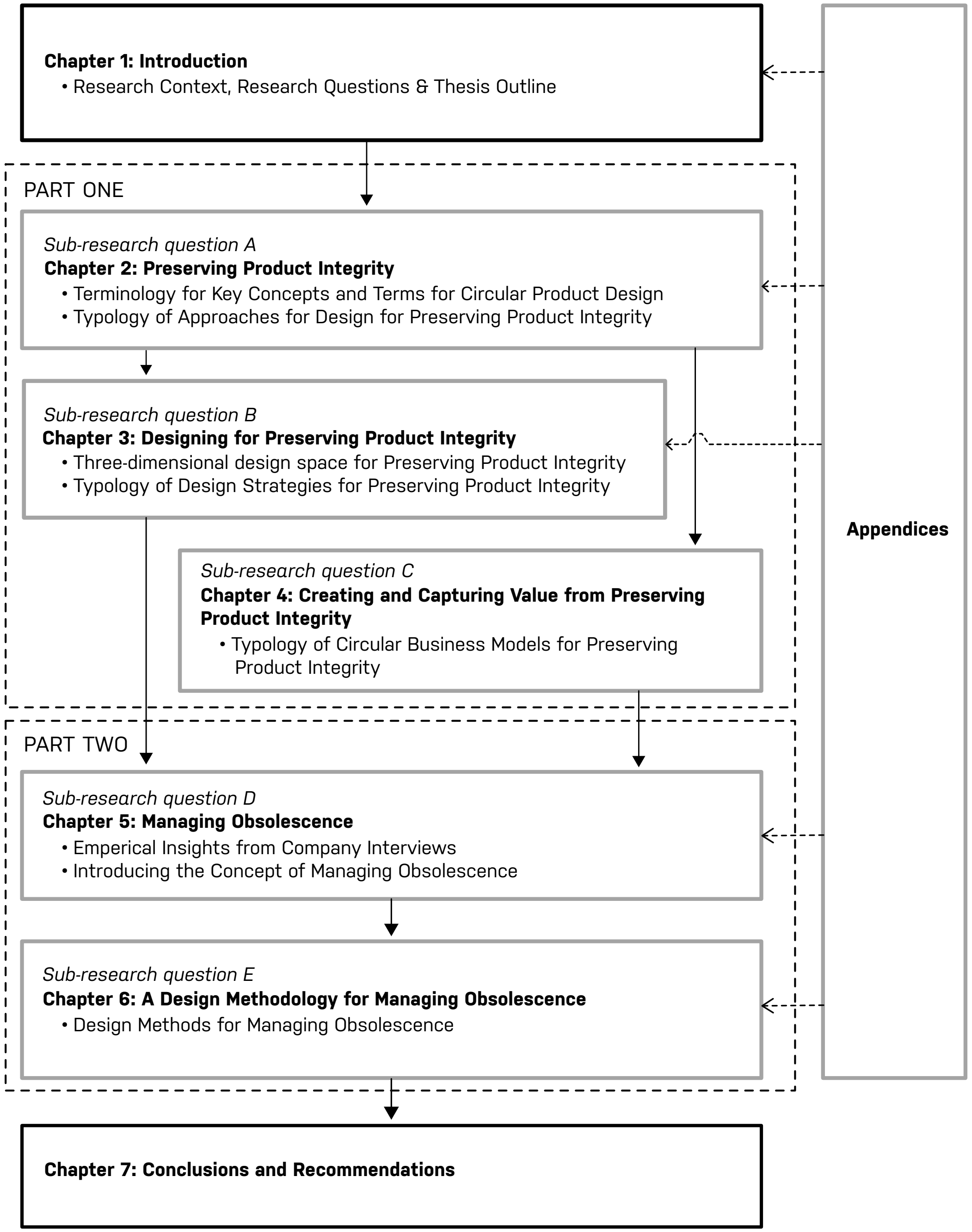

Figure 1.6.1: Thesis outline

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This thesis argues that in order to increase the likelihood that product lifetime extension in a circular economy will be successful from both an environmental and an economic perspective, industrial designers need to be able to control not only the spatial dimension (materialization and geometry) of products, but also their temporal dimension. This temporal dimension is related to the number and duration of product use cycles and the duration of the total product lifetime. To enable industrial designers to capture this temporal dimension, the thesis presents:

- a new design methodology: design for managing obsolescence;
- five new design methods and two typologies in support of managing obsolescence;
- insight into (the factors determining) how and when to best apply these methods;
- insight into where and in collaboration with whom to apply these methods in the product innovation process.

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