# DESIGNING CONSUMER PRODUCTS FOR A CIRCULAR ECONOMY IN INDUSTRY 4.0

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# DESIGNING CONSUMER PRODUCTS FOR A CIRCULAR ECONOMY IN INDUSTRY 4.0

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## Abstract

The research presented in this thesis investigates the implications of the next industrial paradigm shift, Industry 4.0, on the design of consumer products and, in turn the potential achievement of a Circular Economy (CE). As the research deals with a complex real-world problem involving emerging phenomena, a systems perspective and an exploratory, critical realist approach have been adopted.

Since industrialisation began, a linear economic model has prevailed, resulting in an unsustainable system for the production and consumption of consumer products. The CE represents a sustainable alternative, whereby products, components, materials and resources are continually cycled, creating new business models and avenues of economic growth removed from the throughput and degradation of natural capital. As such, the design of products plays an integral role in the achievement of a CE. Whilst isolated examples of products designed for a CE exist, there has not yet been widespread adoption.

Chapter 1 introduces key concepts and developments underpinning the research and provides an outline of the thesis, whilst Chapter 2 sets out the research scope. Chapters 3 and 4 then serve as 'state-of-the-art' literature reviews of *'the CE and the role of design'*, and *'Industry 4.0'*, respectively. Chapter 5 details the nature of the research, and the approach, methodology and specific research methods employed. Chapter 6 reviews pivotal historical industrial developments and their role in shaping design to date. The results provide insights into how and why the present model has come about as well as highlighting the relationship between industry and design. Chapter 7 examines existing barriers to Design for a Circular Economy (DfCE) using a series of semi-structured, in-depth interviews with designers and representatives from entrepreneurial CE companies, supported by a thematic literature review. This identifies a range of DfCE barriers associated with the task, the designer, the organisation and external elements. Chapter 8 then explores the expected design implications of Industry 4.0 through the analysis of case studies depicting early adopters of Industry 4.0 technologies, supported by selected literature. The results identify key developments, including new manufacturing capabilities, new product possibilities, changes to the design process and the transformation of business models. Chapter 9 then serves as a discussion, bringing together the results of Chapters 6, 7 and 8, to determine the potential implications of Industry 4.0 for the future implementation of DfCE.

The results of the research suggest that, as Industry 4.0 has the potential to transform both the design process itself and the technical, economic and cultural contexts within which it is carried out, the phenomenon presents new opportunities and challenges for DfCE. This represents a significant opportunity for embedding CE principles within the next industrial model. The findings are brought together in the form of a DfCE agenda for Industry 4.0, which provides designers, stakeholders and policy makers with an advanced awareness and understanding of the dynamic relationship between Industry 4.0 technologies, design and the CE, enabling a proactive response.

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## Preface

The motivation for this thesis originally stemmed from my personal interest in sustainability and previous experience developing innovative design solutions to sustainability problems with the aim of achieving a Circular Economy (CE). Having successfully exploited emerging digital technologies, such as 3D printing, to realise circular design innovations in the past, I felt it important to further investigate their potential for facilitating Design for a Circular Economy (DfCE).

The findings of the thesis should be of interest to designers as well as business leaders and high-level policy makers, particularly those with an interest or involvement in CE initiatives. In addition, design students and educators are also likely to benefit from early insights into the potential changes to the design process brought about by Industry 4.0's emergence.

The research project, entitled *'Design for a Circular Economy in Industry 4.0',* of which this thesis is a part, was deemed to comply with the *'UCA Research Ethics Code of Practice'* (Appendix A), receiving approval on 10th November 2017.

This research was funded by The Centre for Sustainable Design ® at the University for the Creative Arts, Farnham, UK.

An abridged version of Chapter 9 has been published as a chapter entitled *'Design for a Circular Economy in Industry 4.0'* in the book *'Designing for a Circular Economy'*, the reference for which is as follows:

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## Author's Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Signed 

Dated 28th April 2019

# Chapter 1. Introduction

This thesis explores the relationship between the design of consumer products, the potential achievement of a more sustainable, Circular Economy (CE) and the implications presented by the emergent phenomenon, Industry 4.0.

## 1.1 Background and Motivation

The research is motivated by the urgent need to transition to a CE as a means of avoiding environmental catastrophe, whilst securing the long-term prosperity of industry. Achieving a sustainable model of production and consumption remains a defining challenge of our time and forms one of 17 United Nations global Sustainable Development Goals. Whilst industrialisation has afforded many benefits, including technological innovation and economic development, the limitations of the existing, linear 'take-make-waste' model are becoming increasingly evident and the need for action, increasingly urgent. More natural resources are being consumed than can be regenerated and more waste and pollution is being produced than can be assimilated, resulting in the disruption of the biogeochemical cycles that support life on earth (Meadows & Meadows, 1972). The environmental impacts of this are wide ranging, from climate change to loss of biodiversity, each with several associated implications for society (Vitousek, et al., 1997). However, it is not only the environment and society that are at risk, with industry also reliant on the availability and affordability of resources and the maintenance of social and political stability, conditions necessary for sustained productivity and growth (Bakshi & Fiksel, 2003).

In recognition of the importance of both protecting the environment and securing the economic and social benefits afforded by continued industrial development, the Brundtland Report coined the term sustainable development, defined as development that,

> *'[...] meets the needs of the present without compromising the ability of future generations to meet their own needs.'* (United Nations General Assembly, 1987, p. 7)

This questioned the prevailing perception that there existed an inevitable trade-off between industry and the environment. As such, it was suggested that both could prosper simultaneously through targeted technological advancement, global collaboration and careful planning by governments and businesses.

Faced with increasing pressure from concerned consumers and increasingly stringent government legislation, businesses have since set about implementing measures to mitigate the impacts of their activities on the environment. However, it has become apparent that, despite the efforts of industry, the gap between our current path and a sustainable future has grown ever greater. To date, sustainability efforts have tended to be in the form of select, incremental improvements to existing products and processes. Despite the aim of making continued progress towards the achievement of sustainable production and consumption, so called 'eco-efficiency' approaches have frequently fallen short of this goal. As noted by (Young & Tilley, 2006), there exists a tendency for companies to seek out the changes that require the least investment and disruption, and offer the greatest cost savings, rather than addressing the product features, processes or business activities that cause the most environmental harm. It has also been suggested that eco-efficiency approaches often focus solely on the production of products and fail to address issues associated with their operation, consumption and disposal, thus perpetuating adherence to a traditional, linear 'take-make-waste' economic model. Further, with increasing global populations and per capita consumption rates, a trend that is expected to continue for years to come, growth in productivity and consumer demand will likely outpace the efficiencies achieved through incremental improvements in a phenomenon referred to as the 'rebound effect' (Menoni & Morgavi, 2014). Additionally, in many cases, efficiencies can only realistically be pursued up to a certain point and will never achieve true sustainability. As such it has been argued that the continued pursuit of eco-efficiency strategies may be more harmful than helpful, providing a false sense of progress, whilst diverting efforts and resources away from the development of innovative alternatives, necessary for the decoupling of economic growth from environmental degradation (Ehrenfeld, 2005).

In recognition of the limitations inherent in eco-efficiency, there has been a growing interest in sustainability approaches that follow an alternative, eco-effectiveness[1] approach. This has seen the emergence of the concept of a CE, which may be defined as an economy that is,

> *'[…] restorative and regenerative by design and aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles.'* p.2 (Ellen MacArthur Foundation, 2015)

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[1] Eco-effectiveness is defined by Braungart, et al. (2007, p.1337) as *'[…] a positive agenda for the conception and production of goods and services that incorporate social, economic, and environmental benefit, enabling triple top line growth'.*

Whilst there have been a number of concepts that share many similarities with the CE, including the 'Performance Economy' (Stahel, 2010), 'Industrial Ecology' (Graedel & Allenby, 2010) and 'Cradle-to-Cradle' (McDonough & Braungart, 2010), it is the CE that has gained significant interest and momentum amongst academia, policymakers and industry in recent years (Geissdoerfer, et al., 2017) (Leider & Rashid, 2016) (Sauvé, et al., 2016) (Jensen & Remmen, 2017) (Ghisellini, et al., 2016) (Jawahir & Bradley, 2016) (Ellen MacArthur Foundation, 2015). The central premise of the CE is to ultimately decouple economic growth and development from environmental degradation and the throughput of natural resources. This is essential if true sustainability is to be achieved alongside industrial prosperity. The research presented in this thesis is therefore built on the assumption that in order to truly achieve a sustainable model of production and consumption; one that safeguards the environment, whilst ensuring the needs of society and industry are also met, it is necessary to transition to a CE.

Key to the achievement of a CE is design. This is because a CE requires the creation of new, circular products as well as supporting services and infrastructure to facilitate product life extension strategies, such as repair, remanufacturing and redistribution, and the closing of resource loops. Additionally, design benefits from being at an early stage in the new product development process. As (Bocken, et al., 2016) notes, it is considerably more straightforward, time and cost effective to design products for a Circular Economy (e.g. for ease of disassembly) than to attempt to develop 'end of pipe' solutions for the cycling of products once they are already in existence. The promotion of design as an integral element in the pursuit of a Circular Economy is reflective of the long-standing recognition of the relationship between the design of a product and its environmental impacts and inherent sustainability (Papanek, 1984) (Margolin, 1998) (Sherwin, 2004) (Walker, 2006). The research presented in this thesis is therefore also built on the assumption that design is a crucial factor in the achievement of a CE, adopting a Design for a CE (DfCE) perspective.

In recognition of the important role that design plays in determining the circularity of products, designers have often been promoted as key stakeholders in the transition to a CE (Andrews, 2015) (Ellen MacArthur Foundation, 2015) (Bocken, et al., 2016). Educating designers on CE principles has therefore become a key focus within the literature (Leube & Walcher, 2017) (De los Rios & Charnley, 2017) (Andrews, 2015). To this end, a number of DfCE tools, methods and approaches have emerged in an attempt to embed CE within design, including the Circular Design Guide (Ellen MacArthur Foundation & IDEO, 2017), The Re-Use Atlas (Baker-Brown, 2017) and A Conceptual Framework for Circular Design (Moreno, et al., 2016). However, to date, successful implementation has been limited and has been generally confined to isolated cases with relatively simple products, falling short of widespread or mainstream adoption (de Man & Friege, 2016) (Ghisellini, et al., 2016) (Murray, et al., 2017). This may be suggestive of challenges preventing implementation or a cautious approach, favouring existing design solutions that are synonymous with linear economy models over those that require a greater level of disruption and systemic change. The research presented in this thesis therefore firstly aims to explore and identify existing barriers limiting the implementation of DfCE.

A current development, that is of relevance to design and the CE, is the emergence of a fourth industrial revolution or 'Industry 4.0'. Each industrial revolution to date has been characterised by significant, transformative technological advancements; the advent of steam power in the late 18th Century saw the mechanisation of production and a move away from agrarian society, electrification in the early 20th Century facilitated mass production and division of labour, and the development of electronics and information technology since the 1970's has given rise to automation and the computerised world in which we operate today (Bloem, et al., 2014). Following suit, Industry 4.0 is now beginning to emerge, characterised, not by any singular technology, but by the networked connection of the digital and the physical world through the roll-out of Cyber Physical Systems (CPS) (Schwab, 2016).



**Figure 1.1** The progression of industrial revolutions, past to present (Roser, 2018).

Like the major industrial developments that have preceded it, Industry 4.0 is expected to result in significant, disruptive change to the way in which products are produced, consumed and therefore designed. As a result, business models and the industrial architecture that supports the production and consumption of products will also be forced to evolve and adapt. Changing any one of the following parameters; products themselves, how they are designed, who designs them and the industrial context that brings them into existence through supply and demand, has the potential to remove or reinforce existing barriers to the realisation of a Circular Economy and to present new opportunities and complications for its future implementation. However, unlike previous industrial revolutions, Industry 4.0 has not been labelled in retrospect, but rather foreseen. As (Brambley, 2013) explains, it is not an observed phenomenon, but rather a term relating to a future vision for the next stage in industry's evolution (Brambley, 2013). As a result, there is still time to shape the final outcome and there exists the opportunity to exploit Industry 4.0 to solve, not only economic, but also wider societal and environmental issues (Porter, 2016). The research presented in this thesis therefore asserts that Industry 4.0 has the potential to impact on the implementation of DfCE and, in turn, affect the transition to a sustainable model of production and consumption through the achievement of a CE.

## 1.2 Research Aim and Objectives

The overarching aim of this thesis is to develop an understanding of the potential implications of Industry 4.0 for the implementation of DfCE, mapping this live and emergent subject area to create a DfCE agenda for Industry 4.0. To achieve this, the research is broken down into the following objectives:

- To identify existing barriers currently limiting DfCE implementation.
- To understand the relationship between industry and design and the potential for industrial change to influence the way in which products are designed.
- To explore the ways in which Industry 4.0 is expected, and is already beginning, to transform the design of products.

By meeting these three objectives and synthesising the results, it becomes possible to build an understanding of the interaction between design, CE and Industry 4.0. From this, the potential implications of Industry 4.0 for DfCE implementation may be mapped, helping to achieve advanced awareness of any new opportunities and challenges.

## 1.3 Structure of the Thesis

The research presented in this thesis is structured as follows:

- Chapter 1 introduces the focus of the research, providing essential background information, a description of key aims and objectives and a statement regarding the value of the research and its contribution to knowledge.
- Chapter 2 defines the scope of the research, detailing what is to be included and what lies beyond the boundaries and limitations of the thesis.
- Chapter 3 provides a detailed review of the literature surrounding sustainability and the development of the CE concept, as well as the relevance and role of design and the emergence of DfCE.
- Chapter 4 reviews the literature on Industry 4.0, outlining the origins and emergence of the concept and providing anoverview of associated technologies and developments. The literature is also reviewed in order to highlight any existing insights regarding the relationship between Industry 4.0 and DfCE.
- Chapter 5 outlines the epistemological and ontological positioning of the research and provides an overview of the methodological approach and research methods adopted.
- Chapter 6 examines the relationship between industry and design through the review and analysis of key historical developments.
- Chapter 7 identifies existing barriers to DfCE, combining a review of the available literature and the results of a series of qualitative interviews with designers and representatives from entrepreneurial CE companies.
- Chapter 8 explores the potential impacts of Industry 4.0 on design, presenting the results of a literature review supported by an analysis of case studies depicting early adopters of Industry 4.0 technologies.
- Chapter 9 synthesises the results of Chapters 6, 7 and 8 to provide an analysis of the DfCE implications of Industry 4.0, mapping the research area and creating a DfCE agenda for Industry 4.0.
- Chapter 10 summarises the findings of the research, presenting key conclusions. It also provides a discussion of the potential applications of the research, its limitations and suggested opportunities for further research.

### 1.4 Research Value and Contribution to Knowledge

The research presented in this thesis serves as an original contribution to knowledge in several ways. Firstly, by bringing together consideration of the fields of design, CE and Industry 4.0, it presents a new area of research with significant potential for further enquiry. Through the provision of a high-level exploration of key topics, this thesis successfully maps the research area providing researchers with a structured orientation, helping to highlight opportunities for future projects. Whilst several publications focused on Industry 4.0 and CE have begun to emerge since this research was conducted, thus confirming its relevance and importance, the adoption of a design perspective remains a distinguishing, original factor.

The results of the research, whilst preliminary, also present valuable initial insights into the implications of Industry 4.0 for the implementation of DfCE. The value of this is in the timing, as Industry 4.0 is at an early stage of development, which provides an opportunity for early intervention and to shape the next industrial paradigm and associated design developments towards a CE. Looking beyond the central focus of the thesis, the results from each of the individual research chapters may also prove useful for other applications. The historical review in Chapter 6, for example, collates valuable insights into the role of design and its relationship with industry, providing a new perspective on their co-evolution. Additionally, the barriers to DfCE implementation, as identified in Chapter 7, may serve as valuable insights for designers, educators, businesses and policy makers attempting to facilitate the transition towards a CE and wanting to avoid common pitfalls. Further to this, the advanced understanding of the potential impacts of Industry 4.0 on design, as presented by Chapter 8, may also prove useful for designers considering their future role. Businesses may also benefit should it help them to prepare for possible disruptions and capitalize on new opportunities.

Finally, the success of the thesis as a research project serves as a valuable example of a theoretical and methodological approach suitable for investigating complex, solutions-oriented and transdisciplinary sustainability science problems. This is also a developing subject area in need of practical examples and guidance for researchers operating in this space.

# Chapter 2. Research Scope

This chapter will set out the scope of the research presented in this thesis, providing justification for the decisions made regarding what is considered relevant in order to meet the aims and objectives of the project.

## 2.1 Circular Economy

This research is centrally concerned with the Circular Economy (CE) as a means of achieving sustainable production and consumption. For the purpose of this thesis, the following definition of the CE is adopted:

> *'The circular economy is one that is restorative and regenerative by design and aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles.'* p.2 (Ellen MacArthur Foundation, 2015)

The existence of other theories and models of sustainability are acknowledged in Chapter 3, where justification for the decision to focus on the CE for the purpose of this research is presented.

## 2.2 Consumer Products

As this research addresses the negative environmental, social and economic impacts of unsustainable production and consumption it is consumer products which form the central focus. Whilst it could be argued that all products, including those that are hand-made for personal use or self-expression also have an impact on the environment and consume natural resources, it is the scale and speed of industrial production and mass consumerism that makes addressing the design of consumer products so important. Products produced through art and craft practices are therefore considered outside the central scope of this research, although they may be later explored in the context of assessing alternative models of production and consumption following Industry 4.0.

The COBUILD Advanced English Dictionary (2019) defines the term 'consumer' as *'[...] a person who buys things or uses services'* and the term 'product' as *'[...] something that is produced and sold in large quantities, often as a result of a manufacturing process.'*

Within this thesis, *'consumer products'* are therefore considered objects that are manufactured and sold in large quantities, which are then purchased and used by people (as opposed to businesses).

Whilst the thesis does not narrow the definition of consumer products to specific product categories, apparel, electronics and furniture were chosen as key examples, providing a varied cross-section. Although it is acknowledged that different consumer product categories demand different design solutions in order to become better aligned with a CE model, this research adopts a higher-level perspective. As such, it is focussed on the wider processes through which design decisions, which in turn determine final consumer product outcomes, are made within an industrial context, rather than any particular type of consumer product.

### 2.3 Design

'Design' is a pervasive yet complex term for which there exist many interpretations, even when narrowed to an industrial context. These can include a creative process, a profession, a plan or drawing and a product's specification or purpose. With respect to a CE, it is the design decisions that determine final consumer product outcomes, including material composition, form, function and purpose, that are most relevant. This is because it is these features that determine the existence of mass-produced consumer products and their ability to be reused, repaired, remanufactured and recycled within a CE. The research therefore does not attempt to list product specifications or designs suitable for a CE (e.g. bio-based plastics, snap-fit components), but rather looks at how Industry 4.0 could potentially alter the design decision-making processes that determine final product outcomes and, therefore, circularity. Other aspects of design, such as the activities carried out by designers, or the plans and drawings detailing the features of a product, are covered within this research only in so far as they relate to how the specifications and purpose of a product are determined. For the purpose of this research, design may therefore be defined as the decision making process that ultimately determines final consumer product outcomes.

### 2.4 Designer

The research aims to explore the factors that influence design decision-making within an industrial context. As such, it is primarily focused on the role of the professional product designer. However, in recognition of potential limitations placed on designer autonomy and the additional factors that have the potential to influence and constrain designers' decision making, the scope is widened to also take into consideration those beyond the role of the professional product designer who participate in the making of design decisions. For the purpose of this research, a 'designer' is therefore defined as someone who makes design decisions that ultimately determine final consumer product outcomes.

## 2.5 Design for a Circular Economy (DfCE)

For the purpose of this research, Design for a Circular Economy (DfCE) is defined as the integration of CE principles into the product design process. DfCE remains a developing concept, which has emerged as result of growing interest surrounding the CE and in recognition of the important role that design plays in achieving it. As such, DfCE differs from traditional product design by necessitating a multiple life-cycle perspective, with the aim of closing material loops and decoupling productivity from resource consumption and the generation of negative externalities, such as waste and pollution.

## 2.6 Industry 4.0

Industry 4.0 is a collective term used to refer to industry's vision for the next paradigm shift in industrial production or 'fourth industrial revolution'. Giving rise to this are a number of technological and infrastructural developments associated with sensors, actuators, embedded chips, internet connectivity, cloud computing, Big Data, Artificial Intelligence (AI), blockchain, Virtual and Augmented Reality (VR and AR), as well as Cyber Physical Systems (CPS) and the Internet of Things (IoT). As Industry 4.0 remains an emerging and evolving concept, there exists scope for any precise definition to change as associated technologies and infrastructures materialise. As the research presented within this thesis aims to provide early insights into the potential implications of Industry 4.0 for the implementation of DfCE, attempting to formalise an exact, technical definition of the concept is considered out of scope. Instead, an overview is provided in Chapter 4, whilst the remaining research focuses on the early adoption and application of Industry 4.0 technologies and infrastructure to provide an indication of potential implications for DfCE.

# Chapter 3. The Circular Economy and the Role of Design

This chapter serves as a state-of-the-art on Circular Economy (CE) and the role of design, providing the necessary background information, context and justification for the research presented in this thesis. It begins with an overview of CE, exploring the origins of the concept and its evolution over time (Chapter 3.1). This is followed by a review of literature on the relevance and role of design in achieving a CE, the emergence of Design for a Circular Economy (DfCE) and its implementation to date (Chapter 3.2).

## 3.1 The Circular Economy

The Circular Economy (CE) is a concept predicated on the fact that humanity exists within the confines of a finite planet. The interdependent ecosystems contained within it provide essential services, including the provision of resources, regulation of conditions and cultural enrichment essential for the wellbeing and survival of society (Millennium Ecosystem Assessment, 2005). Whilst biogeochemical cycling can afford regeneration of natural resources, these too are subject to limits. Any excessive extraction or altered input into these finely balanced systems can lead to a disruption of their dynamics and a loss of regenerative capacity as a new equilibrium is sought (Smith, 2014).

### 3.1.1 Industrial Development and the Environment

Humankind has long been extracting natural resources and manipulating them into new forms to better meet their needs, however, challenges arise when resource extraction and waste production exceed regeneration and assimilation. Whilst developments in science and modern technology have improved our knowledge and understanding of biogeochemical cycles and the effects of human activity considerably, an awareness of environmental limits has existed throughout history. In the 18th century, the idea of limits pertaining to the ability for natural resources to support human populations was formalised in a theory by economist, Thomas Robert Malthus. In it, Malthus warned that continued population growth, and therefore consumption, within the agrarian society at the time, would create demands on natural resources that would eventually outstrip the rate of production, resulting in reduced living standards and a subsequent, rapid fall in population (Mebratu, 1998). In other words, the human population would reach what is known as 'carrying capacity' or the maximum population of an organism that a given environment is able to support indefinitely (Daily & Ehrlich, 1992). In the case of finite resources, the avoidance of exceeding carrying capacity therefore requires a reduction either in each individual's demand for resources or the total population. However, as illustrated by the 'tragedy of the commons' principle; a phenomenon originally observed by

(Lloyd, 1883) and later popularised by (Hardin, 1968), voluntary avoidance of exceeding carrying capacity can prove difficult to achieve, despite the threat of negative consequences. This is due to the fact that, in a freely shared commons, benefits are enjoyed by the individual, whilst costs are borne by the collective. This in turn encourages individuals to act in their own interests at the expense of the majority and of the quality and longevity of the resources available (Hardin, 1968). Nevertheless, Malthus' prediction did not come to fruition, despite continued population growth. This was due to the fact that technology afforded intensified exploitation of natural resources, increasing the rate of production and thus enabling carrying capacity to be extended (Mebratu, 1998). As the transition from an agrarian to an industrialised society progressed, production shifted from natural processes to factories, allowing output relative to input to increase dramatically, which in turn supported a significant increase in population worldwide. However, it must be noted that the ultimate limits to the carrying capacity of the earth as a finite entity, were not eliminated by technology, but rather deferred. As such, Malthus' prediction was not necessarily avoided altogether, but merely postponed (Mebratu, 1998).

Through industrialisation, the environment came to be viewed as a source of raw materials and a sink for wastes and pollution in the pursuit of economic growth and prosperity. However, as the negative impacts of industry became increasingly apparent, there emerged a renewed concern for the ability for the environment to accommodate human activity. The 1960's saw the beginning of the modern environmental movement, with Rachel Carson's (Carson, 1962) 'Silent Spring' often attributed as being one of the first publications to draw widespread attention to the fragility of ecosystems and their susceptibility to disruption from industrial processes. The publication, which focused on the deleterious effects of pesticides on biodiversity, challenged existing preconceptions about the benefits of industrial development and human intervention at the expense of natural ecosystems. Despite receiving considerable backlash from the chemical industry, Carson was successful in inspiring a modern environmental movement and in instigating an eventual ban on the widespread use of the pesticide, dichlorodiphenyltrichloroethane (DDT) (Waddell, 2000). However, whilst considered a win for ecological conservation, the outcome of Carson's publication served to highlight growing conflict between the progress of industry and the prevention of environmental harm.

Recognising this conflict, others argued that industry and environment were in fact not distinct, separate entities, but rather innately interconnected parts of a wider system. Reflecting on this, (Boulding, 1966) highlighted flaws in the 'frontier' approach of industry up to that point in viewing the environment as an endless expanse to be exploited, whereby new sources of inputs and sinks for outputs would continue to be discovered indefinitely. Instead, he advocated that the globe is a regenerative, but closed system with finite resources and a limited capacity to assimilate pollution and waste. He presented a vision for a '[...] closed economy of the future [...]' in which,

> *'[...] man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy.'* (Boulding, 1966, pp. 7-8)

In order to achieve such a vision, he explained the need to distinguish between 'exhaustible' and 'reproducible' resources and identifying wastes or 'effluvia' that can be returned to the system as inputs; concepts akin to modern CE thinking. Additionally, whilst (Boulding, 1966) commended efforts to stem isolated and acute damage to the environment, such as pollution of air and water, he advocated for a system-wide change in the economy, from one in which success is measured in terms of the throughput of resources, to one focused on the maintenance of resource stocks. The issue of posterity and the intergenerational consequences of unsustainable consumption and production were also raised. Whilst an early conceptualisation, which raised more questions than answers, (Boulding, 1966)'s theorisation presented many of the ideas that underpin the current CE ideology.

Far from realising Boulding's vision, industry remained tethered to the traditional, linear, 'take-make-waste' model as global populations continued to grow. Echoing Malthus' original theory, international organisation, The Club of Rome published their findings in a report, 'The Limits to Growth' (Meadows & Meadows, 1972), in which models depicting the continuation of exponential trends in population, industrialisation, food production, pollution and environmental degradation, were presented. Assuming business as usual, the simulations forecast an 'overshoot and collapse' scenario, whereby human population and industrial expansion eventually reach the limitations of the environment's carrying capacity, despite the extensions afforded by technological development. As such, (Meadows & Meadows, 1972) presented an ultimatum: continue along the existing trajectory and accept an inevitable, sudden and uncontrollable decline or voluntarily cap growth so that the basic material needs of the population may be perpetually met whilst remaining within the constraints of a finite natural environment.

The realisation that it was not only the environment at risk from industry's unsustainable growth, but also industry itself that would face collapse, inspired several proposals aimed at preventing the bleak predictions foretold by The Club of Rome's models. (Ayres & Kneese, 1969) had earlier proposed accounting for the externalities of industry, such as pollution, by pricing them into the economic equation. They advocated that ecosystem services, such as the capacity for the environment to assimilate wastes, were valuable and limited resources in and of themselves,deserving of a monetary valuation in order to discourage exploitation. (Schumacher, 1973)'s 'Small Is Beautiful', also highlighted the limited nature of natural capital and the economy's undervaluation of it, at least until manufactured into a saleable commodity. Instead, he advocated for a human-centric economy and society, arguing that centralisation and mass production had resulted in growth that had become progressively further away from real human needs, whereby monetary profit was valued over fulfilment. (Schumacher, 1973) therefore argued instead for the use of intermediate and appropriate technology, as well as the return to an economy on a 'human-scale' that is comprehensible in human terms. Later, (Georgescu-Roegen, 1977, p. 361) introduced 'bioeconomics', which set out to reinforce the *'[...] biological origin of the economic process [...]'* and industry's dependency on the environment for continued growth and prosperity. He also emphasised the relevance of social dimensions, noting that resources were not only finite in terms of the planet, but also unevenly distributed geographically and allocated through unfair economic influences, such as developed nations' greater buying power. (Georgescu-Roegen, 1977) therefore, advocated for the voluntary degrowth of developed nations, doing away with what he deemed to be unnecessary consumption. The aim of this was to allow developing nations to catch up, so that all could achieve a sustainable level of development, within the constraints of the earth's resources. Taking a macro-economic perspective, (Daly, 1973, p. 58) advocated for a steady state economy, in which,

> *'[...] the total population and the total stock of physical wealth are maintained constant at some desired levels by a 'minimal' rate of maintenance throughput'.*

Through this theory he aimed to reconceptualise growth and change the means by which progress was measured, with a focus on qualitative development over quantitative growth (Daly, 1973). As such, theories such as these shifted the urgency and agency back on industry and the economy to reform and take the necessary action to avoid overshoot and collapse.

Whilst theories such as these were effective in highlighting the interdependency and complexity of the relationship between the economy, environment and society, calls for voluntary limits to growth contradicted the prevailing economic model, drawing a number of criticisms (Geissdoerfer, et al., 2017). As a result, it attracted a negative response from industry and economists, who suggested that the restriction of industrial growth would limit the innovation necessary to develop less environmentally damaging practices and technical solutions (Higgs, 2014). Those that believed economic growth was essential for improving environmental outcomes argued that there existed a 'poverty-environmental-degradation gap' whereby poverty encourages the immediate and intensive exploitation of resources at the expense of long-term sustainability, in turn leading to further exacerbation of poverty and environmental degradation (Neumayer, 1999). Technology was therefore promoted as a means to help lift communities in developing countries out of poverty and a perpetual cycle of environmental destruction (Mebratu, 1998).

Others were more sceptical of technology's potential as a 'silver bullet' solution. They argued that, just because technology had afforded an extension to the earth's carrying capacity in the past, didn't mean that this would necessarily continue indefinitely. Eventually, the hard limits of a finite world would be realised (Schumacher, 1973); (Meadows & Meadows, 1972). Further to this, (Commoner, 1972) questioned the effectiveness of existing technological solutions to environmental problems, highlighting instances where impacts had merely been displaced rather than eliminated; sometimes producing worse outcomes than the activities they set out to mitigate. At the same time, (Ehrlich & Holdren, 1971) questioned the focus on industry and technology, arguing that population growth was the most influential factor threatening an overshoot and collapse scenario. An exchange between Ehrlich, and Holdren and Commoner eventually culminated in the development of the 'IPAT equation', in which environmental impacts (I) are a function of population (P), affluence (A) and technology (T) (Chertow, 2001). Nevertheless, the exact relationship between environmental degradation, economic growth and social development continued to serve as a matter of contention (Neumayer, 1999). Seeking a way forward, (Ridker, 1973) concluded that neither extreme; i.e. preserving the environment by limiting or stopping growth or simply assuming that 'business-as-usual' could be relied upon to achieve environmental and social posterity, would likely provide a solution. This was evident of a wider realisation that technology alone would not be sufficient to prevent environmental and industrial collapse should unsustainable practices continue, highlighting the need for purposeful and coordinated industrial and social reform, with the promotion of governance and international cooperation as a key factor (Elkington, 2004).

### 3.1.2 Sustainable Development

The change in sentiment by the 1980's was reflected in the United Nations (UN) report 'Our Common Future', otherwise known as the 'Brundtland Report' (United Nations General Assembly, 1987), which is often considered the origin of the 'sustainable development' concept. Taking the middle ground, it suggested that development could help to resolve environmental and social issues, however, only if consciously and intentionally shaped in order to do so.

> *'[...] it [sustainable development] can be consistent with economic growth, provided the content of growth reflects the broad principles of sustainability and non-exploitation of others. But growth itself is not enough'* (United Nations General Assembly, 1987).

Development would therefore need to remain within limits as determined by the technological advancement and social organisation present at the time (Geissdoerfer, et al., 2017). Establishing sustainability within the agenda of the international political community, the Brundtland Report defined the term 'sustainable development' as that which,

> *'[...] meets the needs of the present without compromising the ability of future generations to meet their own needs'* (United Nations General Assembly, 1987, p. 43).

To this end, it proposed that economic growth and environmental conservation need not be considered mutually exclusive, but rather reciprocal objectives, with priority given to the advancement of developing nations and the alleviation of poverty (Mebratu, 1998). It also introduced a temporal element, setting out to address, not only immediate, but also intragenerational sustainability, adopting a long-term perspective (Sauvé, et al., 2016). Sustainable development, as defined by the Brundtland Report, therefore gained traction internationally, becoming a global policy objective that remains relevant to this day (Stern, et al., 1996). Sustainable development therefore provided an optimistic way forward, encouraging governments, policy-makers and industry stakeholders to come together to create a world that would be mutually prosperous for society, the economy and the environment.

### 3.1.3 Practical Implementation of Sustainable Development

Whilst there exists great value in its provision of a succinct, unifying goal, critics of sustainable development have argued that its inherent ambiguity has hampered its practical implementation and left the concept open to misappropriation and misinterpretation (Lélé, 1991); (Harding, 2006); (Loorbach & Rotmans, 2006); (Holden, et al., 2014). As a broadly defined goal, it does not specify the means by which it shall be achieved (Sauvé, et al., 2016). As noted by (Webster, 2013), a systems perspective is essential to the success of sustainable development and it is this that has been lacking in the two decades since the concept's introduction. Although localised and acute environmental damage has been progressively addressed by legislative incentives and controls, such as the European Union's Integrated Pollution Prevention and Control Act, the wider achievement of sustainable development has largely been left to the voluntary actions of individual companies and firms (Glavič & Lukman, 2007). Translating sustainable development into business-friendly terms, Elkington coined the succinct 'triple bottom line' concept to appeal to corporate social responsibility (CSR) professionals (Elkington, 2004). The term set out to encourage businesses to address 'people', 'planet' and 'profit' by developing 'win-win-win' solutions. Nevertheless, whilst many different approaches have been implemented by industry, such as reducing carbon footprint, a systems-wide transition away from the linear, 'take-make-waste' economy has not materialised.

As previously noted, economic growth, the essential, bottom-line objective of traditional businesses, does not necessarily equate to reduced environmental impacts. In many cases, addressing sustainable development has therefore represented an additional task, supplementary to core business activities. As facilitating reductions in waste, pollution and the consumption of energy and raw materials also afford reductions in costs, efficiency improvements have offered a clear financial incentive. Eco-efficiency has therefore proven a popular means of translating sustainable development into tangible and viable actions for businesses to take (Solem & Brattebo, 1999).

### 3.1.4 The Limitations of Eco-efficiency

Several questions have, however, since been raised as to the ability for efficiencies and incremental improvements to amount to long-term sustainable development. One such concern is that, by focusing on the impacts of existing, individual processes and their gradual reduction, opportunities for new, integrated solutions may be missed (Hellström, 2006). Another point raised by (Young & Tilley, 2006) is that there exists a tendency for businesses to selectively address those inefficiencies that demand the least disruptive course of action or which present the greatest potential financial reward, rather than those with the greatest environmental impact. Further to this, without a clear, overarching strategy and objective, there exists a tendency for the implementation of ineffectual activities, contributing to what is known as ‘green washing’, whereby the appearance of taking action is given, whilst the most damaging impacts associated with core business activities continue (Baumgartner & Ebner, 2010). Additionally, actions taken to improve efficiency in one area of a business can have unforeseen, negative consequences in another, leading to a net loss of environmental performance (Hertwich, 2005). This is commonly referred to as the ‘rebound effect’; a concept originally observed by Khazzoom & Brookes who identified a tendency for energy efficiency measures to lead to increased energy consumption due to behavioural and systems responses to simultaneous cost reductions. Building on this concept, (Hertwich, 2005) extrapolates this to the field of industrial economics, relating it to production and consumption, and identifying several mechanisms through which efficiencies may be counteracted through direct and indirect feedback mechanisms. The potential for gradual improvements to eventually result in a truly sustainable system is also questioned by (Arrow, et al., 1995).They express scepticism at the long-standing suggestion that environmental impacts can be expected to worsen before they improve in order to allow development to take place and for technological solutions to materialise, often referred to as the ‘inverted-u curve’ model. This is because such a simplified model is not be reflective of a real system, where changes and adjustments may simply see the impacts of one activity deferred to another. Additionally, with globalisation, production may be outsourced and any associated impacts transferred to other countries, These may then exacerbated by growing consumption rates in countries where the impacts are no longer directly experienced by consumers (Arrow, et al., 1995). Taking a macro perspective, (Menoni & Morgavi, 2014) also highlight the fact that even when efficiency and incremental improvement can be successful in addressing the most polluting activities, more general trends, such as growing populations and per capita consumption, can still outpace efficiency savings. (McDonough & Braungart, 2010) were also strong critics of eco-efficiency approaches to sustainable development, noting that efforts that simply maximise value comparative to negative impacts, i.e. ‘produce more with less’, would only ever slow the rate of demise, rather than offer a solution and viable alternative.

> *‘Plainly put, eco-efficiency aspires to make the old, destructive system less so. But its goals, however admirable, are fatally limited.’* (McDonough & Braungart, 2010, p. 85)

They also highlight that, beyond easy wins, efficiency is restrictive, placing limits on industry, which limits the potential extent of its implementation. It was therefore argued that the potential for eco-efficiency strategies to achieve a truly sustainable outcome whilst remaining within a linear economy is, at best, limited and, at worst, counterproductive (Dyllick & Hockerts, 2002).

### 3.1.5 The Benefits of Eco-effectiveness

As an alternative solution, (McDonough & Braungart, 2010) proposed a shift to an 'eco-effectiveness' approach. Modelled on nature's cycling of nutrients, the aim was to achieve an industrial model that would be regenerative by nature rather than depleting. As part of this vision they outlined several key concepts, including the idea that waste equals food, separating biological and technical nutrients and using available solar income as the source of energy. The development of more holistic approaches to sustainable development, such as eco-effectiveness, therefore represented a shift in thinking from simply addressing acute environmental issues, such as pollution prevention and cleaner production, to focusing on wider, systemic issues, such as the long-term viability of industry and the carrying capacity of the planet. As summarised by (Elkington, 2004, p. 7),

> *'Indeed, the whole concept of 'environmental protection' may be limiting our thinking in terms of the necessary scale of change required for sustainable development. Policies and regulations designed to force companies to comply with minimum environmental standards are inadequate for encouraging the creative, socially responsible entrepreneurship needed to evolve new and more sustainable forms of wealth creation [...].'*

(McDonough & Braungart, 2010) popularised their ambitious future vision for an industry built around the concept of eco-effectiveness in their book, 'Cradle-to-Cradle: Redesigning the Way We Make Things'. Published in 2002 and re-released in 2010, the book's success helped to bring widespread, mainstream awareness of the eco-effectiveness approach to sustainability, highlighting the potential to reform production and consumption through the creation of continuous material cycling loops. The rigorous Cradle-to-Cradle approach to sustainability, as presented in their book, is considered a precursory concept to the CE (Leube & Walcher, 2017).

### 3.1.6 The Emergence of the Circular Economy

However, it must be pointed out that the concept of the CE evolved from several schools of thought, including those that came before McDonough and Braungart's popular publication.

As described by (Gregson, et al., 2015), the CE represents the collation and integration of a diverse range of ideas. The Ellen MacArthur Foundation, a charity that has been an active supporter and promoter of the CE, attributes the concept's development to several schools of thought in addition to Cradle-to-Cradle. One is the 'Performance Economy', coined by Walter Stahel in 2006. Its main premise is dematerialisation through a shift from selling products to selling services or 'performance'. As such, businesses derive value from the functionality of products rather than merely the exchange of their material ownership(Stahel, 2010). The Performance Economy therefore encourages businesses to retain ownership of, and responsibility for products throughout the entire lifecycle. This in turn incentivises businesses to keep products in functional use for as long as possible. As a result, growth is decoupled from the consumption of natural resources, whilst new employment opportunities are created to facilitate asset management (Stahel, 2010). Another concept that has contributed to the development of the CE is 'Biomimicry'. The concept suggests that the greatest value provided by nature is not the material that can be extracted from it but rather the opportunity to learn from natural processes and emulate them to inform and inspire innovation (Benyus, 1997). The aim is to create a society and industry that is respectful of nature and works in harmony with natural processes rather than one that attempts to dominate or fight against it (Benyus, 1997). Another key influential idea at the heart of the CE is 'Industrial Ecology' (Ghisellini, et al., 2016). The concept aims to make structural changes to industry and society, focussing on the flow of energy and materials within and between industrial and ecological systems (Solem & Brattebo, 1999). The foundations of Industrial Ecology can be traced back to (Boulding, 1966)'s 'space-ship earth' concept and (Ayres & Kneese, 1969)'s paper, 'Production, Consumption and Externalities'. As such, Industrial Ecology introduces the idea that industry and the environment are inseparable and interdependent entities and not merely the cause of degradation and the receiver of impacts, respectively (Ghisellini, et al., 2016). Industrial ecology therefore encourages the adoption of a systems perspective, focussing on the recirculation of industrial wastes as the resources for other industrial and natural systems. It therefore requires end-of-pipe approaches to waste and pollution to be replaced with a more holistic, systems perspective (Frosch, 1992). In a similar fashion, (Turner, et al., 1994)presented a theoretical framework, which they termed 'Environmental Economics' in the 1990's. The framework highlights the link between economic dynamics and environmental repercussions, transition from linear economy to circular economy (Govindan & Hasanagic, 2018). A further concept related to CE is that of 'Natural Capitalism'. Foregrounding the economic perspective, Natural Capitalism seeks the valuing of natural and human capital in the same way that financial capital, i.e. goods and money, are valued (Hawken, et al., 2010). The four key principles outlined include; radical improvement in the productivity of natural capital through dematerialisation of products and product life extension, mimicking nature by closing material loops and designing out toxicity, implementing a 'solutions economy' in which services and product leasing business models are rewarded financially, and restoration of and reinvestment in natural and social capital (Hawken, et al., 2010). Like Natural Capitalism, the 'Blue Economy' is another approach that foregrounds the economic case for industrial reform. The concept involves the adoption of an evidence-based approach, with a focus on sharing open-source cases of disruptive innovation and entrepreneurship that demonstrate scientific and technological solutions to sustainability challenges (Pauli, 2010). As such, the Blue Economy is framed as a business opportunity with the potential to contribute to greater employment, providing additional social benefits. In doing so, it highlights the importance of ecosystem services for the economy and promotes sourcing inspiration from nature, such as the cascading of nutrients whereby the waste from one process becomes the nutrients for another (Pauli, 2010). Finally, 'Regenerative Design' serves as another contributory concept to CE thinking. It promotes the substitution of linear resource flows, inherent in a traditional economic model, with cyclical resource flows by linking together sources, consumption centres and sinks to facilitate the continuous cycling of energy and materials (Lyle, 1994). Regenerative Design proposes a pro-active design-led approach, requiring advanced planning and careful and purposeful restructuring on a system-wide level (Lyle, 1994).

From this review of contributary concepts to the CE it is evident that, whilst each takes a slightly different perspective, there exists extensive overlap and the sharing of many common themes. For example, the Blue Economy promotes technological innovation to generate solutions, whilst Regenerative Design and the Performance Economy emphasise organisational and behavioural reform. A central theme throughout, however, is a commitment to eco-effectiveness, although some consider eco-efficiency a complementary approach, as in the case of Natural Capitalism's maximisation of resource productivity. One of the successes of the CE is therefore its provision of a central focus and common term that brings together many similar and related schools of thought.

### 3.1.7 Defining the Circular Economy

As a unifying term, the CE has been defined as,

> *'...one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles.'* (Ellen MacArthur Foundation, 2015, p. 2)

At the heart of the CE is the decoupling of economic growth from environmental degradation and resource consumption (Webster, 2013). This is achieved by recirculating resources through cascading uses, distinguishing between biological and technical nutrient cycles to ensure resources are always kept at their highest potential value (Figure 3.1).

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**Figure 3.1** Circular Economy system diagram (Ellen MacArthur Foundation, 2017).

As a result, biological nutrients are returned to the biosphere, affording the restoration of ecosystems. Additionally, the CE involves switching from finite fuel resources, such as petrochemicals, to renewable sources of energy (Ellen MacArthur Foundation, 2015). As such, 'wastes' are minimised or eliminated, as they simply become the raw materials for future products, whilst the release of toxic substances to the environment is minimised and the need to extract virgin resources from the environment is reduced (Ghisellini, et al., 2016). It is this process that is referred to as ‘closing loops’ and it serves as the foundation of the CE concept, differentiating it from eco-efficiency approaches (Bocken, et al., 2016).

Another element of the CE is ‘extending loops’ whereby products are kept in functional use for as long as possible (Bocken, et al., 2016). This may be achieved by improving the condition and desirability of existing products through maintenance, repair, remanufacture or upgrade processes. Additionally, existing products may be recirculated through sharing, renting, resale and redistribution activities.

A further, complementary approach associated with CE is ‘narrowing loops’, which relates to reducing the quantity of resources incorporated into each product. Whilst (Bocken, et al., 2016) admit that, alone, this constitutes eco-efficiency, when introduced as part of a CE as a supplementary aspect to closing and extending loops, narrowing loops can help to reduce the quantity of resources in circulation at any given time and limit disruption to natural ecosystems and biogeochemical cycles.

### 3.1.8 Implementing the Circular Economy

New products are required in order to achieve the three principles of the circular economy. Product features necessary for facilitating the closing of loops include separability of different materials, such as the avoidance of adhesives and mixed materials, as well as the inclusion of materials that can be closed-loop cycled, either through chemical or mechanical reprocessing for technical materials, or returning to natural biogeochemical cycles, such as in composting, for biological materials. Features such as these ensure that biological and technical nutrients can be effectively and feasibly recovered at the end of a product’s functional life.

In the case of extending loops, there are two key approaches. The first is keeping products functional for longer. One strategy to achieve this is to create durable products that remain operational through multiple use cycles and over time. Others include the optimisation of products for life extension strategies, including maintenance, repair, upgradability and adaptability, as well as standardisation and compatibility with replacement or upgraded parts (Bocken, et al., 2016). In addition to extending the functional life of products, it’s also important to ensure that functional products remain in use, thus preventing the purchase of new products. As such, it’s important to also extend the desirability of products over time to ensure consumers remain willing to use them.  This can be achieved by incorporating elements that facilitate an emotional connection between user and product and by incorporating materials that improve with age, such as leather and wood, which acquire a patina over time. Narrowing loops also requires consideration to be given to the quantity of resources that go into each product. This can be achieved through efficiency savings, as practiced as part of eco-efficiency efforts to date. It is therefore evident that the design of products is an important determining factor, which is essential to consider when attempting to realise a CE.

### 3.1.9 Implementing the Circular Economy: New Business Models

Another key factor in CE implementation is circular business models. Whilst the material and energy efficiency afforded by narrowing loops is a favourable option for businesses, the financial incentives for closing and extending loops are less clear using traditional linear economy thinking. Closing loops requires additional investment by producers to ensure that products are suitable for end of life processing, such as disassembly and material recovery and cycling. However, in a linear economy, it is not typically the producer who stands to benefit from these changes. Instead third-party service providers, such as waste management and recycling companies, tend to be the main beneficiaries as it becomes easier and more economically feasible to recover material value from waste products. Equally, extending loops typically represents a financial disincentive when applying traditional business logic. This is because prolonging the time that a product is in use and, in theory, satisfying consumers' needs, reduces consumers' tendency to purchase new products. In a linear economy, where profits are generated through the sale of products, extending loops can therefore lead to a loss of sales. This dynamic is reflected in the trend of product obsolescence, through which marketing and product design strategies encourage consumers to discard and replace products at a faster rate (Guiltinan, 2009). In order to realise the effective implementation of a CE, new economic incentives are therefore required to encourage key stakeholders to take action, such as prolonging products' functional lives through services such as maintenance and repair, as well as returning the material value held within end-of-life products upstream to be recirculated in the industrial ecosystem (Sauvé, et al., 2016). As such, the CE demands new business models to be developed.

One alternative business model with the potential to provide the financial incentives needed to make the implementation of a CE viable is that of product-service-systems. As explained by (Boehm & Thomas, 2013, p. 252),

> *'A Product-Service System (PSS) is an integrated bundle of products and services which aims at creating customer utility and generating value'.*

As advocated by (Stahel, 2010)'s Performance Economy, there exists potential to transition from business models based on the sale of physical products to those based on product use. It is argued by (Tukker, 2015) that in a product-service-system, the production of physical products and the consumption of resources become a cost borne by the business, as opposed to the consumer, whereby the longer a product remains functional and in use, the greater the revenue generated. As such, there exists an incentive for businesses to keep products functional, desirable and in use for as long as possible, i.e. extending loops. It would also encourage businesses to be conservative about the resources incorporated into products, thus narrowing loops (Tukker, 2015). As businesses retain ownership of products, there would also exist greater potential for the collection of uniform waste streams and for businesses to implement and benefit from specialised disassembly and recycling efforts, recapturing material value and closing loops. This would also provide businesses with an incentive to optimise products for such processes. The economic growth and meeting of societal needs afforded by a CE is therefore no longer achieved by manufacturing and selling more physical products, but by keeping products and materials available and at their highest value for as long as possible, whilst selling utility (Ritzén & Sandström, 2017). However, as (Tukker, 2015) admits, the type of product-service-system (PSS) is an important factor in determining whether a CE is achieved. In product-oriented PSS, where business models remain largely tied to the throughput of products with the addition of some complementary services, the incentives for closing, extending and narrowing loops are limited. However, the further businesses move towards PSS that are based on use and, ultimately, performance, the more pronounced the incentives for a CE become (Tukker, 2015). Therefore, it is important to bear in mind that not all PSS are inherently circular, but PSS are an important facilitator in achieving a CE that makes financial sense for businesses.

The CE therefore necessitates the adoption of a much wider, systems perspective to consider products, their design, material and resource cycles, supporting services and business models and the value proposition for stakeholders across the entire product lifecycle.

> *'The circular economy is an expression of systems thinking revealed through an economy comprised of materials, energy and information stocks and flows.'* (Webster, 2013, p. 553)

It is this systems approach that has been lacking from the incremental, eco-efficiency approaches to sustainable development implemented to date.

### 3.1.10 Criticisms and Limitations of the Circular Economy

The CE is, however, not without its critics. For example, it has been argued that it foregrounds economic and environmental considerations over societal ones, with some scholars going as far as to suggest that the social element is absent from the CE model (Sauvé, et al., 2016) (Murray, et al., 2017) (Geissdoerfer, et al., 2017). However, others have suggested that the CE equally presents opportunities for all three aspects (Leider & Rashid, 2016) (Reike, et al., 2018) (Govindan & Hasanagic, 2018). In considering this point of contention, it is important to remember where the social contingent associated with sustainability originated. Sustainable Development, as detailed in the Brundtland Report, did not set out to address arbitrary social issues, but instead focused on providing developing nations with the opportunity to advance their social wellbeing and grow their economies without degrading the environment and available natural capital. Therefore, if the CE is able to facilitate the decoupling of economic growth from the throughput of resources and environmental degradation, it must go some way towards addressing the original social aspirations of sustainable development. As explained by (Stahel, 2018), sustainable development and CE are complementary terms. The former represents an objective, with happiness as its qualitative measure, whilst the latter is a strategy and means of achieving said happiness that balances ecological, societal and economic criteria (Stahel, 2018).

A further criticism of the CE is that it fails to adequately address other environmental criteria; namely energy efficiency. For example, it has been suggested that, taking energy consumption into account, solutions implemented in the name of the CE can and have resulted in greater environmental impacts than eco-efficiency solutions (de Man & Friege, 2016). Additionally, (Geissdoerfer, et al., 2017) question the sustainability of a CE given the amount of energy consumed in the recovery and recycling of materials, which can be greater than the processes involved in extracting virgin materials. However, as previously noted, the CE is not only about closing loops by cycling materials, but includes other strategies, such as extending loops. Maximising the utility of existing products to meet consumers' needs, requires fewer resources, energy and labour than the creation of new products using virgin materials (Ghisellini, et al., 2016). Further, one of the fundamental principles of the CE is 'renewability', which includes shifting away from traditional, finite energy sources, like fossil fuels, and transitioning to renewable energy, such as solar and wind (Ghisellini, et al., 2016). As explained by (Preston, 2012), such an industry-wide transition to renewables would afford a far greater reduction in impacts than that which could be achieved by improving energy efficiency on an individual process basis. It should also be noted that the CE does not demand the abandonment of efficiency, as the narrowing of loops is encouraged as a part of the concept (ElKersh & El-Haggar, 2015). As explained by (Webster, 2013, p. 547)

> *'Efficiency can support effectiveness to an extent, but it can never substitute for effectiveness. The attempt to do just that is the hubris of our age.'*

The argument regarding energy is therefore less to do with the CE as a concept and more to do with its implementation to date. Until an industry-wide transition to renewables is realised, trade-offs between the immediate energy savings associated with efficiency strategies and the long-term achievement of a CE built on renewable energy must be carefully balanced. As both approaches are not necessarily mutually exclusive, opportunities whereby efficiency, i.e. narrowing loops, and effectiveness, i.e. closing and extending loops, can both be implemented should be sought wherever possible.

There exists a similar case with regards to material resources. Whilst there already exist some examples[2], currently the technology for closed loop cycling that allows materials to be continually recirculated is not yet available for every substance. Further, achieving financial viability for recycling can prove difficult in some cases. As a result, some materials are instead downcycled[3] or become contaminated through the recycling process (Ghisellini, et al., 2016). As such, there may be trade-offs between the immediate benefits of material efficiency approaches and the future potential achievement of closed-loop material cycling in a CE. Another aspect to consider with respect to material resources is scale (de Man & Friege, 2016). Whilst precursors to the CE, such as 'cradle-to-cradle' may have promoted the proliferation of products, provided the resources contained within them could be completely returned to biological and technical cycles, such an approach is not without its impacts. As highlighted by (Mestre & Cooper, 2017), removing and even returning vast quantities of resources from and to carefully balanced ecosystems can cause significant disruption. As such, (de Man & Friege, 2016, p. 93) critique the assumption that,

> *'[...] natural nutrients can be fed into the ecosphere without any problems, regardless of their quantity.'*

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[2] Examples include Aquafil's ECONYL ®, a chemically recycled nylon, and The Teijin Group's Ecocircle ®, a chemically recycled polyester (Watson, et al., 2017)

[3] Downcycling may be defined as recycling whereby the quality of the material is reduced over time through consecutive cycles (Kirchherr, et al., 2017)

stating that,

*'This cannot be guaranteed. There are scale problems even with natural nutrients.'*

Therefore, narrowing loops with regards to limiting the quantity of materials in circulation remains an important aspect of CE implementation. Nevertheless, the return of material resources to biological and technical cycles remains largely less disruptive compared to a linear take-make-dispose economy in which materials are permanently extracted and wastes and pollution are deposited in their place.

(de Man & Friege, 2016, p. 93) present some further, less common, criticisms of the CE. They claim that material loops can never be closed as *'All production processes lead to downgrading materials.'* and that recycling operations will *'[...] cost infinite quantities of energy and infinite time'*. However, it can be argued that even today it is technically feasible to recycle materials, such as glass, without downgrading. New developments in closed-loop cycling for other materials have also begun to emerge. Examples include Aquafil's ECONYL chemically recycled nylon and The Teijin Group's Eco Circle chemically recycled polyester (Watson, et al., 2017). As new technological innovations in material cycling materialise, it is logical that more closed-loop material cycling options will become available. With regards to energy, the incorporation of renewable resources to close energy loops, as well as material loops, forms a key component of the CE concept (Korhonen, et al., 2018). Renewable energy is proving a promising endeavour, with the potential of technological advancements in renewable energy often exceeding predictions (Scheer, 2012). It should also be noted that not all material recycling efforts are energy intensive (e.g. composting) and that complementary CE strategies, i.e. extending and narrowing loops, also have a role to play in reducing the energy required to achieve a CE by closing material loops.

It is therefore evident that the criticisms aimed at the CE are less to do with the ultimate vision and concept itself and more to do with the success and degree of CE implementation to date. Technological and organisational readiness is currently a limiting factor, particularly in the case of renewable energy and closed loop material cycling. Nevertheless, as the CE concept incorporates closing, as well as extending and narrowing, resource and energy loops, solutions remaining true to the CE philosophy should still, in the vast majority of cases, present an advantage over incremental efficiency improvements and an adherence to a linear economic model.

### 3.2 Design for a Circular Economy

Design for a Circular Economy (DfCE), as explored in this thesis, refers to the integration of CE principles into the process of designing consumer products. DfCE is a relatively new phenomenon, however the link between design and sustainability more generally has been established for several decades.

#### 3.2.1 Precursors to Design for a Circular Economy

(Papanek, 1984) was one of the first to recognise and raise widespread awareness of the consequences that design decisions can and do have on the environment and society. At a time when design had become more closely aligned with engineering and also exploited as a marketing tool, Papanek lamented designers' endless creation of what he considered to be unnecessary objects with little purpose other than commercial gain (Keitsch, 2012). Tracing the social and environmental consequences of production and consumption, including waste and pollution, back to design decisions, (Papanek, 1984) effectively placed the ownness on the designer, labelling them a 'dangerous breed'. This in turn implied that designers had the power to be instigators of change, provided they had the necessary awareness, moral imperative and motivation (Keitsch, 2012).

The causational link between design and sustainability has continued to be promoted, with the common assertion that,

> *'More than 80 percent of the environmental impact of a product is determined at the design stage.'* (Ecodesign Directive 2009/125/EC, p.11)[4]

The premise for this is that the decisions made during the design stage are responsible for determining virtually all features of a product's physical manifestation, including its functional and aesthetic qualities, as well as the materials and fabrication processes employed in its creation (Olson, et al., 2011). Additionally, it is recognised that, as design represents an early stage of the product creation process, changes made during a product's design tend to be less costly than those made further down the line. This is because less resources, time and energy have been committed to any particular direction, making changing course easier and less costly. The logical deduction from this is that the design stage presents an opportunity to pro-actively

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[4] Research was conducted to establish the origin of this figure, which is frequently quoted within the wider literature concerned with sustainable design and DfCE. The earliest mention was traced back to a seminar given by The Smallpiece Trust in 1989, as referenced in (Goggin, 1994). Unfortunately The Smallpiece Trust held no record of this seminar, making it impossible to identify the original, empirical source for this figure. Nevertheless, the fact that it is often cited suggests that it is reflective of the general experience of designers.

address environmental impacts, rather than rely on reactive, end-of-pipe solutions. As a result, design has long been promoted as an important tool in leveraging the transition to a more sustainable industrial model (Earley, 2017).

Recognising design's ultimate influence on products' environmental impacts, a number of design approaches have emerged that attempt to address them pro-actively as part of the design process. One of the earliest to be developed is 'Green Design'. As explained by (Bhamra, 2004), Green Design tends to focus on a singular aspect of a product or a particular 'green' solution. This saw the development of a range of 'Design for X (DfX)' approaches focusing on specific environmental aspects, such as 'Design for Recyclability' and 'Design for Disassembly' (Ceschin & Gaziulusoy, 2016). As such, Green Design and DfX strategies represent quite a conservative attempt at integrating environmental considerations into the design process. Green design may therefore be regarded as a 'compromise measure' rather than the radical change that's required to achieve true sustainability (Margolin, 1998).

In comparison, 'Ecodesign' represents a more holistic approach through which the whole product life cycle is taken into consideration. The most significant impacts are identified based on quantitative, comparative analysis, such as Life Cycle Assessment (LCA)[5] (Bhamra, 2004) (Navajas, 2017). As a result, there exists potential for Ecodesign  to encourage designers to make incremental,  improvements, with solutions based on existing product designs.. By focusing on individual environmental aspects, these solutions may lack a systems perspective and fail to take into account wider social and economic criteria (Ceschin & Gaziulusoy, 2016). Nevertheless, with the formalisation of decision-support tools and processes, Ecodesign has been implemented with a degree of success within industry and was incorporated into the European Commission Ecodesign Directive in 2005 (Ceschin & Gaziulusoy, 2016). This initially focused largely on energy efficiency, particularly with regards to electronically powered products, however the revision of the Ecodesign Directive in 2016 has since seen a broadening of the approach to include design for longevity and the optimisation of products for end-of-life processes, such as recycling. As such, Ecodesign has become slightly more aligned with the CE (Mestre & Cooper, 2017).

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[5] Life Cycle Assessment (LCA) may be defined as a study of the *'[...] environmental aspects and potential impacts throughout a product's life (i.e. cradle to grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences'* (Klopffer & Grahl, 2014, p. 5).

Another approach, 'Sustainable Design' or 'Design for Sustainability (DfS)', follows the ethos of sustainable development, attempting to address environmental, as well as social and economic factors (Bhamra, 2004). As explained by (Mestre & Cooper, 2017, p. 1621), the main goal of Sustainable Design is,

> *'[...] the creation of new, added value, eco-efficient products or services that can stimulate the economic competitiveness of industries, while contributing to more sustainable forms of consumption and lifestyle scenarios.'*

Sustainable Design therefore adopts a more human-centric perspective, focussing on meeting the needs of society. It is also a relatively broad approach with a wider scope than that of Green Design or Ecodesign (Keitsch, 2012). As a result, applications have ranged from incremental efficiency improvements to radical innovations, leading to it being considered an umbrella term (Mestre & Cooper, 2017).

### 3.2.2 The Emergence of Design for a Circular Economy

Compared to previous approaches, such as Green Design, Ecodesign and Sustainable Design, 'Design for a Circular Economy (DfCE)' is a relatively new development, which has emerged following the recent surge in interest surrounding the CE. Recognising the role of design in achieving a CE, it aims to integrate CE principles into the product design process.

As explained in Chapter 3.1.8, the CE places an emphasis on closing material loops, differentiating it from incremental, eco-efficiency approaches. Additionally, it advocates extending and narrowing material loops, as well as transitioning to renewable sources of energy. The key, defining element of the CE is therefore its potential to decouple productivity from resource depletion, waste generation and other negative externalities (Sauvé, et al., 2016). As such, the achievement of a CE demands structural changes to the economy and production and consumption patterns. In order to address this, DfCE involves the creation of new, circular products, supply chains and business models, addressing all stages of the product lifecycle (De los Rios & Charnley, 2017). This adds to the criteria considered in the design process, including elements from material flows and service provision to the availability of supporting infrastructure and consumer behaviour (Virtanen, et al., 2017). As such, designing for a CE necessitates a holistic, system-wide approach, as opposed to a more traditional, product-centric focus (Leube & Walcher, 2017). Additionally, there exists a need for innovation and ideation to support the invention of entirely new approaches to production and consumption. This is in contrast to the strategies commonly implemented by industry, such as LCA, which begin with an existing design as a point of reference, from which adjustments and changes are made (Bakker, et al., 2014). DfCE therefore involves both the expansion of the scope of design as well as the adoption of an innovative mindset.

Several design strategies have been proposed to help guide and realise DfCE. With respect to closing material loops, the first strategy is material selection (Leube & Walcher, 2017). When designing products for a CE, designers must ensure resources incorporated into products have the potential to be regenerated, either through biological cycles, such as composting in the case of biological materials, or technological cycles, such as reuse, mechanical and chemical recycling in the case of technological materials (Bocken, et al., 2016) (Mestre & Cooper, 2017). As noted by (Mestre & Cooper, 2017), consumables and materials subject to dissipative losses to the environment should conform to biological materials. Complementary to this strategy is ensuring different materials can be separated once a product reaches end of life (Mestre & Cooper, 2017). This is necessary as combining materials can reduce their ability to be regenerated through their respective biological or technological cycles due to contamination. In addition to making sure materials are separable, designers should also consider the ease of disassembly. This is because the more difficult, complex and labour intensive the disassembly process is, the more costly it becomes, which may mean that it’s not economically feasible in relation to the material value recovered. The closing of material loops therefore requires designers to not only select regenerative materials, but also to design products optimised for disassembly and material recovery, whereby the purity of materials is maintained.

In addition to closing material loops, the CE also advocates for a transition to renewable energy to replace the linear throughput of exhaustible fossil fuel resources. As energy supply is a macro issue (i.e. determined by the available infrastructure), transitioning to renewables may be considered beyond the control of the designer and even organisations, unless a product incorporates its own energy generation. As explained by (Ghisellini, et al., 2016, p. 11),

> *‘The lesson learned from successful experiences is that the transition towards CE comes from the involvement of all actors of the society and their capacity to link and create suitable collaboration and exchange patterns.’*

What is within the scope of design is preparing products to be compatible with renewable energy supplies due to come on line in the future (e.g. prioritising electricity supply over conventional batteries). In addition to the powering of products, consideration may also be given to their production by designing features compatible with manufacturing processes that can utilise renewable energy. Therefore, whilst the wider transition from conventional to renewable sources of energy is largely an issue for the energy sector, designers have the role of optimising products ready for the transition.

In terms of extending loops, there are many strategies available to designers. The first is designing durable products that last through multiple use cycles. This may be achieved by incorporating high-quality materials and opting for a construction that provides reliable, long-term performance (Virtanen, et al., 2017). Designing accessible products that make maintenance and repair activities easy and effective may also facilitate an extension of product life (Virtanen, et al., 2017). For example, this may involve incorporating standardized components so that sourcing compatible spare parts is as simple a process as possible (Virtanen, et al., 2017). In addition to maintaining the functionality of products, designers also have an opportunity to address their long-term desirability. This follows the observation that many products are disposed of long before a loss of functionality, as a result of evolving trends or changes in consumers' needs over time. The former may be addressed by establishing an emotional attachment between consumer and product (Virtanen, et al., 2017). Examples include embedding personal meaning within a product, through means such as storytelling and customisation. Additionally, products may be designed so that their aesthetics improve with wear. An example of this is the patina that leather products obtain over time. Changing consumer needs can then be tackled through strategies, such as designing products to be upgradable and updatable to meet changing requirements (Virtanen, et al., 2017) or through business models that support the redistribution of existing products to new users (Leube & Walcher, 2017), including performance-based product service systems (PSS), product rental models and the sharing economy[6].

Another benefit of designing business models wherein companies retain ownership of their products is that products become the assets from which companies generate profit via the sale of performance (Leube & Walcher, 2017). As such, the assets used to provide that service become a cost rather than revenue stream in and of themselves (De los Rios & Charnley, 2017). This therefore provides a strong incentive for designers to improve products' material and energy efficiency, both in terms of production and operation, effectively narrowing loops. Narrowing loops through efficiency improvements such as these may be achieved using well-

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[6] The 'sharing economy' may be defined as *'[...] consumers granting each other temporary access to under-utilized physical assets (idle capacity), possibly for money'* (Frenken & Schor, 2017).

established design-decision support tools, such as LCA. Narrowing loops can also play an important role in reducing impacts during the transition to a more radical, CE model (Ghisellini, et al., 2016). The DfCE approaches discussed can therefore be summarised in Figure 3.2.

**Closing Loops**

- ⇨ Selection of regenerative materials
- ⇨ Design for biological and technical cycles
- ⇨ Design for material purity and ease of separation
- ⇨ Transition to renewable energy

**Extending Loops**

- ⇨ Extending functionality
  - ⇨ Selection of durable materials
  - ⇨ Design for durable construction
  - ⇨ Design for ease of maintenance and repair
  - ⇨ Design for standardisation and compatibility (e.g. spare parts)
- ⇨ Extending desirability
  - ⇨ Design for emotional attachment
  - ⇨ Design for aesthetic improvement over time
- ⇨ Accommodating changing consumer needs
  - ⇨ Design for upgradability and updatability
  - ⇨ Product service system design for product redistribution

**Narrowing Loops**

- ⇨ Maximising value extraction relative to resource use
  - ⇨ Product-Service-System design for product sharing
  - ⇨ Design for energy and material efficient products

**Figure 3.2** Design for a Circular Economy (DfCE) strategies.

As such, there is a general consensus within the literature on the key design approaches necessary to see the CE implemented from a design perspective. However, it should be noted that, whilst both the concept of a CE and the relationship between design and sustainability in general are well established, DfCE, as a specific, unifying concept has only emerged in recent years. The first attempts to formalise DfCE can be seen in recent publications including the ‘Circular Design Guide’ (Ellen MacArthur Foundation & IDEO, 2017), ‘The Re-Use Atlas: A

Designer's Guide Towards a Circular Economy' (Baker-Brown, 2017) and 'Designing for the Circular Economy' (Charter, 2018). Design is also featured as a key facilitator in the 'EU Action Plan for the Circular Economy' (European Commission, 2015).

### 3.2.3 The Implementation of Design for a Circular Economy

As knowledge of earth systems and industry's impact on them has improved and the severity of issues, such as biodiversity loss, climate change and ocean plastic, have come to light, the urgency of taking action has increased. As a result, renewed attention has been given to potential solutions, such as the CE, in recent years, even though many underlying concepts have existed for several decades (Reike, et al., 2018). (Preston, 2012) also highlights three key developments driving interest in the CE in particular. One of these is volatility and uncertainty surrounding the price of resources, as the CE provides the opportunity to shift value creation from the throughput of resources to new avenues, such as services and performance-based business models. Another driver is the development of supporting technologies and material advancements, which make possible, or better facilitate, the transition to a CE (Preston, 2012). Further to this, government policy and support for high-tech manufacturing and resource efficiency is also highlighted as a potential driver of interest in the CE (Preston, 2012). Looking to Europe in particular, CE incentives, as advocated by the European Commission, include the potential to reduce net resource spending in the EU by €600 billion by 2030, representing a considerable saving, which could help improve the competitiveness of EU businesses (European Parliamentary Research Service (EPRS), 2016). Additionally, as the EU is a net importer of material resources, it is particularly exposed to resource price volatility (Ellen MacArthur Foundation, 2015). As such, the CE is a potential means of securing resources by retaining the value of imported materials for recirculation within the EU (Gregson, et al., 2015). Finally, the CE has also been put forward as a driver for innovation with the potential to generate economic growth, decoupled from environmental degradation, as well as creating employment opportunities, thus benefiting both society and businesses (European Parliamentary Research Service (EPRS), 2016). However, despite these drivers and incentives, implementation has been relatively slow to date (Gregson, et al., 2015). As a result, CE remains in its early stages of implementation (Ghisellini, et al., 2016), with CE principles having only been applied rarely and fragmentally (Ritzén & Sandström, 2017). This lack of CE realisation suggests that there may exist challenges limiting the implementation of DfCE.

Challenges to CE implementation have been well covered in the literature (Preston, 2012) (Heshmati, 2015) (Rizos, et al., 2016) (Ritzén & Sandström, 2017) (European Parliamentary

Research Service (EPRS), 2016). Those identified include difficulty financing the transition to a CE, the need to up-skill workforces in relation to CE capabilities, changing consumer behaviour and insufficient governmental support and initiatives to encourage CE adoption businesses (European Parliamentary Research Service (EPRS), 2016). Design-specific challenges in relation to CE implementation have not been addressed in depth to date. At the same time, DfCE is promoted within the design literature as a means of successfully achieving a CE, with many articles positioning design and/or the designer as an instigator of the transition from a linear to a CE (van den Berg & Bakker, 2015) (Andrews, 2015) (Bocken, et al., 2016) (De los Rios & Charnley, 2017) (Mestre & Cooper, 2017) (Leube & Walcher, 2017). It is therefore important to understand how the existing challenges associated with CE implementation relate to design (i.e. could DfCE approaches offer solutions or will DfCE efforts also be hampered by existing CE challenges?). There is a further need to understand the practical challenges associated with implementing DfCE, particularly from a design perspective, as, whilst it may be an important facilitator of a CE, it has not yet been widely adopted, for reasons currently unknown.

In summary, this chapter has provided a background on sustainability and the emergence of the CE concept. It has also explored the relationship between sustainability and design, detailing the development of Design for a Circular Economy (DfCE) and the key design strategies that it promotes for achieving a CE. The chapter has also identified disparities between the advocacy of DfCE as solution and a means of facilitating the transition to a CE and the lack of progress made to date. Additionally, it was observed that the CE challenges outlined within the CE literature have not been addressed within the design literature concerning DfCE. Therefore, in order to understand the true power of DfCE in driving CE implementation and whether it will be facilitated by the transition to Industry 4.0, it is necessary to firstly identify the potential challenges and barriers associated with and applicable to DfCE in more detail.

# Chapter 4. Industry 4.0

This chapter serves as an exploratory literature review on the emergent phenomenon, Industry 4.0, providing essential background information, context and justification for the research presented in this thesis. It begins with an overview of precursory concepts and foundational theories and developments (Chapter 4.1). A comprehensive description of Industry 4.0 is then provided, detailing the motivations and expectations currently promoting and shaping its implementation (Chapter 4.3). This is followed by an overview of key facilitating technologies (Chapter 4.3) and expected outcomes (Chapter 4.4). Finally, a review of the literature related to Industry 4.0 and its impact on DfCE is reviewed (Chapter 4.5), identifying important knowledge gaps.

## 4.1 Precursory Developments to Industry 4.0

The following chapters address the precursory developments that have contributed to the development of Industry 4.0. These include Ubiquitous Computing, Cyber Physical Systems (CPS) and the Internet of Things (IoT).

### 4.1.1 Ubiquitous Computing

Mark Weiser's vision for the future relationship between humans and technology, termed Ubiquitous Computing (UC), may be considered an early conceptualisation of Industry 4.0. (Weiser, 1991) coined the term UC in reference to what he foresaw as the pervasive and seamless integration of innumerable, tiny, connected and networked computers throughout the physical environment. Through the use of sensors, (Weiser, 1991) suggested that these computers would not only become aware of their location and able to sense their surroundings, but would also be able to recognise, identify and communicate with each other, in a process that would later be referred to as Machine to Machine (M2M) communication. As a result, it was expected that they would become intelligent and self-organising, enabling computing to be carried out autonomously in the background. Associated with this was the prediction that computing would eventually become as commonplace and unremarkable as the written word or electricity:

> *'[...] like the wires in the walls, these hundreds of computers will come to be invisible to common awareness. People will simply use them unconsciously to accomplish everyday tasks.'* (Weiser, 1991, p. 68)

According to Weiser's vision, computing would become a pervasive and, at the same time, unobtrusive force within peoples' daily lives, with the technology and inner workings fading from view, revealing only the most necessary or useful information, as and when required.

As explained in Weiser's seminal work, ubiquitous computing would be made possible by three key technological developments. The first would be a continuation of the progression towards increasingly powerful, compact, affordable and low-energy computing components, such as microprocessors, displays and auxiliary storage devices (Weiser, 1991); in line with the trend known as 'Moore's Law'. The second would be the development of flexible and adaptable software solutions able to be accessed, updated and reconfigured remotely. Such solutions would also need to be universally compatible to allow cross-communication between various, geographically dispersed microprocessors and displays (Weiser, 1991). The third would be the creation of a high-speed network capable of transferring large volumes of data seamlessly and wirelessly between what Weiser imagined to be hundreds of machines in every room (Weiser, 1991). These developments, as outlined by Weiser, closely resemble the technological advancements that are now beginning to give rise to Industry 4.0.

Weiser's predictions also went beyond the mere consideration of technical factors, suggesting UC would alter the relationship between humans and machines. (Weiser & Brown, 1997) had already observed human-computer interaction undergoing considerable change and development, from the era in which a few select experts would operate a single mainframe computer to one in which individual personal computers (PC's) were the norm. However, Weiser was critical of the one-to-one relationship and what he considered a constrained interaction between humans and the computers of the time (Weiser, et al., 1999). It was argued that the process of operating a desktop PC was too complex and that the centralised, stationary screen interface demanded too much of a user's attention, isolating them from surrounding people and activities (Weiser, et al., 1999). In contrast, ubiquitous computing was expected to make computing mobile and remotely accessible, not by simply allowing devices to be moved from one location to another, but by making computing accessible everywhere at all times. As such, each individual would be served by many computers embedded throughout their environment, freeing them to be able to focus on and interact with their physical surroundings, whilst maintaining continuous access to computerised information as needed. (Weiser & Brown, 1997) claimed that this development would prevent information overload in a future in which UC would generate vast volumes of data and information.

The human and societal implications were a key focus throughout Weiser's work, as evidenced by the following quote:

> *'The growing number of researchers working on ubiquitous computing will surmount the daunting technical challenges. This leaves only the psychological, social, and business challenges. The most profound revolutions are not the ones trumpeted by pundits, but those that sneak in when we are not looking.'* (Weiser, 1993, p. 72)

As such, the expansion of human machine interfaces to incorporate video and audio in addition to graphics and text were also a part of the UC vision to transform people's interactions with electronic interfaces into more interpersonal ones (Weiser, 1993). This was reflected during Weiser's time at the Xerox Palo Alto Research Centre (PARC), through which a series of experimental research projects and proof-of-concepts were developed. These included an interactive white board, a touch screen tablet and a wearable access tag. These demonstrated the focus on computing that accommodated more natural human movements, such as writing on a whiteboard, and supported human needs, such as the need to be mobile and free to go about normal, daily activities without being inhibited by the need to be located in front of a screen. It was also expected that further applications would emerge, building on the underlying devices and architecture (Abowd & Mynatt, 2000). As a result, (Weiser & Brown, 1997) predicted that computing would come to be thought of as 'commonplace' and 'unremarkable', as the written word or electricity, whereby the average individual would not consciously think about the significant impacts that it has on everyday life. Building on existing technology, the concept of UC was therefore as much about deployment and implementation as it was the technological challenge.

It is evident that there exist many similarities between the early conceptualisation of UC and the presently emerging phenomenon of Industry 4.0. The technological advancements, as predicted by Weiser, are certainly a close match to those that are now facilitating Industry 4.0. However, whilst Industry 4.0 has evolved with a central focus on manufacturing, Weiser's UC vision presents an expanded perspective with added insights regarding the wider, societal implications of such technologies. As such implications may be of relevance to design and CE, it is important for them to also be considered when exploring potential interactions between Industry 4.0 and DfCE.

### 4.1.2 Cyber Physical Systems

Cyber Physical Systems (CPS) constitute the lowest common denominator building block (main underlying architectural unit) of Industry 4.0, and closely resemble what was described in Weiser's UC vision (Wan, et al., 2015). Several definitions for CPS can be found within the literature. (Lee, et al., 2015, p. 18) provide a relatively high-level description of CPS:

> *'[…] transformative technologies for managing interconnected systems between its physical assets and computational capabilities.'*

Whereas, (Monostori, 2014, p. 9) provides a slightly more detailed explanation:

> *'Cyber-Physical Systems (CPS) are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet.'*

Meanwhile, (Ma, 2011, p. 921)'s succinct description stresses the importance of the basic underlying design of the concept:

> *'CPS emphasizes the information exchange and feedback, where the system should give feedback and control the physical world in addition to sensing the physical world, forming a closed-loop system.'*

CPS can therefore be considered to be distinct, functional units that facilitate the capture, exchange and materialisation of information between the physical world and the digital. The basic architecture of CPS comprises five key stages (Figure 4.1). The first is smart connectivity facilitated by sensor networks and wireless data transmission (Lee, et al., 2015). This is followed by the conversion level in which data is converted into useable information. Next, information is exchanged, stored and analysed within a digital hub in the cyber level, before progressing to the cognition level in which the information is translated into knowledge and then wisdom using Artificial Intelligence[7] (AI) or Big Data[8] analytics, the results of which

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[7] 'Artificial Intelligence' may be defined as *'[…] a variety of human intelligent behaviours, such as perception, memory, emotion, judgment, reasoning, proof, recognition, understanding, communication, design, thinking, learning, forgetting, creating, and so on, which can be realised artificially by machine, system or network'* (Li & Du, 2017).

[8] 'Big Data' may be defined as *'[…] a cultural, technological, and scholarly phenomenon that rests on the interplay of Technology (maximizing computation power and algorithmic accuracy), Analysis (to identify patterns on large data sets) and Mythology (meaning the belief that large data sets offer a higher form of intelligence with an aura of truth, objectivity and accuracy)'* (De Mauro, 2015).

support decision making. Finally, these decisions are transferred back to the physical world where they are actuated in the configuration level (Lee, et al., 2015) (Qin, et al., 2016).

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**Figure 4.1** Five-stage architecture of a Cyber Physical System. Adapted from (Lee, et al., 2015).

This is achieved by employing a combination of sensors, actuators, computer processors and communication networks. In a CPS, sensors embedded in the physical world are able to gather information about their surroundings, such as context, location, condition and status. This information is then relayed to a computational unit, like a cloud computing centre, via a digital communications network, like the Internet (Lu, 2017). Here, the information can be processed into knowledge and ultimately wisdom by either analysing it on its own or in combination with other data inputs from other sensors. Typically, this will generate an instruction of some kind in response, which is sent to an actuator that will follow those instructions and manipulate the physical world accordingly (Lu, 2017). CPS are therefore able to run autonomously, continuously and in real-time without purposeful human input. As such, CPS present two new opportunities. The first is advanced connectivity facilitating live, two-way data capture and exchange. The second is the autonomous storage, processing and analysis of data (Lee, et al., 2015).

CPS therefore represent a clear departure from the information and communication technologies (ICT) of the past. Traditionally, embedded computer applications have simply replaced traditional mechanical controllers to automate existing, rigid processes. Whilst, this has afforded greater efficiency, it has not added any further functionality. In contrast, CPS enable new, flexible and autonomous processes to be realised. It is with this added flexibility that agile, reconfigurable automated control loops are made possible, thus differentiating CPS from existing computational control systems (Poovendran, 2010). As a result, CPS present new possibilities in human-to-human, human-to-machine and machine-to-machine interactions, blurring the boundary between the physical and digital worlds (Wu, et al., 2011).

### 4.1.3 The Internet of Things

A further foundational development of Industry 4.0 is the Internet of Things. Whilst CPS enable connectivity between the physical and digital worlds, the Internet of Things can be thought of as an architecture that enables connectivity between multiple CPS to create a digital network of physical objects (Lu, 2017). As explained by (Jazdi, 2014, p. 1),

> *'A CPS is an embedded system that is able to send and receive data over a network. The CPS connected to the internet is often referred to as the 'Internet of Things'.'*

The IoT is therefore facilitated by the mass rollout of CPS via the embedding of sensors, actuators and processors within products, equipment and devices, as well as the provision of connectivity networks, such as 5G internet (Lu, 2017). Whilst these networks may be wired or wireless, wireless networks present several advantages, from flexibility and scalability, enabling the connection of various heterogenous objects at a given time, to mobility, which is becoming increasingly important with the development of self-organising robots and smart autonomous vehicles.

As summarised by (Ma, 2011), the achievement of an IoT comprises three key stages. The first is the digitisation of objects using embedded computer chips so that they may be individually identified and addressed. The second is the installation of autonomous, networked terminals through which individual objects are able to connect and relay data, enabling interconnectivity with other connected objects. The third stage then involves the development of pervasive, intelligent services, whereby the data gathered from digitalised objects and relayed via networked terminals is collated and analysed to serve various applications, converting data into instructions and actions that ultimately create value for users. As such, the real benefit of the IoT is in the opportunities it presents for building services and applications using the large volumes of networked data generated, delivered via connected objects. As noted by (Ma, 2011, p. 921),

> *'The IoT emphasizes [...] networking, and is aimed at interconnecting all the things in the physical world, thus it is an open network platform and infrastructure.'*

The range of potential applications supported by the IoT is therefore likely to grow as more objects become digitalised and connected, increasing the volume, quantity and quality of data. From this, the IoT is enabling the realisation of new and innovative functionalities, which in turn provide the foundation for Industry 4.0.

### 4.1.4 The Fourth Industrial Revolution

To place Industry 4.0 in perspective, the phenomenon constitutes the fourth in a series of industrial revolutions, signifying the next paradigm shift in manufacturing and production (MacDougall, 2014). As such, it follows as a natural progression, building on previous technological advancements. The first industrial revolution was typified by the gradual adoption of water and steam power in the late 18th century, giving rise to mechanisation and factory production. The second followed from the end of the 19th century with the development of electrification, enabling mass manufacture of affordable consumer products and the emergence of the production line in the early 20th century (MacDougall, 2014) (Zhou, et al., 2015). The third saw the emergence and integration of ICT within industry, leading to computer-numerical control and automation (Bahrin, et al., 2016). The next industrial revolution is then being driven by further technological developments, including the mass roll-out of CPS, advances in internet connectivity and information and communication technologies, such as the IoT, giving rise to Industry 4.0.

However, the next paradigm shift is expected to deviate from those that have preceded it. As explained by (Perez, 2009), each industrial revolution to date has provided a new set of fundamental technologies, infrastructures and organisational principles. In turn, this has seen a significant disruption to the wealth-generating potential of the economy, accompanied by extensive opportunities for innovation and the achievement of efficiency and productivity improvements across industrial sectors. Each previous industrial revolution has therefore seen a progressive shift towards increasingly automated, standardized and centralized production processes in the pursuit of increased efficiency, productivity and economies of scale. Whilst efficiency and automation gains are expected to continue in the fourth industrial revolution, other trends, such as centralisation, standardisation and mass manufacture may be reversed, as decentralised production and the mass customisation of products become not only possible, but profitable (MacDougall, 2014). A further differentiating factor is the fact that the fourth industrial revolution has been identified in advance in anticipation of the roll out and mass adoption of facilitating technologies, whereas previous revolutions have tended to be observed and labelled in retrospect (Hermann, et al., 2016). As such, there exists an opportunity to gain advanced understanding of the potential outcomes of the next industrial revolution before it materialises completely. This provides an opportunity to shape its evolution and achieve an improved industrial model, which is what the concept of Industry 4.0 attempts to harness.

## 4.2 Industry 4.0

This chapter details the development of Industry 4.0 and the motivational factors behind the phenomenon, as well as its key principles and current implementation status.

### 4.2.1 Defining the Concept of Industry 4.0

The concept of Industry 4.0 is at times used synonymously or interchangeably with the fourth industrial revolution (Monostori, 2014) (Lu, 2017) (Hermann, et al., 2016). However, as (Brambley, 2013) and (Wang, et al., 2017), explain, the term, fourth industrial revolution, refers to technological developments that occur inevitably, resulting in the next paradigm shift, whereas Industry 4.0 represents an advanced vision or plan aimed at maximising the value of such developments, suggesting that the two are subtly different. However, as admitted by (Hermann, et al., 2016), there exists no generally accepted definition of the concept of Industry 4.0. Similarly, (Porter, 2016) asks whether Industry 4.0 is merely a collection of manufacturing technologies or if it's a strategic economic plan. As admitted by (Vogel-Heuser, 2016) and (Qin, et al., 2016), whilst the concept continues to evolve, there exist several differing opinions about what constitutes Industry 4.0. However, there remain some common defining elements common throughout the literature. According to (Varghese & Tandur, 2014) and (Weyer, et al., 2015) IoT and CPS form the underlying technologies giving rise to Industry 4.0, whilst (Vogel-Heuser, 2016) foreground CPS and (Wan, et al., 2015), the IoT. As such, there exists some level of agreement that Industry 4.0 represents an advanced vision for the application of both CPS and IoT within an industrial context (Weyer, et al., 2015).

It is also important to acknowledge that the term 'Industry 4.0' initially originated from Germany. Several conditions of the German manufacturing sector have placed the nation in an optimal position to reap the value provided by the coordinated implementation of CPS and IoT. Firstly, the country has been motivated by the need to recover economically following the global financial crisis (Zhou, et al., 2015). They have also recently faced strong competition from low-wage manufacturing economies, such as China, whose product quality has improved significantly in recent years. As such, it has become impossible for German manufacturers to compete on mass production based on price alone. As such, one of the key deliverables of Industry 4.0 for Germany has been the ability to diversify and offer increasingly individualised products, quickly and on demand. Additionally, with one of the most competitive and innovative manufacturing industries in the world, Germany has been a global leader in industrial production research and innovation. As such, the nation maintains a significant domestic manufacturing sector (MacDougall, 2014). This sector is also technologically advanced, with 90% of their industrial manufacturing chains already supported by ICT, thus existing manufacturing capital was primed for connectivity upgrades (Wan, et al., 2015). As a result, Germany has been quick to recognise the potential opportunities afforded by increased connectivity and the implementation of CPS and the IoT within a manufacturing context. In 2011, the National Academy of Science and Engineering, Acatech, assembled a panel of industry experts and academics to explore these opportunities, which then coined the term 'Industry (Industrie) 4.0' (Kagermann, 2016). This strategy was then backed by the German government as a key development, necessary to strengthen Germany's position as a manufacturing market leader and went on to form part of the German government's Strategy 2020 Action Plan as one of ten 'Future Projects'.

Whilst Industry 4.0 may be considered synonymous with German manufacturing, similar courses of action are being taken by manufacturing sectors across the globe, including in North America, Korea, China, India and Japan (MacDougall, 2014). The terminology used varies to include 'Smart Production', 'Smart Manufacturing', 'The Industrial Internet' and 'Advanced Manufacturing'; however, all refer to the intelligentisation of industrial manufacturing through the implementation of cyber-physical systems and associated technologies (Kagermann, et al., 2013). For the purpose of this research, the term Industry 4.0 is therefore used as a general term describing an advanced vision for the application of both CPS and IoT within an industrial context, rather than pertaining to any specific initiative or location.

### 4.2.2 Motivational Factors Behind Industry 4.0

The actual realisation and implementation of Industry 4.0 is fuelled by both a 'technology push' and 'application pull' (Lasi, et al., 2014). The technologies that comprise the foundational building blocks of Industry 4.0, CPS and the IoT, are not necessarily new developments. Embedded chips, such as Radio Frequency Identification (RfID) devices for example, have existed since the mid-20th century (Pio Di Monte, 2016) The technology push behind Industry 4.0 is therefore not based on the discovery of radically new technologies, but rather advancements that improve the performance and deployment potential of many existing technologies. As per Moore's Law, computing power has continued to increase exponentially, leading hardware to become increasingly compact, powerful and affordable. As such, it is now possible for hardware components to be economically produced and deployed en masse (Sniderman, et al., 2016). A technology push is therefore afforded by a reduction in the size, weight, power consumption and price of sensor technologies (Roblek, et al., 2016) (Lee, et al., 2015). The second technological dimension supporting the rollout of Industry 4.0 is blanket internet connectivity. Whilst this has been going on for several decades now, it provides the means necessary to support the networked connectivity of all the distributed hardware computing components to create cyber physical systems. As such, the technology push behind Industry 4.0 is actually less to do with any one particular novel technology and more to do with the economic feasibility and availability of the components necessary to create CPS and the IoT, and to roll these structures out at scale.

The application pull, on the other hand, reflects the existing pressures faced by industry and the developments that are needed to support them into the future. As the markets and supply chains for consumer goods have become increasingly globalised over the past few decades, many of these pressures are common across manufacturing the world over. (EEF The Manufacturers' Organisation, 2016) break these down into four key trends. The first is the need to innovate and develop new products and the pressure to be the first to market in order to maximise profitability before the entry of competitors with similar products. A key motivation is therefore to minimise product development times by cutting inefficiencies and delays and streamlining collaboration. Another challenge faced by producers is the increased complexity of supply chain management processes, where the need for additional supporting activities and services raise costs (EEF The Manufacturers' Organisation, 2016). Additionally, whilst globalisation improves availability, selection and visibility of suppliers, complexity is added with each additional cross-border movement resulting in challenges, such as lead-time variability. Finally, as industry has moved from a sellers' to a buyers' market, consumers are demanding increasingly individualised products and shorter delivery times; requirements which are poorly met by traditional manufacturing infrastructure (EEF The Manufacturers' Organisation, 2016). Current market demands and industry challenges such as these therefore provide the motivation and guidance for the design of Industry 4.0.

In addition to addressing existing production challenges, the adoption of Industry 4.0 also presents new application possibilities and opportunities. As explained by (Lu, 2017), these include developments such as new services and business models supported by interaction, connectivity and the Internet of Things, as well as the introduction of new manufacturing processes and product possibilities. (Lee, et al., 2015) predict that the implementation of such developments will lead to significant economic opportunities, most of which are yet to be realised at this early stage of Industry 4.0 adoption. Interestingly, the key driver identified by (Samaranayake, et al., 2017) was not simply cost or waste reduction, but rather the flexibility of manufacturing processes, suggesting that Industry 4.0 possesses more of an innovation and process transformation focus, rather than a gradual improvement of existing processes. This point is reinforced by (Brettel, et al., 2016) in their review of the value provided by manufacturing flexibility. They suggest that consumer demand for increasingly heterogenous products and shorter product lifecycles is driving producers to find new ways of providing variety whilst maintaining high quality standards and price competitiveness. In turn, as individual organisations begin to implement Industry 4.0 and realise some of these benefits, traditional manufacturers will likely face growing competition and increased pressure to follow a similar route (Lee, et al., 2015).

The applications are then closely related to the pressures identified. As (Lasi, et al., 2014) explain, there are several key expectations of firms looking to implement Industry 4.0. The first is an ‘individualisation on demand’ model of production in which products can be made in batches of one quickly and economically using RfID controlled production, digital fabrication techniques and intelligent robotic assembly. The second is flexible and reconfigurable production processes whereby factories are decentralised as a network of processes, which products will navigate themselves. Decision-making will also become increasingly decentralised, whereby AI is able to feed off the data captured via sensors to produce appropriate actions in response (Lasi, et al., 2014). Opportunities such as these provide an application pull for companies to implement Industry 4.0.

### 4.2.3 Key Principles of Industry 4.0

Whilst Industry 4.0 remains an emerging concept, there has been a considerable effort by researchers and industry leaders to develop some key guiding principles (Qin, et al., 2016). Four key elements are put forward by (Hermann, et al., 2016). The first is interconnectivity facilitated by the implementation of CPS and the IoT, giving rise to new forms of interaction and collaboration between humans and machines. It is this interconnectivity that is enabling the flexible, modularised and reconfigurable smart factories of the future. The second is information transparency in which data gathered from connected products is collectively stored, processed and accessed, providing the intelligence necessary for the development of new, real-world applications. As explained by (Stock & Seliger, 2016) and (Zhou, et al., 2015), Industry 4.0 will involve three distinct modes of data integration. One is vertical integration, connecting processes within individual organisations; another is the end-to-end integration connecting the various stages of product lifecycles and the third is horizontal integration, facilitating connectivity between organisations to form value-creation networks. These transitions will be supported through the digitization, automation and linking of processes and entities to develop comprehensive, agile supply chains (Roblek, et al., 2016). The third is autonomous, decentralised decision-making, allowing intelligent processes to run in the background with minimal human intervention and maintenance. This is made possible as CPS monitor and control physical processes using real-time sensed data. The fourth is technical assistance, whereby (Hermann, et al., 2016) predict shop floor workers will not be replaced, but instead transition from operators to strategic decision makers, supported by smart and connected assistance systems, such as robotic assembly and augmented reality. Industry 4.0 therefore remains an evolving phenomenon, which is yet to be fully realised (Vogel-Heuser, 2016). Nevertheless, there exist core elements that are guiding its implementation.

As explained by (Qin, et al., 2016), the impacts of Industry 4.0 are expected to extend beyond the factory to also affect businesses, products and customers. Factories will benefit from agile, robotic assembly, autonomous, self-configuring production lines, predictive maintenance of factory equipment and modularised, decentralised and simulated manufacturing processes. Businesses on the other hand are expected to benefit from improved resource management, raw material efficiency and maximised profits, as well as dynamic communication networks between companies enabling improved, real-time data insights into product demand and status. Further, products are expected to become 'smart' through the embedding of sensors to create CPS and the IoT. These smart products will then be able to support additional functionality and associated services, as well as valuable data visibility and insights past the point of sale. This information is then expected to become an important influential factor in the design, production and maintenance of products. Finally, consumers are also expected to benefit from new opportunities presented by Industry 4.0, including new purchasing methods, tracking of their purchases' production and the alteration, customisation and co-design of products (Qin, et al., 2016). These predictions are largely in agreement with the expectations of (Lu, 2017), who outlines a progression from smart factories to smart products and eventually smart cities, driven by the pursuit for improved quality of life, citizen safety and energy efficiency. As such, this closely resembles Weiser's UC vision as detailed in Chapter 4.1.1.

Whist the literature provides insight into what Industry 4.0 is, the real outcomes will be seen following the mass rollout of associated technologies and the assembly of various applications into complex, automated, intelligent networked systems that deliver real value to manufacturers and consumers. As suggested by (EEF The Manufacturers' Organisation, 2016), to understand the ways in which industry 4.0 technologies will be implemented, it is important to firstly understand the motivating factors behind their adoption.

### 4.2.4 Current Status and Implementation of Industry 4.0

Industry 4.0 is largely being driven by academic research, driving the technology push, and political strategy, creating an application pull. The first Industry 4.0 solutions are also being developed by technology providers to demonstrate the value of Industry 4.0 to potential clients. As admitted by (Weyer, et al., 2015), although applications are beginning to emerge, these are currently limited to isolated, proprietary examples. A systematic literature review on Industry 4.0 implementation, as conducted by (Liao, et al., 2017), also suggests that, whilst academic research on Industry 4.0 has expanded considerably since the introduction of the concept, several contextual challenges have limited the successful application of proposed solutions and the transition from theoretical to practical progress. These include a lack of engagement and collaboration between industry and academia, scepticism surrounding Industry 4.0 benefits, a cautious approach on behalf of companies in adopting new and unproven technologies, concerns regarding data security and intellectual property and a lack of top-down direction with regard to regulation and technology standards that facilitate compatibility and interoperability (Liao, et al., 2017) (Lu, 2017). As such, Industry 4.0 is currently tending towards a technology in search of applications. However, as with any potential major paradigm shift, there exists some lag between the introduction of breakthrough technologies and the emergence of applications that bring about disruptive innovation and change (Magruk, 2016). As uncertainties are removed and risks are able to be mitigated, the potential benefits for actors are expected to become clearer, helping to accelerate adoption of Industry 4.0 (Magruk, 2016).

## 4.3 Enabling Technologies of Industry 4.0

This chapter outlines some of the key technologies associated with Industry 4.0. These include those which form the components of CPS and IoT, such as sensors, actuators, embedded chips and barcodes, cloud computing, Big Data and AI, as well as complementary technologies that use the data generated, including blockchain, virtual reality and simulation, as well as augmented reality.

### 4.3.1 Sensors

Sensors are devices that are able to gather information from the physical environment, such as acceleration, pressure, temperature and location, and convert this into digital information. Sensors already have many widely available and common applications, such as fire alarms, thermostats, wearable heart-rate monitors and car engine warning systems. The cost of these sensors has reduced dramatically in recent years, in line with Moore's Law, allowing them to be embedded within objects, such as products and machinery, and to be rolled out en masse. These form a key component of CPS, facilitating the IoT and Industry 4.0 (Gilchrist, 2016).

### 4.3.2 Actuators

Actuators are complementary to sensors in that they convert digital information, such as instructions, into physical actions in the real world. These actions can include just about any physical outcome, from switching processes on and off, to the movement of mechanical parts (Hozdić, 2015). As such, digital fabrication technologies, such as 3D printing, computer numerical controlled (CNC) milling, laser cutting and robotic assembly may be considered examples of actuators as they translate digital instructions into physical outcomes. Actuators also form a key component of CPS.

### 4.3.3 Embedded Chips

A further essential facilitating component of CPS is unique identifiers that enable physical objects to be identified in the form of digital information. These include embedded chips, such as RfID and Near Field Communication (NFC) devices that are readable by sensors (Gilchrist, 2016).

### 4.3.4 Internet Connectivity

Internet connectivity is another essential enabling technology for the implementation of CPS, the IoT and the realisation of Industry 4.0. Connectivity in Industry 4.0 environments must support reliable, real-time, two-way data exchange and coordination, both within organisations and between relevant stakeholders (Varghese & Tandur, 2014). The fundamental considerations essential for Industry 4.0 connectivity networks may therefore be summarized as 'latency', 'longevity' and 'reliability' (Varghese & Tandur, 2014). Latency may be described as the delay between inputs (e.g. sensed data) and necessary outcomes (e.g. actuation of tasks). In order to realise the expected 'real-time' information capability associated with Industry 4.0, it will be necessary to keep latency to a minimum. As explained by (Doherty, et al., 2012), access to 'live' data is necessary for many industrial processes requiring rapid responses and real-time control. Delayed data may therefore be of no use at all in some applications. Longevity then relates to the amount of time that the connectivity network remains operational and fully functional. At the same time, there exist pressures to keep maintenance to a minimum, both from the perspective of cost reductions and to limit the need to access difficult to reach locations common across manufacturing environments. As such, longevity of wireless connectivity networks is being tackled both through the extension of battery life and by reducing the energy consumption of sensors and actuators that transmit data wirelessly (Varghese & Tandur, 2014). Reliability then relates to the continuity, volume and quality of data. The autonomous control of manufacturing equipment will require constant and pervasive wireless network connectivity that supports high volumes of data and maintains connectivity of mobile devices (Varghese & Tandur, 2014). As explained by Doherty et al. (2012), discontinuous data supply can trigger alarms and shutdowns within a manufacturing environment, which can be very costly to businesses. In order to meet these requirements, a fifth generation (5G) network is currently in development (Lu, 2017). Whilst still in its infancy, IoT and machine-to-machine communication requirements are at the heart of its design.

#### 4.3.5 Cloud Computing

With the mass roll out of sensors in Industry 4.0 generating significant volumes of data, the real value of which is realised when combined and triangulated, new modes of data storage and access will be required (Almada-Lobo, 2015). Cloud computing provides a data storage and access platform that is accessible via the internet and able to cope with large data sets uploaded by and shared between many different sources (Zhou, et al., 2015). As such, companies are able to access only the necessary information for their needs on demand, as and when required. Cloud computing therefore forms an important component in the delivery of CPS, the IoT and Industry 4.0.

#### 4.3.6 Big Data Analytics

Conventional database technology is unlikely to be able to handle the scale of data organisation, management and analysis required in Industry 4.0. Additionally, with new capabilities emerging, such as the mass customisation of products, companies will need to be able to retrieve increasingly specific, tailored information in ever shorter timeframes (Zhou, et al., 2015). New modes of data processing and analysis, referred to as Big Data analytics, will help to quickly and efficiently draw useful insights from large data sets stored in cloud based storage platforms (Zhou, et al., 2015). Big Data analytics may also help to automate data analysis, helping to identify patterns that would not have otherwise come to light from purposive analysis (Almada-Lobo, 2015).

### 4.3.7 Artificial Intelligence

AI is necessary for turning the data gathered by sensors, and made accessible by cloud computing, into valuable insights and outcomes using algorithms, software and machine learning. This enables the intelligentisation of objects and processes, in turn facilitating automation (Li, et al., 2017). AI has significant potential to integrate and optimise different aspects of product design and manufacture by combining and making sense of data streams from various sources. This may facilitate various applications, such as collaborative, consumer-led customisation, by automating a large proportion of the process, making it feasible from a time and cost perspective (Li, 2017).

### 4.3.8 Blockchain

In its simplest terms, blockchain may be described as a distributed digital ledger where transactions, agreements and other forms of data are verified and stored securely using peer-to-peer public-key cryptography. As the verification and storage of information on the blockchain is not carried out by any one centralised party, but rather achieved through distributed consensus across a network, it is near impossible for records to be falsified. Further, as each 'block', containing batches of recent transaction records, is date stamped and added to the sequential list of all previous blocks in the 'chain', retrospective adjustment of a given record is not possible without altering all subsequent records, or 'blocks', in the chain. It is for these reasons that blockchain technology provides an interesting avenue for achieving supply chain transparency. It has the potential to provide a secure alternative to traditional, centralised data management and third-party authentication processes, which are often lengthy and costly and can be vulnerable to fraud, security breaches and systems failures (Abeyratne & Monafred, 2016).

### 4.3.9 Simulation and Virtual Reality

The mass roll-out and the embedding of sensors within objects is facilitating the capture of real-time data about the physical world. In turn, this is enabling the creation of virtual simulations of physical objects and processes, known as a 'digital twins' (Sniderman, et al., 2016). This enables physical objects and processes to be viewed and monitored as a virtual simulation in real time.

### 4.3.10 Augmented Reality

Augmented reality involves mapping and overlaying digital information over the physical world in real time using cameras and screens or wearable augmented reality glasses. As such, the data and imagery displayed is reflective of the current situation, which can help to guide processes, such as operations, maintenance and repair (Vaidya, et al., 2018).

## 4.4 Expected Outcomes of Industry 4.0

This chapter explores key outcomes that are expected as a result of the implementation of Industry 4.0 technologies. These include the development of smart factories, assisted work environments and digital fabrication.

### 4.4.1 The Smart Factory of the Future

Industry 4.0 is typified by 3 key integrations. The first is horizontal integration between producers to create a connected, collaborative production network (Zhou, et al., 2015). The second is the vertical integration of all processes and activities within a factory or organisation (Zhou, et al., 2015). Finally, end-to-end integration extends along the entire product lifecycle and value chain, which enables consumers to become part of the design and production of products (Zhou, et al., 2015).

### 4.4.2 The Assisted Work Environment

As Industry 4.0 technologies are expected to transform production processes and the wider manufacturing landscape, shop-floor workers will be required to adopt new tasks and gain new skills. This is particularly the case where simpler tasks and decision-making processes are fulfilled by technologies, such as CPS, IoT and AI, leaving the more challenging, strategic decision-making tasks for human workers. In the case of rapid change, it may not be possible to train sufficient workers quickly enough, resulting in skills shortages (European Economic and Social Committee, 2017). However, Industry 4.0 technologies are also finding roles in supporting workers with the transition to new, dynamic production environments. As explained by Romero et al. (2017), Industry 4.0 opens up new opportunities for creating a human-centred factory of the future, in which ‘human-automation-symbiosis’ is achieved. This involves the improvement of worker’s manual abilities, e.g. through physical aids or workers perception, e.g. through augmented reality and sensed data inputs. However, whilst the vision put forward by (Romero, et al., 2016) is certainly a socially sustainable option, the review of the digitalisation and automation of jobs by (European Economic and Social Committee, 2017), proved inconclusive on whether workers would indeed be incorporated into the factory of the future as digitally assisted employees, or whether they would eventually be displaced by increasing automation. It is likely that, whilst the technologies remain at an early stage of development and deployment, workers will continue to be required on the shop floor, despite the addition of Industry 4.0 technologies.

### 4.4.3 Digital Fabrication

Digital fabrication involves the direct translation of digital plans into physical objects, whereby data dictates the movements of an actuator to add or subtract material. Examples include 3D printing, laser cutting and computer-numerical-control (CNC) milling. Whilst digital fabrication has gained considerable interest across a range of industries, there exist several limitations, including product quality, reliability and the rate of production (Bikas, et al., 2016). As such, digital fabrication technologies, in particular 3D printing, have tended to be limited to creating rapid prototypes during the product design, development and testing process. However, as these technologies improve and their application moves into the actual manufacture of products, new opportunities are uncovered, including iterative product development and incremental design improvements. This allows manufacturers to enter the market with lower risk and up-front investment, whilst helping to speed product design improvements, making products more successful more rapidly and reducing waste (Brettel, et al., 2016). However, these benefits and opportunities are not restricted to established manufacturers. As explained by (Montelisciani, et al., 2014), when digital fabrication technologies become viable as manufacturing processes, product design and creation become increasingly available to individuals and even consumers. Digital fabrication is therefore likely to have significant impacts on product development, initially, and as the technologies improve, manufacturing and production.

## 4.5 Sustainability and CE Implications of Industry 4.0

The expected deliverables of Industry 4.0 include, increased automation of production, reduced labour costs, increased manufacturing flexibility, the capacity to produce customised products and components, shortening of lead times and improved manufacturing productivity and efficiency (Qin, et al., 2016) (Lasi, et al., 2014) (Roblek, et al., 2016). It is the latter quality that has led many to conclude that Industry 4.0 will also include an element of improved industrial sustainability (Kagermann, et al., 2013) (Monostori, 2014) (Stock & Seliger, 2016) (Zhou, et al., 2015). However, this assumption may be problematic for a number of reasons.

The first issue is the lack of quantifiable evidence, in the form of a comprehensive and balanced investigation into the sustainability impacts of Industry 4.0. It may be true that resources, energy and capital assets will be utilised more effectively and efficiently with the addition of automated optimisation processes afforded by connected and intelligent manufacturing environments (Kolberg & Zühlke, 2015). However, this represents a narrow view and only offers a partial analysis of a much wider system. As noted by (Kurk & Eagan, 2008) the environmental impacts of a product extend well beyond the manufacturing phase, to include the entire product lifecycle, from use and maintenance to end-of-life disposal. Secondly, the shorter lead times and increased productivity rates afforded by Industry 4.0 (Schuh, et al., 2014), may in turn see an increase in overall production and consumption, negating the benefits of any improved efficiencies. As previously discussed, this type of 'rebound' effect is a common pitfall in well-intentioned, eco-efficiency approaches (Braungart, et al., 2007).

There also exists a lack of consideration of potential eco-effectiveness opportunities, such as the achievement of a CE, within the Industry 4.0 literature. Only a small number of studies go beyond the efficiency rhetoric. Examples include (Pan, et al., 2015), who explore the potential for Industry 4.0 to facilitate industrial symbiosis between manufacturers to create a connected 'eco industrial park', and (Stock & Seliger, 2016), who suggest that connected products will enable the tracking and recovery of core elements for remanufacturing. However, it must be noted that all of these examples follow a piecemeal approach, focused largely on the direct application of Industry 4.0 technologies, rather than wider system developments, such as changes to socio-economic dynamics. As such, they fail to address wider influential factors that will inevitably determine whether or not CE principles are implemented and to what extent. To further illustrate this point, many technologies exist today, which could facilitate the transition to a Circular Economy. For example, the technologies necessary to recycle higher percentages of waste currently exist, but are not implemented to the fullest extent due to other financial, cultural and behavioural barriers (Huesemann, 2003). What is lacking from the discussion is therefore the consideration of the social, economic and cultural implications of Industry 4.0 and their relevance to the achievement of a CE. Further to this, as identified in Chapter 3.2.3, design is key to realising a CE. As such, the omission of design from the discussion around CE and Industry 4.0 also presents an opportunity for further investigation.

It is therefore evident that there exists a gap in the knowledge regarding how Industry 4.0 will impact on the CE, not only from a technological angle in terms of what's possible, but also in terms of the subsequent impact on wider economic, social and cultural aspects that may be transformed by Industry 4.0. It is also important to consider how these changes will impact on the design of products and, ultimately, the achievement of a CE. Additionally, there exists a need to balance positive sustainability rhetoric surrounding Industry 4.0 with an objective evaluation of the potential for increased automation and connectivity to exacerbate existing barriers to a circular economy and to even create new, unforeseen challenges. As noted by (Estevez & Wu, 2016), the integration of CPS could be positive or negative for the environment.

### 4.5.1 Addendum

Since completing the research presented within this thesis, the relevance of Industry 4.0 to CE has begun to be recognized, with a number of publications on the topic emerging since 2018. Some researchers, such as (Tseng, et al., 2018) and (Blunck & Werthmann, 2017), address CE opportunities within manufacturing environments. As such, they explore the potential for Industry 4.0 to facilitate circular initiatives, such as industrial symbiosis, in order to achieve more sustainable processes. Also adopting a process perspective, (Rajput & Singh, 2019) consider the potential for Industry 4.0 to present new CE opportunities for supply chains. The ability for Industry 4.0 to facilitate new CE business models is another point of focus for researchers, such as (Lopez de Sousa Jabbour, et al., 2018) and (Nascimento, et al., 2019) who present high-level overviews of possible opportunities, and (Garcia-Muiña, et al., 2018) who adopt a case study approach. This demonstrates that the intersection between Industry 4.0 and CE represents a very new and live field of research that has just begun to emerge.

A gap that remains is the adoption of a design perspective. As highlighted in Chapter 3.2.3, design forms a key facilitating factor in the realisation of a CE through the development of products that are conducive to CE strategies. Of the literature that has emerged since the completion of this research concerning CE and Industry 4.0, only one paper appeared to expressly address CE, Industry 4.0 and design. This comprised a case study presented by (Lin, 2018), exploring the potential for Industry 4.0 to improve the appeal of products by better understanding the needs and preferences of consumers. The strategies identified are then applied to products manufactured using recycled glass. As such, the research does not directly explore the whether such DfCE strategies will be adopted within a real-world context, but simply whether they are possible. As such, this thesis remains an important initial contribution to this nascent topic, carving out a new research area defined by the intersection between design, CE and Industry 4.0.

In summary, this chapter has reviewed the literature associated with Industry 4.0 to understand the precursory developments behind the phenomenon (Chapter 4.1), it's key characteristics (Chapter 4.2), motivational factors (Chapter 4.2), associated technologies (Chapter 4.3) and expected applications (Chapter 4.4). Additionally, a review of Industry 4.0 and sustainability was provided to identify and evaluate existing literature on the potential impacts of Industry 4.0 on CE and design (Chapter 4.5). It was found that Industry 4.0 is predicated on concepts, such as ubiquitous computing, cyber physical systems (CPS) and the Internet of Things (IoT). Whilst there is no definitive definition of Industry 4.0, there exists a widely agreed upon basic technological infrastructure and a shared vision for its realisation. However, the phenomenon is still unfolding and the foresight surrounding it presents an opportunity to shape it. As a result, further applications in addition to those outlined are expected to be realised going forward. A key knowledge gap was identified in the form of a limited exploration of CE within the Industry 4.0 contained within the literature to date and, in particular, a lack of research on Industry 4.0 and CE adopting a design perspective.

# Chapter 5. Methodology

This chapter provides a detailed description and justification of the processes used to conduct the research presented in this thesis. It begins with a discussion of the nature of the problem and the associated theoretical and methodological implications of sustainability science research. This is followed by an overview of leading research paradigms and a rationale for the adoption of a critical realist positioning, detailing the ontological and epistemological assumptions that underpin the research. A justification for the selection of the methodological approach is then provided alongside a detailed description of the specific methods employed for the collection and analysis of data and theory development. Finally, the ethical considerations and limitations of the research methodology are presented and discussed, providing recommendations for future research.

## 5.1 Nature of the Research

The research presented in this thesis is centrally concerned with a sustainability problem: the urgent need to achieve a more sustainable model of production and consumption by transitioning to a circular economy. More specifically, it aims to provide an early exploration and advanced understanding of the potential opportunities and challenges presented by Industry 4.0 for the successful implementation of Design for a Circular Economy (DfCE) practices. As such, the scope of the research is not delineated by focusing on a narrowly defined segment within a particular field, but rather by the intersection between three interrelated focus areas: the circular economy, design and Industry 4.0 (See Figure 5.1.)

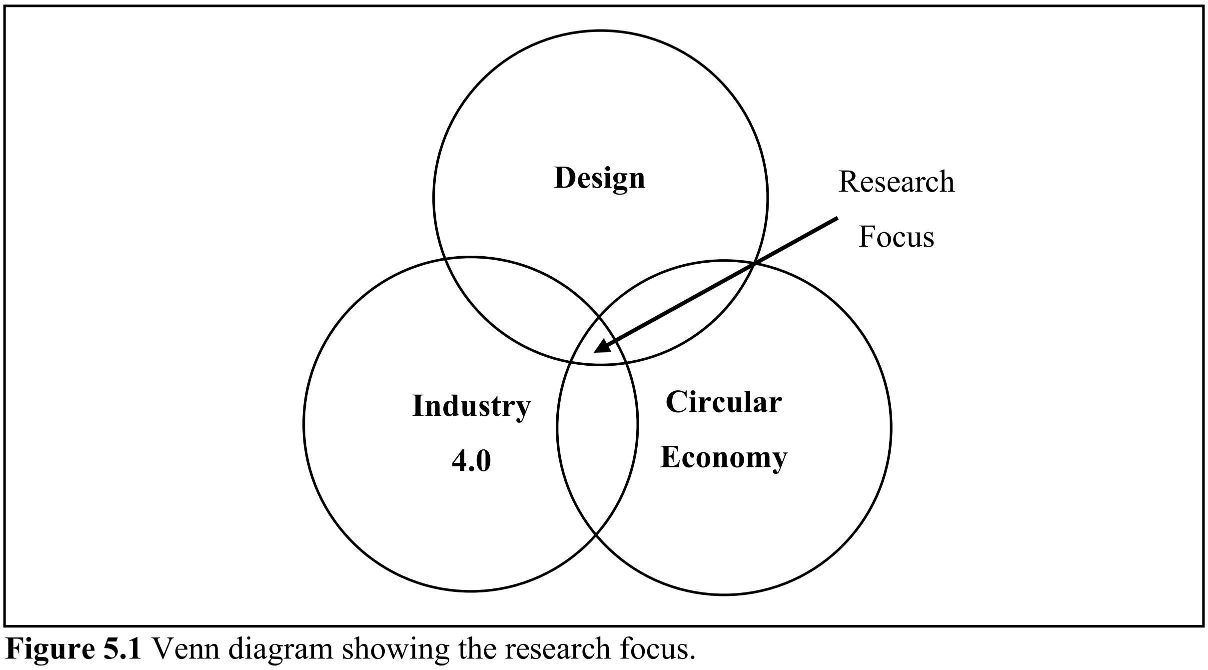


**Figure 5.1** Venn diagram showing the research focus.

This embeddedness within multiple, intersecting systems spanning numerous disciplines is typical of sustainability problems. As a result, they are often described as ‘wicked problems’, presenting a number of inherent challenges and complexities that make addressing them particularly difficult (Zijp, et al., 2016) (Waddock, 2013) (Dovers, 2010) (Peterson, 2009).

(Rittel & Webber, 1973) originally coined the term wicked problems in reference to those associated with multiple, dynamic, interrelated systems, which are difficult to define and conceptualise, eluding traditional reductive scientific research techniques. As there are many potential solutions to a wicked problem, there exists no clear stopping point, and the arrival at any given solution is determined by the somewhat subjective framing of the problem (e.g. consumption may be ‘good’ for producers, but ‘bad’ for communities affected by waste and pollution). Another challenge is that it is not possible to definitively test solutions; as to trial a solution is to implement it, which may ultimately transform the problem at hand. Expanding on (Rittel & Webber, 1973)’s description, (Levin, et al., 2012) define four additional features specific to wicked problems as they relate to sustainability, coining the term ‘super wicked’ problems. These include urgency, as there exists a limited amount of time in which to develop and implement solutions, complexity, due to the fact that the parties responsible for causing the problems simultaneously endeavour to provide solutions, a lack of a central authority necessary to enforce solutions, and an illogical delay in addressing problems, shifting consequences into the future. As such, the challenge with super wicked sustainability problems is that they are incredibly difficult to address, whilst at the same time, finding solutions grows increasingly imperative. In light of this, a new discipline has emerged in the form of ‘sustainability science’, aimed at helping researchers navigate these important issues.

### 5.2 Sustainability Science

Sustainability science provides a way forward for researchers who wish to address complex, and increasingly urgent sustainability issues that span multiple, dynamic and interrelated systems. It is a burgeoning field of research that has emerged since the 1990’s in response to an observed disconnect between the contextualized, applied knowledge needed to address real-world sustainability problems and the specialized, abstract knowledge produced by traditional academic disciplines (Hadorn, et al., 2006). As such, sustainability science has a number of key differentiating features. The first is that the scope of the research is defined, not by a specific subject area, but by the boundaries of the sustainability problem with which it is centrally concerned (Brandt, et al., 2013). Sustainability science is therefore flexible in terms of its approach, accommodating a wide variety of potential sustainability problems, as well as the perspectives and research methods necessary to address them. One of the most important elements in sustainability science research is therefore the effective framing of the problem. This is a collaborative process involving both researchers and stakeholders to provide a deep, contextualized understanding of the problem at hand and a clear definition of the knowledge required in order to address it (Mauser, et al., 2013).

In addition to being problem-focused, sustainability science research is also solutions-oriented. As such, the aim is to generate knowledge and insights that will help to effectively address a given sustainability problem. A variety of research outputs are therefore accommodated by a sustainability science approach, from detailed descriptions and analyses that contribute to the better understanding of a problem, to the generation, implementation and evaluation of evidence-based solutions (Wiek & Lang, 2016). This differs from the research carried out in traditional academic disciplines, which tends to focus on increasingly narrow, subject-specific gaps, with the aim of expanding disciplinary knowledge (Hadorn, et al., 2006). One of the defining features of sustainability science research is therefore that outputs reflect the premise that they will eventually be applied, supporting decision making and leading to practical action and transformational change.

Another requirement of sustainability science research is that a transdisciplinary approach is adopted. This is due to the fact that real-world sustainability problems encompass a variety of complex and interrelated systems, such as social, natural, political and economic systems. As such, they cannot be reduced to simple, linear models of cause and effect, confined to individual disciplinary fields (Sterman, 2012). Whilst an official definition of 'transdisciplinary' may not be available, it is considered the most integrated research approach available. This is in comparison with 'multidisciplinary' research, which simply involves the employment of numerous disciplinary approaches focused around a unifying theme, requiring minimal collaboration, and 'Interdisciplinary' research, which involves a more collaborative approach and the blurring of disciplinary boundaries to provide new perspectives on a particular problem (Stock & Burton, 2011). Instead, transdisciplinary research aims to achieve the holistic integration of disciplines, with the aim of dissolving disciplinary barriers and immersing the research within the context of the real world. As such, it is differentiated by a strong focus on problem solving, stakeholder engagement and the practical application of findings (Stock & Burton, 2011). A transdisciplinary approach is therefore well aligned with the goals of sustainability science.

Lastly, as sustainability science research is grounded in real-world problems, there is a strong emphasis on stakeholder engagement and the co-production of knowledge (Clark & Dickson, 2003). Incorporating stakeholder perspectives helps to provide valuable, contextualized understanding surrounding the sustainability problem being addressed. This is essential for both the accurate framing of the problem and the development of appropriate solutions and actionable insights. More specifically, including the perspectives of practitioners and those involved in the implementation of solutions can help to ensure any proposals are achievable and realistic (Wickson, et al., 2006). Stakeholder engagement therefore plays an important role in ensuring the success and relevance of sustainability science research.

It is therefore evident that sustainability science differs from traditional, disciplinary research in terms of both motivation and output. It can be summarized as a problem-focused approach that transcends disciplinary boundaries and engages with stakeholders to produce findings that support the development of solutions (Lang, et al., 2012). It is for these reasons that sustainability science was identified as a suitable approach for the research presented in this thesis. However, whilst the guiding principles were clear and well justified, they also presented a number of points of contention that needed to be addressed.

The first was the need to bring together various forms of knowledge, skills and expertise in order to unite diverse disciplines and subject areas in an integrated manner. This would typically be addressed through collaboration between multiple researchers with different backgrounds and specialisms, however, within the constraints of the PhD, it was necessary for the research to be conducted by a single researcher. As such, the merging of multiple disciplines was instead facilitated by the researcher's own varied background. This included formal training in environmental science, sustainability and design for a circular economy (DfCE), as well as previous experience using technologies associated with Industry 4.0 within a design context. Additionally, as the research provides an initial mapping of an emergent subject area it is expected that it will serve as a guide for future research, drawing contributions from a variety of additional researchers to further develop the concepts and theories presented.

In addition to accommodating transdisciplinarity, it was also necessary to consider how stakeholder engagement would be incorporated into the research process, particularly with respect to the framing of the research problem. As explained by (Lang, et al., 2012), stakeholders are individuals or parties with a significant connection to the sustainability problem at hand. This may include those contributing to the problem, those who are impacted by it or those tasked with the implementation of solutions. With the central focus of the research being the need to transition from a linear to a circular economy through the implementation DfCE practices, designers were identified as the main stakeholders in the study. It was therefore important to engage with designers as part of the research process in order to capture their views and experiences. However, it was necessary to be mindful of the fact that, whilst key stakeholders, designers may not necessarily be willing or able to commit considerable quantities of time to be involved in academic research. Additionally, it was acknowledged that there were no resources available with which to compensate designers for their time and contribution. It was therefore necessary to balance the requirement for significant stakeholder involvement with the need to ensure that the process would be convenient and not too time consuming for those involved. For this reason, a program of semi-structured, qualitative interviews was identified as a suitable and efficient means of capturing the perspectives and experiences of designers. In turn, this would support the effective framing of the problem and support the co-production of knowledge, incorporating stakeholder engagement within the research process. A detailed discussion of the processes followed is provided in Chapter 5.4.2.

Another point of contention was the theoretical dilemma associated with the integration of multiple disciplines with divergent ontological and epistemological underpinnings, as necessitated by transdisciplinary, sustainability science research (Brandt, et al., 2013). This needed to be addressed as the theoretical positions inherent in individual disciplines denote particular views about reality (ontology), what can be known about that reality (epistemology) and the possible means by which that knowledge may be acquired (methodology) (Jerneck, et al., 2011). Simply merging different disciplines, especially those with as diametric theoretical positions and methodological norms as the natural and social sciences, was therefore considered problematic. As such, it was necessary to establish a conciliatory theoretical framework, upon which the research could be based, in order to inform both the methodology and determine what claims could be made about the research findings. A solution was identified in the form of a critical realist approach, which provided a clear path forward that was compatible with transdisciplinary, sustainability science research. An in-depth discussion and justification are provided in Chapter 5.3.

The final challenge associated with sustainability science research was the lack of established research methods. Traditionally, the adoption of a particular methodology and set of research methods within academia is heavily influenced by research discipline (Jerneck, et al., 2011). This is because the organization of research within disciplinary silos has worked to perpetuate a number of discipline-specific norms (Krishnan, 2009). Over time, this has led to each discipline having developed its own explicit, central object of focus, amassed body of specialist knowledge, collection of concepts and theories for the effective organization of knowledge, and discipline-specific terminology and research methods. These disciplinary norms have then been upheld through institutional formalization and the education and training of successive academic generations. Therefore, whilst the research approach and means by which knowledge is generated or discovered is not technically determined or constrained by discipline, the adoption of certain theoretical assumptions, methodological conventions, and communication styles tends to be heavily influenced and guided by disciplinary norms (Khagram, et al., 2010).

Whilst sustainability science is often referred to as a discipline, it lacks the convenience of a narrowly defined central focus and established theoretical and methodological norms, typical of traditional disciplines. As (Lang, et al., 2012, p. 26) explain in their analysis of the emerging field,

> *'[...] the [sustainability science] literature is rather fragmented and dispersed, without providing good guidance to interested researchers and practitioners [...]'*

Further, the diversity of real world problems that sustainability science sets out to address requires a degree of flexibility, allowing for the selection and compilation of methods relevant to the types of data demanded by each specific problem (Brandt, et al., 2013). Unlike traditional disciplines, it has therefore been suggested that sustainability science should serve as a generic research platform, accommodating a wide range of methods, spanning the natural and social sciences and beyond, reflective of the variety of sustainability problems that exist in the real world. Whilst such an approach is in contrast to the rigid, reproducible research demanded by other disciplines, (Brandt, et al., 2013, p. 5) has suggested it is a price worth paying in order to meet the aims of sustainability science research.

> *'A completely reproducible, uniform approach to methods is probably neither possible nor desirable within the dynamic, problem and solution orientated field of sustainability science.'*

Sustainability science may therefore be thought of as a flexible research approach, albeit with a set of guiding principles, that is directed by the specific problem being addressed and the overarching aim of developing solutions and achieving transformational change. In light of this degree of flexibility and on the recommendations of (Brandt, et al., 2013), it was considered necessary to provide a clear outline and justification for the specific selection of research methods employed within this thesis. This is documented in Chapter 5.4.

### 5.3 Theoretical Positioning

One of the main objectives of PhD research, and indeed any research, is to make a significant and original contribution to knowledge. However, in order for any such claims to be made and before a suitable approach to generating knowledge can be designed, something must be said of the nature of knowledge and ways of knowing and that which constitutes reality (Rugg & Petre, 2004). Over the years there has been much philosophical debate regarding what is real and what can be known, which has resulted in the emergence of numerous philosophical paradigms. Each paradigm denotes a specific ontological and epistemological position and associated assumptions, which in turn influence the approaches and methods employed by researchers to discover or generate new knowledge. Of the various paradigms, positivism and interpretivism have tended to dominate the debate, representing two diametric philosophical positions (Howe, 1992).

Positivism is adopted throughout the natural sciences and promotes the idea that there exists an objective reality that can be observed and studied directly. Positivist researchers therefore employ quantitative research methods to facilitate the collection of extensive empirical data. This is conducted in controlled experiments whereby certain variables are isolated in an attempt to identify cause-effect relationships between them. Statistical analysis techniques are then employed in order to prove or disprove a given hypothesis through the replication of results, helping to establish the universal, generalizable laws, which supposedly govern reality (Wahyuni, 2012). Positivism also assumes a reductionist mentality, in which complex phenomena are explained as the simple sum of their constituent parts, divisible to a series of universal laws (Gasparatos, et al., 2007)

In contrast, interpretivism refutes the existence of an independent and objective reality. Instead, it focuses on the human experience, promoting the idea that reality is socially constructed and subjective, accommodating multiple perspectives (Wahyuni, 2012). Interpretivism therefore relies on intensive, contextualized data obtained through qualitative research methods. Both the researcher and research participants actively contribute to the interpretation and reconstruction of their realities, from which meanings about the social world can be extracted (Khagram, et al., 2010). In contrast to positivism, the findings of interpretivist research are not considered generalizable, as they are specific to the individual. Instead, the aim is to develop rich, in-depth descriptions of social constructs to further our understanding of particular social realities. Interpretivism is therefore commonly, though not exclusively, adopted in the social sciences.

It is therefore evident that positivism and interpretivism represent two diametrically opposed philosophical positions (Sale, et al., 2002). Attempting to integrate them, as is necessary for conducting transdisciplinary sustainability science research that encompasses both natural and social science disciplines, therefore becomes paradoxical. As (Fam & Sofoulis, 2017, p. 237) explain,

> *'Integration is especially problematic when teams combine positivist science and engineering approaches with post-positivist and interpretive perspectives, because of deep differences in perspective on the form, purpose and value of knowledge [...]'*

At the same time, one cannot escape from the fact that a transdisciplinary approach is essential for generating the varied knowledge necessary to understand and solve complex, real-world sustainability problems. The natural sciences fail to account for the intricate, everchanging interplay between economic, social and environmental systems, which defines sustainability issues. Such dynamism cannot be comprehensively explained in terms of a single metric or group of metrics, as is the case with a reductionist, positivist positioning.

> *'Completely understanding the constituent parts of a complex adaptive system does not allow a complete description of it because the interrelations between its parts also have a significant effect on its overall behaviour... the whole system is greater than the sum of its parts'* (Gasparatos, et al., 2007, p. 4)

Likewise, whilst the social dimension forms an integral component of sustainability science research, an interpretivist approach is not compatible with the existence of an objective, external reality. Yet this notion underpins the natural sciences, upon which sustainability problems are predicated and effective solutions must be based. As (Brown, et al., 2010, p. 9) explain,

> *'The moral imagination evokes our conscience, telling us what should be, while the scientific imagination reframes substantive issues, such as the passage to sustainability [...]'*

In light of these limitations and of the importance of a transdisciplinary approach in sustainability science research, two additional philosophical paradigms are presented in the form of pragmatism and critical realism.

For researchers carrying out transdisciplinary research and faced with the apparent incompatibility between positivist and interpretivist paradigms, a pragmatic approach is often sought as a solution. However, rather than resolving the contentious issue, pragmatism merely omits ontology and epistemology from the discussion by foregrounding the problem at hand (Wahyuni, 2012). As such, it permits mixed methods, whether quantitative or qualitative, provided findings are useful in addressing the subject of focus. However, the criteria by which research may be considered useful can only be a subjective judgement, relative to a very specific, applied research context (Easton, 2010). Pragmatism therefore exists on unstable theoretical foundations. As (Sale, et al., 2002) note, positivist research observes an objective reality, whilst interpretive research focuses on multiple realities comprising subjective lived experiences. Therefore, whilst they may be unified through a shared theme, these different approaches actually study different phenomena in accordance with their respective philosophical paradigms. The approach of researching around a common theme from different disciplinary angles is more akin to multidisciplinary research. It therefore lacks the integration and transcendence of disciplinary boundaries required for true transdisciplinary, sustainability science research. Secondly, there exist questions regarding the validity, reliability and transferability of results where pragmatism has been adopted as the guiding philosophical paradigm. These are explored in depth by (Modell, 2009), who warns that failing to address the inherent immiscibility of epistemological and ontological positions when attempting to mix positivist and interpretivist research approaches can lead to,

> *'[...] an excessively eclectic mix of research practices with incompatible ontological points of departure [...]'* (Modell, 2009, p. 210)

This can in turn imply that the research is,

> *'[...] dominated by assumptions embedded in the functionalist paradigm at the expense of deeper and multifaceted depictions of social realities.'* (Modell, 2009, p. 210)

Considering the limitations of pragmatism, an alternative philosophical paradigm capable of accommodating transdisciplinary sustainability science research is presented in the form of critical realism.

Critical realism is a philosophical paradigm that arose in response to what its founder, Roy Bhaskar, observed as the ‘epistemic fallacy’ committed by those operating within the prevailing research philosophies whereby ‘reality’ is conflated with ‘knowledge of reality’. Instead, critical realism supports the idea that reality is separate from our knowledge of it. As such, it promotes the notion of a stratified reality, divided into several layers. The first is referred to as the ‘real’ and comprises the enduring structures and mechanisms that exist as part of an objective reality. The interplay between these structures and mechanisms give rise to causal powers, which, when activated under certain conditions, generate events, referred to as the ‘actual’. The witnessed proportion of these events constitutes the ‘empirical’, which may include observations, measurements and experiences (Figure 5.2).

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**Figure 5.2** The stratified domains of reality in critical realism. Adapted from (Mingers, 2004).

Critical realism is therefore accepting of all forms of empirical results, whether intensive or extensive in nature, provided they are not misconstrued as direct observations of reality. Instead, they simply serve as clues or evidence that can be interpreted in order to support the development of theories about ‘real’ underlying structures and mechanisms. Therefore, through this conceptualisation, critical realism effectively resolves the ontological and epistemological conflicts that typically arise in transdisciplinary research (Isaksen, 2012).

In addition to the stratification of reality, critical realism also supports the existence of human agency. This suggests that human behaviour is not simply determined by causes, but rather influenced by the mechanisms, structures and causal powers that underpin society. By interpreting their experiences and making decisions, individuals either replicate or transform the extant reality through their actions and behaviours (Archer, et al., 1998). As such,

> *'[...] society is both the condition and outcome of human agency and human agency both reproduces and transforms society'* (Archer, et al., 1998, p. XVI)

This aspect of critical realism is of particular relevance to sustainability science research as it implies that society is not locked into a particular trajectory at the mercy of external factors. Instead, its course may be consciously altered by the considered and purposeful actions and behaviours of individuals, leading to transformational change.

In order to develop explanatory theories about the causal powers and underlying structures and mechanisms that constitute reality, critical realists adopt an iterative process of abductive reasoning and retroduction (Modell, 2009). The former refers to the formulation of reasoned explanations for observed evidence, whilst the latter involves the revision and refinement of explanations by seeking out further evidence, which would need to be present (or absent) in order for those explanations to be true (Easton, 2010).

> *'Thus theoretical explanation proceeds by description of significant features, retroduction to possible causes, elimination of alternatives and identification of the generative mechanism or causal structure at work [...] applied explanation by resolution of a complex event (etc.) to its components, theoretical re-description of these components, retroduction to possible antecedents of the components and elimination of alternative causes [...]'* (Archer, et al., 1998, p. XVII)

Unlike in the case of probability-based analyses, there are no claims of a guarantee. Instead, any explanation remains fallible and open, but becomes more believable and robust the more evidence is found to explain it. As such, the aim is to develop a deep understanding of the subject of focus and well-reasoned explanatory theories that are robust and enduring with respect to further empirical evidence.

A critical realist philosophy therefore provides an appropriate theoretical positioning upon which transdisciplinary sustainability science research may be conducted. In addition to reconciling the epistemological and ontological issues typically associated with transdisciplinary research, critical realism also provides a solid and comprehensive theoretical grounding. Whilst critical realism does not specify nor restrict the research methods to be employed, its provision of a clear rational about reality, knowledge and ways of knowing provides valuable guidance upon which appropriate methods may be selected. This also helps to define what can be claimed of the results in terms of credibility, confirmability and transferability, which are discussed in more detail in Chapter 5.5. For these reasons, a critical realist theoretical positioning was selected for the research presented in this thesis.

### 5.4 Methodological Approach and Research Methods

Neither sustainability science nor critical realism specifies a particular methodology or set of methods through which research should be conducted. Instead, they provide broad guiding principles to be followed. In the case of sustainability science, research should be problem-focused, solutions oriented, transdisciplinary and incorporate stakeholder engagement. Meanwhile, critical realism remains open to various means of gathering both intensive and extensive forms of information, provided these observations are not conflated with direct observations of reality (Sayer, 2000). An iterative process of abduction and retroduction is recommended for the interpretation of empirical evidence and the development of explanatory theories about reality (Easton, 2010). As such, the focus of the research is on understanding and explanation, accepting the fact that any conclusions drawn are unavoidably fallible. With these guiding principles in mind, it was necessary to devise an appropriate methodological approach and set of methods, relevant to the problem at hand and which would support the development of solution-oriented understanding and explanation.

As previously stated, the central focus of the research was on understanding the potential implications that Industry 4.0 may present for the implementation of Design for a Circular Economy (DfCE). The main subjects of the research, DfCE and Industry 4.0, were both emergent concepts at the early stages of theoretical development within the literature (See Chapters 3 & 4). The relationship between them had therefore not yet been explored, despite the existence of broad links established between the more generalised topics of design-and-circular economy, design-and-industry and circular economy-and-industry, which suggested that DfCE and Industry 4.0 would be of relevance to one another. Therefore, with no existing theories or frameworks from which to work, it was determined that the key contribution that could be made was to map the research area, providing advanced insights and directing future research efforts.

In order to research an emergent topic for which there was limited existing information and real-world examples, it was necessary to take an indirect approach to avoid mere speculation.

The study was therefore designed to combine three converging lines of investigation, for which information and empirical evidence would be available, to provide insights into the relationship between DfCE and Industry 4.0. The three lines of enquiry were summarised in the following research questions:

1. What are the existing challenges and barriers to the successful implementation of DfCE in the design of consumer products?
2. How have key developments in industrialisation and manufacturing technology impacted on the design of consumer products throughout history?
3. How are early applications of Industry 4.0 technologies beginning to impact on the design of consumer products?

The coordinated merging of multiple datasets, investigators, theories or methods in order to investigate a particular subject is a process referred to as triangulation (Berg, 2001). The incorporation of multiple lines of enquiry falls under the category of 'theory triangulation'. Key to triangulation is not only the bringing together of multiple perspectives, but also the process of relating them to one another so as to understand the bigger picture and to interrogate and verify findings.

As explained by (Berg, 2001, p. 4),

> *'By combining several lines of sight, researchers obtain a better, more substantive picture of reality; a richer, more complete array of symbols and theoretical concepts; and a means of verifying many of these elements.'*

By implementing this process of cross-referencing, triangulation helped to increase the validity of the research and reduce the potential for arriving at a biased or narrow understanding of the problem. In addition to theory triangulation, the research also employed multiple methods, or 'methodological triangulation', to obtain sources of both primary and secondary information, relevant to the research questions. These methods included integrative literature review, historical literature review, a series of in-depth, semi-structured interviews, as well as case studies. The results were then organised using thematic analysis before applying abduction and retroduction to develop and refine theory. Triangulation was deemed to be well aligned with a transdisciplinary, sustainability science approach as it supports the integration of multiple perspectives relative to the problem at hand. Additionally, from a critical realist perspective, the more evidence gathered, the more refined and robust the resulting explanations become. A detailed description of each of the specific research methods employed is provided below, alongside justification of their selection and details of their implementation.

### 5.4.1 Historical Review

An historical review involves the exploration and examination of previous events in order to build a comprehensive picture and understanding of the past. Such reviews go beyond the simple gathering together of records, dates and facts, to include an element of critical evaluation and analysis aimed at illuminating the underlying relationships and ideas that have helped shaped society (Berg, 2001). By doing so, researchers have the opportunity to gain greater insight into human actions and behaviours than would otherwise be possible by observing only the present (Berg, 2001). Historical reviews therefore provide an additional pool of insight and information that researchers can draw from in order to inform the evaluation of contemporary phenomena. As explained by (Berg, 2001, p. 211),

> *'It [historical research] is the study of the relationships among issues that have influenced the past, continue to influence the present, and will certainly affect the future.'*

A historical review was therefore selected as an appropriate means for addressing research question 2. This set out to understand the evolution of design and its relationship with manufacturing technology, including the impact of major developments associated with industrialisation and progressive technological and organisational transformation. The aim of this was to support the development of theory with respect to questions 1 and 3, helping to make sense of findings by providing useful context and background information. In relation to research question 1, the historical review was intended to provide insights into how a linear industrial model came to be and design's role within it, helping to understand the reasons behind the existence of the DfCE barriers identified. In the case of research question 3, the historical review was aimed at providing a basic understanding of the ways in which design had been impacted by previous changes in industrial technology and production. The intention was to help make sense of the observed impacts that early Industry 4.0 implementation was having on design. The historical review was therefore not intended to serve as a comprehensive and detailed history of design and industrial development. Instead, the aim was to provide an in-depth analysis of key events, as relevant to the research, which would help to build a clearer picture and deeper understanding.

(Berg, 2001) sets out the main steps in conducting an historical review. The first is to decide the central topic of focus, which can be a broad area of research initially. This is followed by a background literature review, whereby basic information is gathered and analysed so as to provide a general orientation on the topic. Throughout this process, the research focus is continuously revised and refined, in turn, giving rise to further or more specific research questions. Selecting historiography as the means of data collection, primary and secondary sources of data relevant to the research questions are sought out by searching databases and repositories. Each source of data is then evaluated in terms of its authenticity and accuracy using processes of external and internal criticism, whereby 'external criticism' refers to determining whether or not the data is genuine and 'internal criticism' involves establishing the intent and meaning behind the data to determine its reliability. The final stage in the historical review process is analysing the data to produce a narrative exposition of the findings. This involves firstly collating and categorising all of the data thematically. This is then followed by content analysis, supplemented by the researcher's own evaluations and interpretations in order to identify patterns and relationships within and between the data. The original literature review is consulted throughout this process and new sources of data are progressively sought out in order to elaborate and expand upon the patterns and relationships identified, grounding the research in the data and background literature (Berg, 2001).

Following the methods set out above, the historical review began by formulating the central topic of focus, which was as the historical relationship and co-evolution between industry and design. A background literature review was conducted using the search terms 'history + design + industry' in the search engines 'books.google.co.uk' and 'scholar.google.co.uk'. Textbooks were primarily consulted initially in order to give a comprehensive grounding in the subject and a basic framework of significant historical developments from which to work. This helped to generate additional research questions regarding the specific aspects and events that represented pivotal transformations in industrialisation and the design of consumer products. Purposive sampling was then used to select relevant primary and secondary resources specific to the key developments identified, providing further, more detailed information. These included journal articles, published books and original documents, sourced through searches of 'books.google.co.uk', 'scholar.google.co.uk' and The British Library catalogue via 'explore.bl.uk'.

As an EU-centric lens was adopted for the overall thesis (Chapter 2.3.4), material was included if it was deemed directly or indirectly relevant to developments that have contributed to the evolution of industry and design in what is the EU today. More isolated or less consequential developments that didn't have a significant impact on the overall trajectory of industry and design were excluded for concision. Whilst the thesis was focused on consumer products (Chapter 2.3.3), including clothing, furniture and electronics, this was of limited relevance for a historical review as the types of products produced varied and evolved over time. As such, the focus shifted to developments in design that came to influence the design of consumer products in the present day. Additionally, the review touched on a variety of forms of design, from architecture to war provisions, vehicles and new materials, whilst the overall thesis was focused on consumer product design (Chapter 2.3.2).

Sources were evaluated in terms of their internal and external validity, by considering their relevance, origin, authority and citation record. An effort was made to uncover multiple and potentially contrasting perspectives on the events so as to build a balanced range of material. Due to the time and resource constraints of the research process, many of the resources comprised secondary, peer-reviewed sources rather than original artefacts, which would require additional authentication and interpretation. Nevertheless, as the research was aimed at understanding and explaining major developments and the relationships between underlying causal mechanisms that gave rise to them, as opposed to a complete and comprehensive historical record of events, the evidence gathered was considered sufficient.

The gathered material was grouped around the particular developments and events, which were pivotal for the development of industry and design, before a thematic analysis was performed for the purpose of developing explanatory theory. Further information was gathered as new questions arose through a process of abduction and retroduction. The sourcing and analysis of material therefore continued as an iterative process until the point at which a robust explanation of each event or development could be reached. The findings were presented in a narrative format focusing on paradigmatic changes in the relationship between design and industry. An effort was made to present these in a chronological order for ease of comprehension; however, as findings comprised thematic analysis, rather than mere description, there was inevitably some overlap between themes.

As denoted by a critical realist stance, explanations remain fallible and can be refined and improved with further evidence. The extent of evidence gathered was therefore limited by the time and resources available and focused by the purpose of the review, which was to provide key insights to support the analysis of findings from other research activities, which it achieved.

Whilst all knowledge is interpreted from experiences, in historical reviews, which are concerned with past events, the researcher is further distanced from direct experiences of those events, relying on artefacts, historical accounts and secondary information, which may already constitute interpretations themselves. However, historical reviews benefit from their provision of an additional and valuable perspective and source of evidence, providing insights that can help to strengthen the development of explanatory theories. It was therefore deemed an important component in the triangulation of results, contributing to understanding surrounding the relationship between DfCE and Industry 4.0.

### 5.4.2 Integrative Literature Review

An integrative literature review is one that brings together representative information on a topic, which is then synthesised, critiqued and analysed in order to generate new insights and frameworks (Torraco, 2005). Integrative reviews are therefore well suited to research concerning emerging phenomena, such as those covered in this thesis, as they address the need for an initial, holistic conceptualization and consolidation of a new research area (Torraco, 2005). This contrasts with systematic literature reviews, which aim to document and summarize the findings of existing research on a narrowly defined topic (Torraco, 2005). An integrative literature review was therefore deemed an appropriate means of researching the emergent concepts of design for a circular economy (DfCE) and Industry 4.0 to address research questions 1 and 3.

The process for conducting an integrative review is outlined by (Whittemore & Knafl, 2005) framework, which includes four key stages. The first is the problem identification stage, whereby an initial review of the literature is used to identify knowledge gaps that could benefit from an integrative review, helping to determine the focus and scope of the task. The second step is the literature search stage through which relevant literature is identified and gathered from a variety of sources. Integrative literature reviews encourage a more flexible and wide-ranging search approach compared to other types of reviews, accommodating techniques such as purposive sampling. For the purpose of transparency and methodological rigour, however, the sampling strategy must still be clearly documented, specifying elements, such as search terms, inclusion and exclusion criteria and the justification for any sampling decisions made. The next step in the process is the data evaluation stage, whereby the literature returned in the search is assessed based on quality. This can be gauged by evaluating each source against criteria, such as the value of the information presented, the quality of methodological approaches employed and the extent to which they may be considered representative of the available material. Finally, the data analysis stage begins with the extraction of data from the literature, reducing the volume of material. This data is then categorised and arranged thematically through a process of constant comparison, enabling the identification of patterns, variations, commonalities and relationships. Conclusions are then drawn to provide a new understanding of the subject. Throughout this process, the literature is continuously revisited so as to prevent premature closure of the analytic process (Whittemore & Knafl, 2005).

Following the method outlined above, an integrative literature review was employed as part of the process of addressing both research question 1 and 3. As previously stated, question 1 aimed to understand the 'existing challenges and barriers to the successful implementation of DfCE in the design of consumer products'. An initial literature review (Chapter 3) explored the development of the circular economy concept, the role of design and the emergence of design for a circular economy (DfCE) and identified the problem as a lack of successful DfCE integration and a gap in terms of understanding the reasons why. With this as the research focus, a literature search was conducted using search terms 'circular economy + design + challenges OR barriers OR limitations OR obstacles' in the 'Web of Science TM' and 'scholar.google.co.uk'. A sequence of purposive and snowball sampling was then applied to identify additional material necessary to elaborate on the specific DfCE barriers identified. Sources were included provided they were concerned with the design of physical, consumer products, excluding those focused on architecture and the built environment, chemical engineering, primary industry, utilities and intangibles. The selection of material was also centred on DfCE, as this constituted the main focus of the research, however, the fact that DfCE was a relatively emergent concept meant that there was a finite amount of literature available, particularly with regards to specific barriers. As such, the scope of the literature search was expanded to include consideration of concepts that were precursory or related to DfCE, including eco-design, sustainable design and design innovation. Whilst such concepts were not regarded as being interchangeable, a considered judgement was made to identify commonalities relevant to DfCE. As a critical realist theoretical positioning remains open to various methodological approaches, sources were not limited by the methods employed. Instead, a judgement was made based on the evidence that each presented in respect to the claims authors made. The literature was then categorised, and a thematic analysis applied so as to begin to uncover the mechanisms, structures and causal powers relevant to the implementation of DfCE.

Whilst literature represents a secondary source of data, with the potential for introducing bias, it benefits from providing access to a large volume of diverse information incurring minimal time and resource demands in comparison to empirical research. Additionally, in the case of this study, the searching, categorising and thematic analysis of the literature formed an ongoing process that was complemented by a series of semi-structured, qualitative interviews with designers on the same topic (see Chapter 5.4.3). This not only ensured stakeholder engagement formed an integral component in framing the problem, but it also served as a means of methodological triangulation, helping to improve the reliability of results. The combined findings of the integrative literature review and stakeholder interviews therefore provided an in-depth understanding of the barriers currently limiting DfCE implementation, acting as a framework from which the potential impacts of Industry 4.0 could be evaluated.

An integrated literature review was also employed to address research question 3, which aimed to understand how 'early applications of Industry 4.0 technologies are beginning to impact on the design of consumer products'. In a similar approach, an initial literature review (Chapter 4) explored the concept of Industry 4.0, the key technologies involved and the knowledge gaps regarding the impacts on design with reference to sustainability and the achievement of a circular economy. As such, a literature search was conducted using the search terms 'Industry 4.0 + design' in the 'Web of Science TM' and 'scholar.google.co.uk'. A combination of purposive and snowball sampling was then employed to identify additional material necessary to elaborate on the specific design implications relevant to Industry 4.0. This necessitated the expansion of search terms to include technologies related to Industry 4.0, as identified in Chapter 4. Sources were included provided they were concerned with the design of physical, consumer products, excluding material focused on the design of digital systems, manufacturing environments, logistics and intangibles. Once again, as a critical realist theoretical positioning remains open to various methodological approaches, sources were not limited by the methods employed. Instead, a judgement was made based on the evidence that each presented in respect to the claims authors made. The literature was then categorised, and a thematic analysis applied so as to begin to understand the potential impacts of Industry 4.0 technologies on the design of consumer products.

Recognising the limitations of the integrative literature review approach using secondary sources of information, case studies analysing the early adoption of Industry 4.0 technologies and the subsequent impacts on product design were gathered (see Chapter 5.4.4), facilitating methodological triangulation and helping to increase the reliability of the theories developed.

This provided a deeper, more contextualised understanding of the relationship between Industry 4.0 and design. This in turn revealed insights necessary to begin drawing parallels between the potential transformation of design as a result of Industry 4.0 and the DfCE barriers identified earlier in the research process.

### 5.4.3 Semi-Structured, Qualitative Interviews

Qualitative interviews involve asking a selection of participants a series of open-ended questions in order to elicit their individual experiences regarding a particular issue. The aim is to therefore generate rich, contextualised data, helping to develop a deeper understanding of the issue of focus. Qualitative interviews can range from structured to unstructured in terms of the degree to which questions are pre-determined and explicitly followed during the interview process. Falling somewhere in the middle, semi-structured interviews generally involve working from a pre-prepared interview guide, whilst allowing for some degree of freedom for new topics and concepts to arise during the interview process, particularly those that may have been missed initially. Semi-structured interviews are therefore most suitable in situations when the central concepts in a study are already somewhat formed, whereas entirely unstructured interviews are more suitable in the initial exploration of a subject (Ayres, 2008). As the interviews were intended to complement the integrative literature review on the same subject, semi-structured, qualitative interviews were selected as a suitable research method for gaining a deeper and more contextualised understanding of the factors limiting DfCE implementation.

The first stage in conducting semi-structured, qualitative interviews is to prepare an interview guide that broadly sets out what will be covered in each interview. This includes introductory information to be provided to participants, as well as the suggested questions and topics to be covered during the interview. The interview guide is designed around the research focus and informed by any provisional conceptual models underpinning the research (Ayres, 2008).

The next stage is sampling, whereby interview participants are identified and selected. In the case of qualitative research, the emphasis is on obtaining rich, contextualised data, as opposed to the extensive, abstract data sought in quantitative studies. As such, qualitative research typically involves smaller samples. The sample size tends to be determined by the maximum amount of data that is manageable, in terms of the time and resources available for analysis, or by the point at which data saturation is achieved (Morgan, 2008). Determining the individuals to be included within a sample involves formulating a set of qualifying criteria. Purposive sampling, a form of non-probability sampling, is widely implemented in qualitative research to select individuals from a population that meets the qualifying criteria so as to provide data that is relevant to the objectives of the research. Prior to contacting potential participants, it is also necessary to seek ethical clearance and to identify any permissions and data storage protocols that need to be established before interviewing can commence (Hennink, et al., 2011).

The next stage is the interview process itself. Interviews may be conducted in-person, via telephone or via online video-conferencing applications, allowing for two-way communication between the interviewer and participants (Hanna, 2012). An important element of qualitative interviews is building rapport with participants in order to make them feel at ease and comfortable sharing information. As such, it is important to open the interview with some broad, general questions about the participant, which are easy to answer. An additional benefit is that responses to these questions may also provide useful contextual information, for data analysis (Hennink, et al., 2011). These are then followed by the main questions of the study. In the case of semi-structured interviews, the questions largely follow the topics outlined in the interview guide. However, some deviation is encouraged, such as follow-up questions to elicit further elaboration or to accommodate previously unexplored areas of relevance as they arise in conversation (Ayres, 2008). Additionally, confirmatory paraphrasing may be used to ensure accurate interpretation of responses (Ayres, 2008). The potential for extracting rich and relevant data is therefore dependent on the interviewer's ability to understand, interpret and respond to the experiences and perspectives provided by participants as they are revealed. Findings are therefore co-produced by both the interviewer and participant (Hennink, et al., 2011). As such, a good quality qualitative review should reveal new perspectives and insights, helping to support theory development.

In order to enable analysis, interviews are initially audio recorded and later transcribed to produce a written document. Transcription may be carried out automatically or manually, however the latter provides an additional opportunity for the researcher to immerse themselves in the data. Immersion in the data is the first step towards analysis and involves the reading and re-reading of interview transcripts so that the researcher becomes familiar with their content (Green, et al., 2007). The analysis of interview transcripts then relies on the researcher's ability to understand participants' individual experiences and extract personal, social and cultural meaning (Hennink, et al., 2011). In order to manage the large volumes of data and the insights drawn from it, a process of coding is generally recommended (Green, et al., 2007). This involves applying a descriptive label to individual sections of the transcript to capture the essential meaning of each passage. Codes are then revisited and refined as each transcript is coded (Green, et al., 2007). Ideally this process is carried out iteratively after each interview, providing an opportunity for the researcher to reflect on findings and to adjust or add questions prior to the next (Hennink, et al., 2011). After coding, the next step is to link related codes together to form categories. A sufficient number of interviews have been conducted, coded and categorised when it's possible to thoroughly understand and make sense of each category (Green, et al., 2007). Whilst categories provide descriptive insights into the data, further analysis and interpretation is required in order to generate a detailed explanation of the research subject. This involves testing emergent, preliminary theories against the rest of the interview data, as well as the available literature. This allows researchers to locate categories within a wider theoretical context, including similar but related scenarios, helping to increase the transferability of the findings (Green, et al., 2007).

In line with the methods outlined above, a series of semi-structured, qualitative interviews were carried out with designers, to provide a deeper and more contextualised understanding of the barriers to DfCE implementation. The first step was to develop an interview guide, which set out the key topics necessary to investigate the existing barriers to DfCE implementation. This was informed by the integrative literature review on the same topic, which began in advance of the interview process and then continued concurrently (see Chapter 5.4.2). The key topics also reflected the fact that the designers interviewed were unlikely to be experts on the topic of circular economy and may not have had first-hand experience implementing DfCE. It was therefore necessary to cover a wide variety of topics and questions, including those indirectly related to DfCE, such as designers' experiences of sustainability, so as to gather relevant information that would shed light on DfCE implementation barriers. Topics were therefore centred around factors inherent in the design of consumer products, which were identified through the literature review as having the potential to impact DfCE implementation. This was done with a view to extracting the detailed, contextualised accounts of designers' experiences of design, complementing the findings of the literature review and supporting the development of explanatory theory.

The sampling strategy employed was a form of purposive sampling, referred to as stakeholder sampling[9]. Designers were identified as the key stakeholders, capable of providing information

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[9] 'Stakeholder Sampling' may be defined as, *'[...] identifying who the major stakeholders are who are involved in designing, giving, receiving or administering the program or service being evaluated, and who might otherwise be affected by it'* (Palys, 2008).

about the design of consumer products. It was important to select individuals representative of the wider population of consumer product designers, as opposed to particularly well known or specialist, sustainability-focused designers. This was due to the fact that it is these designers who make design decisions that determine the final outcomes for the majority of consumer products. The scope was then further narrowed in accordance with the focus of the research (see Chapter 2), to include designers of consumer products, including apparel, furniture and electronics, working within EU countries. In order to ensure designers were speaking from experience, a minimum of one year's industry experience was stipulated as an additional requirement. Interview participants were recruited via LinkedIn as the platform provided a convenient search engine with the ability to search by profession and location, as well as to review each designer's career history to ensure that they met the necessary criteria. LinkedIn also provided a means of easily contacting those identified. As purposive sampling was used to select interview participants, an effort was made to include a cross-section of designers across apparel, electronics and furniture and those working in different EU countries. The latter being due to the fact that some countries may be more advanced than others in either design, CE or Industry 4.0. Recruitment of participants, however, proved a challenging task, as the response rate to the initial invitation was low (approximately 1 in 50), yet the LinkedIn application does not enable follow-up messages to be sent without a response from the recipient. Whilst it was not possible to determine the cause for the low response rate, however, possible explanations include delays in checking LinkedIn messages, a lack of compensation and incentives for involvement in the process, a lack of time available for participation and a lack of interest in the topic of the research or participation in academic research in general. In addition to LinkedIn searches, designers meeting the selection criteria were also sought through professional connections and snowball sampling, provided they had had no prior direct contact or connection with the researcher to avoid introducing bias.

Interviews were conducted via Skype as this provided a convenient means of enabling two-way communication between participant and researcher, regardless of location, whilst facilitating audio recording of the interviews. Each participant was provided with a definition of 'sustainability' and 'circular economy' prior to beginning the interview for continuity. Interviews began with general questions regarding the designer and design process, helping to ease participants into the interview process and providing useful background information. As the interview went on, concepts more strongly associated with DfCE were introduced in order to elicit a more contextualised explanation of the barriers identified through the literature review. A flexible approach was adopted throughout the interview process to enable follow-up questions to be asked as new, relevant areas of focus were introduced by participants. Confirmatory questioning was also used to ensure that interpretation of participants' responses was accurate. Whilst the interviews were qualitative and in-depth in nature, it was acknowledged that designers had a limited amount of time available to participate. In order to respect this, interviews were kept to approximately 60 minutes duration.

After each interview, the audio recording was manually transcribed, providing an additional opportunity for the researcher to become immersed in the data, helping to inform the next interview. This meant that questions evolved over the interview process according to the information required. In order to conceal designers' identities and enable them to speak freely about any challenges and issues, the transcripts were anonymised, removing personally identifiable details and those of their workplace/s. Whilst the interviews were transcribed verbatim, each participant was provided with a copy of their interview transcript with an opportunity to make corrections or redactions should any details have been provided in error or incorrectly interpreted during transcription. This also provided an opportunity for the designers involved to check they were happy with the level of anonymity achieved.

In total, 10 designers participated in the semi-structured, qualitative interviews. Of these, two were deemed to not meet the inclusion criteria following more in-depth questioning, leading to a revision of the qualifying questions asked to participants prior to interview. A further interview could not be included due to the designer not returning a signed ethics form. Another withdrew from the process following receipt of a copy of their interview transcript. This left a total of 6 interviews for inclusion in the study.

Following these interviews, a need to include the experiences and perspectives of those who have had first-hand experience of implementing DfCE was identified, to look, not only at the barriers to DfCE implementation, but also at the solutions implemented by early adopters. As such, purposive sampling was used to select three leading examples in the form of Mud Jeans, Fairphone and The Library of Things. Initially, a similar, semi-structured interview process was planned, however, it was necessary to adapt the approach according to the constraints stipulated by the organisations. In the case of Mud Jeans and Fairphone, it was necessary to join a group webinar, submitting a selection of questions in advance. This limited the questions specific to the study, however, benefitted from a longer question and answer session, enabling the capture of related information provided as answers to other researchers' questions. In the case of The Library of Things, it was necessary to sign up for their workshop and tour. This provided background information and an opportunity to ask unlimited questions. The webinars and workshop were also audio recorded and transcribed, although anonymity was not required or requested on behalf of the companies involved. This enabled additional information to be sourced from their respective websites, providing further insight into their design processes, business models and approach to DfCE.

Interview transcripts, including the webinars and workshop, were then analysed through a process of coding, categorisation and theory building as outlined earlier in this chapter. This formed an iterative process, with the continual revision and refinement of codes and categories. Further literary sources were introduced into the integrative literature review as necessary to investigate particular design aspects as they arose in the interviews. Using a thematic analysis and process of abductive reasoning and retroduction, it was possible to build theory explaining the existing barriers to DfCE implementation. Results were presented thematically forming a framework for directing research into Industry 4.0 and its impacts on design and in turn, DfCE implementation.

A series of semi-structured, qualitative interviews with key manufacturing stakeholders, following the same process as outlined above, were also initially planned in order to provide contextualised understanding surrounding the early implementation of Industry 4.0 technologies and the impacts on design. However, following the integrative literature review on the same topic and the completion of the first interview, it was confirmed that Industry 4.0 was still at a particularly emergent stage, requiring a more targeted, alternative approach to interviews with stakeholders. As such, an alternative method of case study analysis was instead employed (Chapter 5.4.4).

### 5.4.4 Instrumental Case Studies

Case studies can be broadly described as the process of gathering information about an individual, organisation or event in order to better understand the way in which it operates (Berg, 2001). As such, they are especially useful when attempting to answer ‘how’ and ‘why’ questions, which are commonly the case with exploratory, descriptive and explanatory research (Rowley, 2002). ‘Instrumental’ case studies in particular go beyond developing a detailed understanding of a specific case. Instead, the aim is to use case studies to support the development of theoretical explanation and conceptualisation. Whilst individual cases may not be considered generalisable, the aim is to provide additional insight with respect to the overarching theory or research problem (Berg, 2001).

> *'Instrumental case studies may or may not be viewed as typical of other cases. However, the choice of a particular case for study is made because the investigator believes that his or her understanding about some other research interest will be advanced.'* (Berg, 2001, p. 229).

Multiple instrumental case studies may therefore be conducted and brought together in order to provide a broader range of perspectives and a greater body of evidence, helping to further theoretical development. Such an approach is therefore well suited to the study of new and emergent phenomena where there is a lack of existing theory (Rowley, 2002). Additionally, case studies enable the study of complex systems, which cannot be isolated for experimental purposes and must be examined within their real-world contexts (Schwandt & Gates, 2018). A series of instrumental case studies was therefore selected as an appropriate method for investigating the impacts of Industry 4.0 technologies on the design of consumer products, complementing the integrative literature review on the same topic.

Case studies remain open to various methods of data collection and accommodate multiple types of information. It is therefore important that the processes followed are made explicit for transparency and replicability (Berg, 2001). This includes an explanation of the existing theories and ideas underpinning the research, along with a list of the research questions guiding the case study process. A description of the criteria used to determine and identify the relevant subjects of analysis, i.e. the individuals, organisations or events to be studied, is also required. These criteria are typically determined by factors, such as the purpose of the study, the research questions, resource constraints and accessibility (Rowley, 2002). Sources of evidence and information that could be obtained include, but are not limited to, documents, artefacts, observations and interviews (Rowley, 2002). Once the material has been gathered, analysis typically involves familiarisation with the data and the seeking of patterns and trends that corroborate or refute existing theories and provide additional elaboration or explanation. In the case of exploratory research, where existing theory is limited, case studies may also contribute to the initial formulation of theories. The greater the number of cases found to corroborate or refute the prevailing theory, the more robust the research is considered to be. Case study research therefore aims to achieve a level of transferability, not by identifying generalisable, universal trends, but by enabling a more in-depth explanation and understanding of a given theory (Rowley, 2002).

Following the methods outlined above, a series of instrumental case studies were employed so as to provide a more in-depth, contextualised understanding of how the early implementation of Industry 4.0 technologies were impacting on design. This approach was deemed more appropriate than the initially planned in-depth, qualitative interviews with manufacturing stakeholders as it would provide illustrative examples of real Industry 4.0 implementation, enabling direct interpretation by the researcher, rather than high-level speculation of what may happen.

A process of purposive sampling was employed to select real-world examples of Industry 4.0 implementation, which was guided by the literature review on the same topic. The literature review was therefore carried out in advance of the instrumental case studies and then continued in parallel as part of an iterative process. In addition to online searches via 'www.google.co.uk', cases were identified through consultation with digital media publications and podcasts and by attending external lectures, industry exhibitions, conferences, webinars and networking events. The inclusion criteria were that cases were related to the design of consumer products, demonstrated Industry 4.0 technology implementation and were in existence (i.e. not merely proposed). A range of information sources were collated, including 'grey' and academic literature, images and audio-visual files (e.g. podcasts and promotional videos). The case studies were analysed thematically in conjunction with the integrative literature review on the same topic. A such, they provided contextualised examples of the themes emerging from the literature, helping to illustrate concepts and build in-depth understanding and explanatory theories.

### 5.4.5 Thematic Analysis

The final stage of the research involved bringing the findings of each of the previous chapters together in an integrative way so as to inform explanatory theory development in relation to the bigger picture. As such, the aim was to analyse the evidence thematically so as to answer the overarching research objective of understanding the implications of Industry 4.0 for the implementation of DfCE practices. To do so, the theoretical frameworks developed in Chapter 7, Existing Barriers to DfCE Implementation, and Chapter 8, Design Implications of Industry 4.0, were initially cross-referenced in order to identify commonalities and linkages. This was supplemented with the findings of Chapter 6, Industry and Design, A Historical Review, to provide added context, helping to support understanding of how things came to be and how changes occurred in the past. The development of theory was supplemented with additional, targeted literature as necessitated by the emergent themes and theories. An iterative process of abductive reasoning and retroduction were employed to develop, revise and refine theories, ensuring they were grounded in and supported by the evidence. These explanatory theories were then presented thematically in Chapter 9, Design for a Circular Economy in Industry 4.0. A schematic of the research is presented in Figure 5.3.

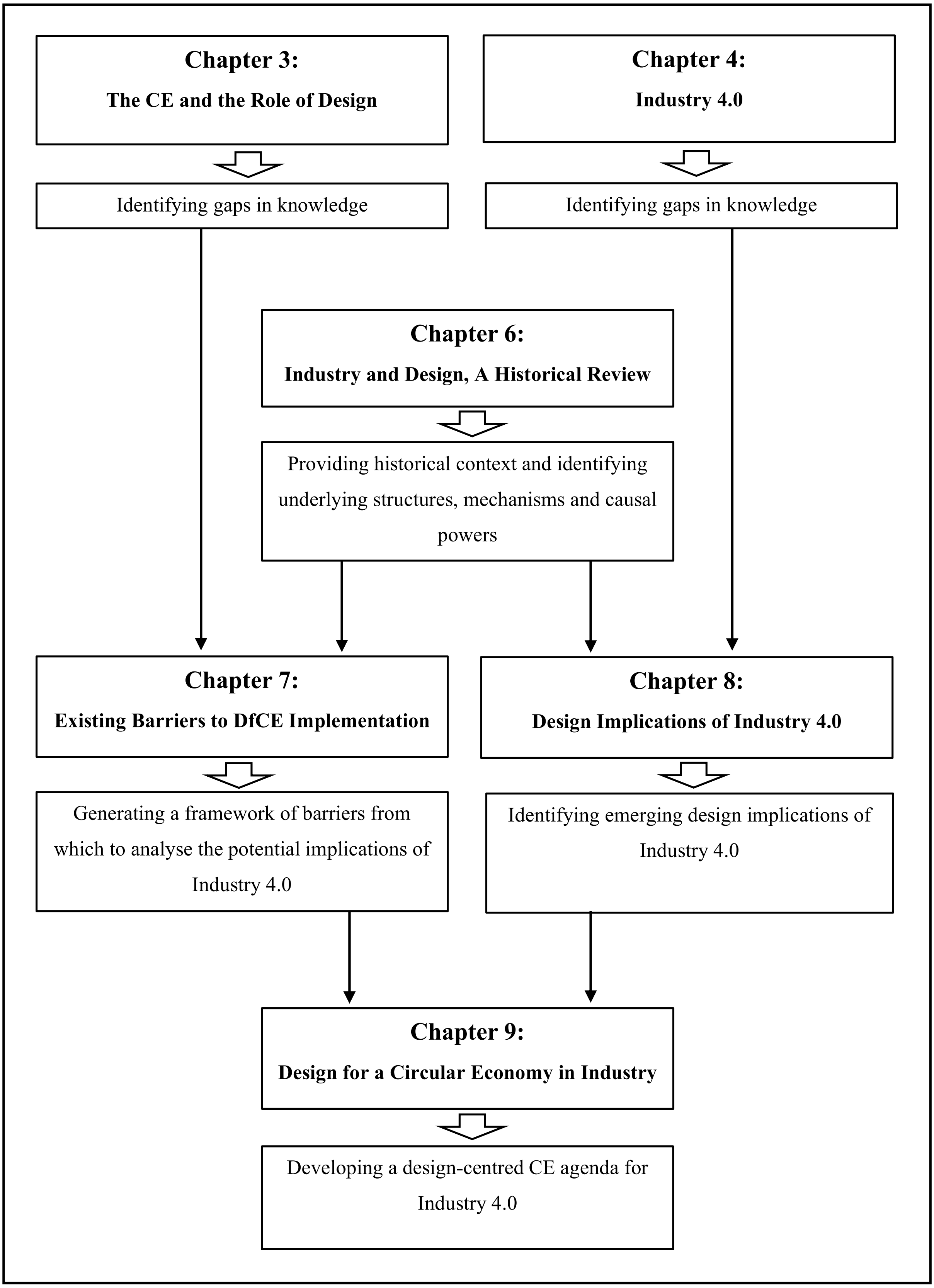


**Figure 5.3.** A schematic diagram of the research design.

### 5.5 Strengths and Limitations of the Research

The research set out to address a real-world, sustainability problem, encompassing emergent phenomena in the form of DfCE and Industry 4.0. Without an existing methodological framework to build from, it was necessary to devise an original research approach, in accordance with the research aims and guided by the principles of sustainability science. As such, the research effectively transcended disciplinary boundaries, framing the scope of the research around the problem of focus. Stakeholder engagement and consultation formed an integral part of the research process, ensuring the research was grounded in the real world and that any solutions proposed were realistic. Thus, the research met the requirements of a sustainability science approach.

The adoption of a critical realist theoretical positioning supported the transdisciplinary nature of the research and also helped to give meaning to the results, determining what can be claimed in terms of the knowledge produced. As such, the research reflected the belief that complex systems cannot be reduced to a collection of simple cause and effect rules. This directed the methodological approach to incorporate methods that allowed complex phenomena to be studied in situ, including integrative literature reviews, semi-structured, qualitative interviews and case studies. The aim of the results was therefore not to identify rules that support prediction, nor to provide rich, descriptive accounts of personal experiences, but to provide deep, contextualised, explanatory theories that can help support decision making, providing a detailed understanding of the problem and an advanced awareness of potential challenges and solutions. This included a detailed framework outlining the challenges to DfCE implementation, a set of advanced insights into the impacts of Industry 4.0 on design and a design-centred circular economy agenda for Industry 4.0. Due to the emergent nature of the topics covered, these findings serve as an initial mapping of the research area, helping to illuminate the relationship between DfCE and Industry 4.0, which may also be used to identify areas for further research.

In terms of the reliability of results, critical realism takes the position that all forms evidence is permissible, with the development of explanatory theories grounded in the results of the research. As such, the more evidence considered, the more re-evaluation and refinement of theories is possible, helping to improve their robustness. Nevertheless, as critical realism stipulates that reality can never be directly experienced, relying on the interpretation of experiences to provide evidence of underlying mechanisms, structures and causal mechanisms, no theory can ever be considered ‘closed’. Any theories produced therefore remain ‘open’ and fallible in light of further evidence. As such, further evidence can always be sought. In a bid to ensure the theories developed were as reliable as possible, methodological and theoretical triangulation was employed to provide a wide range of diverse results from which to draw from. The time and resource constraints of the PhD therefore served as the limits for gathering further research. However, as the outputs provide a springboard from which further research can be launched, the research can be considered as part of a wider body of potential research, which will help to build upon the theories presented.

# Chapter 6. Industry and Design, an Historical Review

This chapter aims to build an in-depth understanding of how design has evolved with the transformation and advancement of industry. The goal is to provide insights into the emergence of underlying mechanisms that have shaped and influenced the design of everyday consumer products. These insights will help to build an understanding of how current models of industry and design have come about, giving rise to existing barriers to Design for a Circular Economy (DfCE). Additionally, they will provide context for the identification of the potential implications Industry 4.0 presents for design. To this end, an historical review of the literature is employed considering the social, cultural, economic consequences of industrial technological advancement and their impact on design (Chapter 5.4.1). This approach is in line with previous research exploring material objects and their existence as part *of 'larger systems, cycles and environment'* (Buchanan, 1992, p. 11).

As a review focused on the history of design and industry, it is important to recognize that, whilst a definition of design for the purpose of this thesis is provided in Chapter 2.2, the notion of 'design' has changed over time. (Buchanan, 1992) highlights design's evolution and transformation over time in response to contextual changes, from trade activity, to a segmented profession, a field for technical research, and a liberal art of technological culture. As such, a high-level definition has been adopted for the purpose of this review, so as to encompass all of the term's potential iterations.

> *'All design terms [...] involve the creative visualisation of concepts, plans and ideas; and the representation of those ideas (as sketches, blueprints, models or prototypes) so as to provide the instructions for making something that did not exist before, or not in quite that form.'* (Walsh, 1996, p. 513).

However, as the overarching theme of the thesis is the design of consumer products for a Circular Economy (CE), particular attention is paid to the factors that ultimately influenced the physical or embodied design of products. As such, it is necessary to consider all major aspects that have influenced design in so far as they relate to or have impacted on product outcomes.

### 6.1 Pre-Industrialisation

Throughout history, humans have extracted raw materials and manipulated them into value-added objects to better meet their needs. To be human is to be design. Prior to industrialisation, design was a non-commodified activity, with everyday products brought into existence by individuals, in a process referred to subsequently as 'craft' production. This took a number of forms. As society was still largely agrarian in nature and focused on subsistence in terms of meeting basic needs for survival, much of the population lived rurally and was employed in agriculture. As farming was very much a seasonal vocation, individuals would hand craft products in between periods of agricultural work. This would be carried out in peoples' own homes in what is referred to as 'handicrafts'. The objects created were generally intended for personal use or for use within the local community, serving and surrounding villagers throughout their everyday lives.

Alongside the domestic, small-scale production of handicrafts existed specialised craftsmen organised in craft guilds, which tended to be located in urban centres. These organisations were a hangover from medieval times and were associated with an established organisational structure. Apprentices would join the guild and partake in several years of vocational training, closely following the orders of the master, often residing with them (Jones, 1992). The design of crafts and the methods of production were tightly controlled, to achieve a high quality and standardised output according to long standing traditions passed down from generation to generation. As pointed out by (Jones, 1992), craftsmen would know the correct dimensions and construction required, but often not why those particular attributes or the actions taken would make a successful product. As such, process and product innovation tended to emerge involuntarily from incremental practical experiments and random variations through daily practice. One unintended source of such innovation was the movement of apprentices between guilds, resulting in technological cross-fertilization. This also occurred to some extent as a result of the 'clustering' of guilds in close geographical proximity, so as to be able to effectively monitor apprenticeship and craft activities, ensuring accordance with guild rules and expectations. However, the benefits and returns on such incremental improvements tended to be limited by the costs involved with breaking away from established processes (Epstein, 2008). For more than half a millennium, craft guilds organised the craft profession. In addition to their economic role as a producer, they also held political significance, providing services including political representation, dispute settlement and poor relief (Prak, 2006). The craft guilds paid for exclusive rights to make and sell certain products in a particular area and held political sway to protect their rights. What this demonstrates is that prior to industrialization, design was an iterative process, rather than one that constituted careful planning prior to execution. Product outcomes were also designed according to personal tastes and requirements, as opposed to those of the masses.

At the same time, the tastes of European elites and the resulting fashion cycle was at the heart of consumption, which demanded products and furnishings of sufficient exclusivity, quality, novelty and decoration, to meet exacting expectations. As (Raizman, 2003) explains, this saw the setting up of state-owned 'manufactories' in France and Germany in the 17th and 18th centuries. In contrast to the division of labour and poor working conditions in the mechanised factories that would later arrive in the 19th century, these manufactories housed highly skilled craftsmen. Far from carrying out simple, repetitive tasks, their role was to work closely with painters and sculptors who would supply the manufactories with their artful designs. It would then take a great deal of invention and ingenuity to develop the processes, patterns and resources, such as dyes, that would facilitate the recreation of these works in the form of decorative products and furnishings (Raizman, 2003). The source of inspiration for artists and sculptors at this time was classic art, which heavily influenced the style of luxury goods at the time. The turnover of the consumption patterns of the elite consumed a large amount of materials and labour. However, it was argued that the existence and activities of manufactories provided employment to the local community and boosted the economy (Raizman, 2003). Production and consumption of European elites was therefore quite different to that of the rest of society, driven by social status and the fashion cycle.

### 6.2 Proto-Industrialisation

The availability of home workers able to produce handicrafts was eventually capitalised on by urban merchant entrepreneurs. They would lease production equipment, such as looms and spinning wheels, to villagers, providing them with the raw materials to convert into saleable products, which could then be traded at international markets (Rosner & Theibault, 2015). As rural villagers of the time were not so familiar with capitalist concepts, focusing more on achieving sufficient gross production for subsistence, rather than achieving additional earnings through the sale of superfluous products, urban entrepreneurs saw an opportunity to pay village home workers relatively low wages, selling the products onto domestic and international markets and extracting surplus value for themselves. Whilst the quality would be lower than that produced by guild craftsmen the wages paid to untrained villagers meant that the products produced could be sold much more cheaply. This trend was referred to as 'putting out'. It is argued that this move away from subsistence to the production of value-added products in exchange for wages helped form the basis for 'proto-industrialization' seen in the late 17th and early 18th centuries, as villagers became more used to this capitalist, industrial form of working arrangement (Houston & Snell, 1984). This increasingly centralized and regulated production, centralized in its distribution therefore served as a precursor to capitalist manufacturing.

In contrast to handicrafts and products produced by craft guilds, proto-industrial production represented a move towards the fabrication of large volumes of identical products, often for export. Further to this, the design of products was stipulated by the merchant who then enlisted various home workers to generate orders to his specifications (Styles, 1988). As such, the form and aesthetic of what was being produced was largely out of the control of the makers. However, unlike industrialised production lines, the machines employed in these proto-industrial operations were not optimised or restricted to particular specifications, which enabled workers some flexibility. As noted by (Styles, 1988), the ability to switch between product designs was essential given consumers' propensity for fashion and novelty, with lower end markets aspiring to copy from the metropolitan high society. However, this flexibility also came with some challenges. Workers were often distant from the trendsetting urban centres and the individuals who would ultimately consume the products that they were producing. Whilst manufacturers sought advice from agents on the latest London tastes, they then had to communicate these design details and instructions to the home workers. Whilst complex products like those incorporated into intricate woven silks were drawn up into loom patterns, others would be communicated verbally or via written correspondence. The development of industry specific language to effectively communicate trends to manufacturers from agents, and to communicate instructions from manufacturer to worker was therefore extremely important. As explained by (Styles, 1988, p. 15),

> *'The initiative in design innovation flowed predominantly from master manufacturer to worker, but the ability of workers autonomously to interpret and adapt the manufacturer's instructions was also essential.'*

As explained by (Berg, 2001), the art of imitation was seen as a particular skill. Rather than simply making copies of luxury goods in cheap materials, those practicing imitation attempted to reinterpret objects in new forms, displaying ingenuity and inventiveness. This enabled the effective commercialization of luxury, which in turn gave rise to new product inventions and considerable process innovation. As such, products that resembled or were suggestive of the tastes and fashions of the rich upper classes were made available to the aspirational middle and even lower echelons. Such products of imitation included candlesticks, sugar-tongs, brass furniture ware, snuff boxes, buttons and buckles (Berg, 2001).

The spread of putting out and of proto-industry was further supported by technological improvements in agricultural production. This was particularly the case in England, where the percentage of the population employed in rural agriculture declined from 74% to 35% between 1500 and 1800, whilst productivity continued to rise (Crafts & Knick Harley, 2002). The domination of capitalist farming within Britain meant that landowners were unlikely to keep on any superfluous staff at unnecessary cost, when technological improvements meant that greater outputs could be achieved with fewer workers, thus maximising profits. This in turn resulted in workers seeking additional employment to supplement agricultural work. As observed by (Crafts & Knick Harley, 2002), it was this capitalist agricultural structure that set England apart from other European economies, which moved to that model much later. Coupled with a growing population, this drove up the number of people seeking employment in craft production in exchange for wages. (Crafts & Knick Harley, 2002), initially questions this, as it would seem logical that with a technological advantage in terms of agricultural productivity compared to overseas markets, Britain would inevitably become a lead exporter in food, thus driving up agricultural expansion and a rapid increase in the demand for agricultural workers. However, on further consideration (Crafts & Knick Harley, 2002) explains that it's important to consider the wider economy and international trade advantages across all industries. Whilst Britain was technologically advanced in agriculture, it was more advanced in the production of textile industries such as cotton, gaining a considerable lead (Crafts & Knick Harley, 2002). According to Ricardo's comparative advantage principle[10], as the gains from cotton would exceed what could be earned from the same (labour/opportunity) investment in agriculture, it would make more sense for Britain to earn more from cotton and in turn import food from international markets using some of the profits than to invest in a mix of both. This is backed up by records showing that Britain still imported 20% of its agricultural consumption by the mid nineteenth century, despite a considerable lead over international markets in terms of productivity (Crafts & Knick Harley, 2002). As such, it makes sense that the shift from agriculture and the promotion of certain other industries in Britain would be influenced by the extent of their competitive advantage afforded by technological advances.

[10] Ricardo's comparative advantage principle can be summarized as the economic benefit of specialising in the production of a particular product or good in the context of international trade (Findlay, 2008). For a detailed explanation see Findlay, R. (2008) Comparative Advantage. In: Durlauf, S.N., Blume, L.E. (eds.) *The New Palgrave Dictionary of Economics*. London: Palgrave Macmillan, pp.28-29.

It is therefore observed by (Riley, 2001), that this proto-industrial era demonstrates the fact that advanced economic growth and the development of a consumer market was not the simple and direct outcome of industrial technologies, but rather the precursory demographic shift from rural workers with a subsistence lifestyle to increasingly urbanised, individuals employed in the manufacturing of products and who in turn became the consumers of those products.

> *'Modern economic growth emerged instead in the demand of urban consumers for larger quantities and a sharply diversified variety of goods and services, a demand that was satisfied largely by artisans and craftsmen working at home or in small shops'* (Riley, 2001, p. 264)

This highlights the importance of social, economic and cultural developments to the evolution of design and industry, and the need to look beyond merely technological advancements.

**6.3 Industrialisation**

The industrial revolution is regarded as beginning in Britain in the late 18th and early 19th centuries, and was characterised by the centralisation of manufacturing in large factories in urban centres, that incorporated new technologies, such as steam power and process mechanisation (Dorn Brose, 2010). Industrialisation followed on from proto-industrialisation as a result of several factors. Firstly, there was an imperative for merchants to centralise their workforce, as, with growing rural 'putting out' businesses spread over greater areas, it was increasingly difficult to supervise the workforce. This limited their ability to enforce quality controls and deadlines, as well as monitor raw materials for embezzlement. As explained by (Hudson, 2014), the centralisation of labour in factories and the introduction of automated mechanised equipment were mutually beneficial. As well as overcoming the challenges with supervising a dispersed workforce, the establishment of factories provided the space in which large, noisy machinery could be housed. Prior to this, employees were working out of their homes with much smaller hand-operated machines. In return, the significant efficiency gains afforded by machinery more than made up for any shortcomings incurred by no longer having dispersed production.

Industrialisation also provided a solution for the challenges associated with a seasonal rural workforce. As Britain worked to maximise their advantageous position in industries such as cotton production, the demand for proto-industries, such as the putting out of production to rural home workers in exchange for supplemental income increased. However, as pointed out by (Mendels, 1972), agricultural production was still prioritised during the months when working the land and harvesting were required, creating periods of disruption for the merchants that employed rural workers in craft production. As the demand for the products wasn't seasonal, pressures such as this encouraged the development of industrialisation and the urbanisation of workers so as to keep production in a continuous stream and products at a competitive price, maximising the profits for the merchant entrepreneurs.

The shift to mechanised production equipment wasn't necessarily a simple decision as it represented a considerable up-front investment. Rather than re-investing yearly earnings into the next year's production, as happened with earlier practices, industrialisation represented a shift to a new model in which large upfront sums or 'sunk costs' would need to be invested, requiring an evaluation of how many units the merchant planned to be able to sell and at what price (Mendels, 1972). As such, due to the high capital outlay for machines, it was important to maintain productivity and throughput of materials at a constant, high rate in order to achieve effective capacity utilisation and spread the 'sunk costs' across many units to keep unit prices down. The profits accumulated by merchants from proto-industrial manufacturing ventures helped to provide the capital necessary for investment in machinery and fixed capital. If successful, this in turn had the effect of lowering the costs of products through the economies of scale principle, causing an increase in demand due to products becoming more affordable and available to a wider class of people, as production increased to meet growing demand (Chandler & Hikino, 2004).

However, this wasn't always the case, as industrialisation and mechanisation brought their own limitations. As observed by Marx, the breaking down of a fabrication process into discreet tasks enabled the automation of that process to some extent using machines (Sabel & Zeitlin, 1985). However, whilst this division of labour would inevitably afford significant efficiency gains, the price paid was an increase in rigidity in terms of both the process and the specifications of the products being produced. As more steps in a process become segregated and automated, the more difficult it becomes to deviate from the original design. As such, division of labour and mechanisation was limited by demand and, by association, the presence of tax and tariff barriers, prohibitive transportation costs, a lack of disposable income experienced by potential consumers or the existence of too many variations on a product, which could be merged into a standardised unit. In the case where there was sufficient demand, industrialisation had a positive feedback effect, as the greater efficiency achieved made products even more affordable to a wider range of people, widening the market. As (Styles, 1988) suggests, the increase in fashionability and acquisitiveness in society as observed by many historians may well have been less to do with a spontaneous appetite for consumption and more to do with gaining the ability to purchase, taking into account wealth and wealth distribution at the time, as well as the social construction of markets and the trading of goods. Another practical explanation for the increase in consumption observed by (Riley, 2001) was the fact that owning physical assets provided a means of storing value, which could be liquidated in hard times through their sale in lieu of access to a banking account.

Industrialisation also inevitably had a significant impact on the existing, traditional forms of production. As (Desmet, et al., 2017) point out, whilst craft guilds were not against innovation when it came to raw material conservation or skill enhancement, they were strongly opposed to any innovations aimed at labour savings. As technological and organisational developments that cut labour requirements became established as part of the industrial revolution, the craft guilds protested and revolted. However, by that stage, many had come to see the guilds as protectionist, antiquated and standing in the way of technological development and opportunity and the political and economic climate had shifted in favour of capitalist businesses. This sentiment saw craft guilds gradually abolished by decree in England, France and Germany (Epstein, 1998), however, many craft guilds had already suffered in the face of competition from proto-industrial practices and the growth of factories that benefited from economies of scale and cheap labour, which the guilds could not, or would not, adopt. Improvements in transportation and the increasing demand for low-skilled labour also made the guilds' regional control and rules of membership untenable to enforce (Epstein, 1998).

When urban industrialisation began, it caused those involved in agricultural production to move to urban areas, separating living environments from the location of income generation, separating family members and creating the need to invest in human capital. In other words, it was more advantageous to invest in specialist training than to simply have more family members to carry out tasks (Mendels, 1972). This created a split whereby urban areas focussed on industrial activities with specialised workers, and other areas increased agricultural yields in order to meet the demand of those in urban centres who were no longer self-sufficient.

> *'The extent of capital accumulation as well as the political and social terrain in which it took place and the personnel in whose hands it fell determined very much the course of future (factory) industrialisation.'* (Mendels, 1972, p. 246)

Industrialisation therefore signified a new means of production and a paradigm shift, from designing products according to individuals' needs and requirements, to designing for manufacture. In turn, industrial production also unwittingly created its own consumer market. By centralizing workers in cities, they were removed from environments that facilitated subsistence, making them reliant on purchases. Through employment within factories, they were also provided with the means to then buy and consume the products of their labour. Because industrialization afforded greater efficiency and per unit cost savings, more products became affordable to the middle classes, whereby consumption was longer a pursuit exclusive to the European elite. This signalled the beginning of what is today considered a consumerist society.

### 6.4 Design Reform and Innovation

The design of products was inevitably impacted on by the move away from traditional, handcrafted products and the rapid development of new technologies, possibilities, modes of production and markets. The rise of the aspirational middle classes as a result of success in the industrial revolution (e.g. merchants, factory owners) began to emulate the highly decorative and ornate tastes that were a sign of frivolity, excess and wealth previously exclusive to royalty and the aristocracy. As (Black, 1994, p. 81) explains,

> *'By 1851, British product design had become confused and undisciplined... Only Britain's engineering products appeared to retain a degree of functional and aesthetic sanity - but even this was under threat from the over-ostentations of mid-Victorian taste.'*

Whilst earlier held notions of quality, functionality and fitness for purpose were lost, manufacturing began to churn out 'shoddier' and 'more pretentious' imitations of existing designs (Black, 1994). As explained by (Raizman, 2003), the accumulation of commodities was a demonstration of social status and the newfound wealth as a result of industrialisation and market expansion provided an opportunity for social mobility through the purchasing of products. The challenge for manufacturers was to keep creating new products and styles to encourage consumption by the wealthy, which would filter down to the middle and lower classes, encouraging them to emulate their peers (Stankiewicz, 1992). Style became important as the volume and variety of products proliferated, with manufacturers appropriating styles from the past and from overseas cultures and traditions, such as the East (Raizman, 2003). The emergence of early marketing techniques in the United States from the beginning of the twentieth century was effective in driving up consumption and creating consumer desires and needs. These included things like illustrated mail order catalogues, which became increasingly detailed and decorative. These early marketing activities were further aided by simultaneous improvements in transportation and mail services (Woodham, 1997). Retail then changed with the establishment of department stores. This created a leisure activity of shopping and meeting at department stores, particularly for groups of women (Woodham, 1997). As such, these new technological and social developments were in effect democratising culture and, at the same time, commodifying the desire and demand for individualism (Raizman, 2003).

However, this unconsidered and un-laboured application of aesthetic styles drew criticism and attempts to reform the design of manufactured products through formal arts education to achieve some kind of unified standard (Raizman, 2003). Known as the 'Aesthetic Movement', it held that beauty should be prioritised over wealth and other values, and that the well-considered selection of particular aesthetics served as evidence of a superior character. The features that were considered to constitute 'good' design were advocated through the dissemination of arts literature, national arts education and museums displaying exemplary examples of good taste (Stankiewicz, 1992).

Whilst the Aesthetic Movement was largely focused on refining and coordinating the visual appearance of manufactured goods towards some kind of unified artistic style, another initiative, the Arts and Crafts Movement took reforms of production and design a step further, highlighting the moral and social aspects of industrialisation. Key figures associated with the movement, such as John Ruskin and William Morris lamented the separation of the creative and manual aspects of bringing products to fruition, questioning the ability for unskilled labour and mechanised manufacturing processes to achieve the same standards and quality as traditional artisan craft practices (Stankiewicz, 1992). The nostalgic sentiment for the traditional methods of hand-producing meaningful and useful products can be seen in (Blount, 1910, pp. 1-2) writing on the subject.

> *'[...] the first principle of all art is to create and decorate useful things instead of useless ones. We have forgotten this principle for a long time, and have been busy instead in making useless and expensive things, or in inventing labour-saving machines to take the place of human heads and hands when we wish to make necessary ones.*
>
> *This neglect has brought about a separation between the artist and the artisan which is fatal to both; for the artist has lost that connection with the everyday*

> *necessities of life which keeps art vigorous, and the artisan has lost that touch with culture which alone can make his work beautiful.'*

However, the Arts and Crafts Movement was as much a political initiative as it was a revival and tribute to the aesthetics and qualities of traditional crafts. As industrialisation progressed, the reality of the division of labour and mass production, including poor factory conditions and the repetitive dehumanising tasks performed by unskilled labour, became evident. The Arts and Crafts Movement aimed to once again provide workers involved in producing products a connection to the creative process and to revive the connection between maker and user so that products would once again embody the functionality and simplicity of past times, enriching the lives of workers and reinstating the importance and position of art within society (Woodham, 1997). Whilst the Arts and Crafts Movement advocated that art should be an essential and enjoyable part of everyday life, the works of members of the movement became increasingly out of reach for everyday people as mass produced products became more affordable thanks to automation and economies of scale, whilst more rudimentary, hand-crafted goods were priced highly in order to support those making them in representation of the hours that went into their fabrication. This was also the experience of other similar movements, such as the Wiener Werkstatte in Austria (Bürdek, 2007). The arts and crafts therefore thrived in locations where patronage was sufficiently wealthy to afford the handcrafted products (Stankiewicz, 1992), but this had a limited impact on the mass production and consumption of consumer goods (Woodham, 1997).

Throughout this period, design decisions about products remained firmly located within the tradition of the 'decorative arts' and stylization. The Arts and Crafts Movement's criticisms of manufactured products regarding their lack of authenticity was reflective of the fact that design decision making had been separated from the act of production for the first time.

In the early 1900's the invention of electricity drastically revolutionised life. Firstly, the introduction of electric motors promoted decentralised manufacturing, freeing processes from the need to be close to steam power and enabling the creation of portable machinery and tools. Another benefit was the ability to have electric lighting illuminate factories and homes alike, freeing productivity and day-to-day life from the limitations of darkness and oil-based lamps in the evenings. The introduction of innovations such as electric lighting and refrigeration into the home then opened consumers up to new electrified household products, from vacuum cleaners to washing machines (Perez, 2009). The early twentieth century, often referred to as the 'Production Era' saw manufacturers capitalize on this, developing and producing new products in order to generate demand and sales. Consumption was transformed by creating completely new and growing markets through the stimulation and awakening of consumer needs that hadn't previously existed or been acknowledged. As such, industrialism became a new 'way of life' with the organised and coordinated arrangement of manufacturing overtaking rural production practices (Mendels, 1972). According to (Chandler & Hikino, 2004, p. 17), economies of scale, i.e.,

> *'[...] those that result when the increased size of a single operating unit producing or distributing a single product reduces the unit cost of production or distribution achieved through factory production.'*

were important in significantly reducing the cost of products, opening up consumption to almost every class of individual. This was also important for manufacturers as, due to the high capital outlay for machines, it was important to maintain productivity and throughput, and demand for the resulting products, in order to achieve effective capacity utilisation and spread the sunk capital costs across as many units as possible to keep unit prices down. The minimal efficient scale was therefore determined by both technological capacity and market demand dynamics, whereas, previously, output had been directly proportional to labour and raw materials (e.g. the putting out system where individuals were enlisted to manufacture from home) (Chandler & Hikino, 2004). In other words, the automation and mechanisation of production facilities meant that the capital outlay per unit output decreased as the number of products created increased. Further to this, where a company could produce a variety of products using the same components assembled differently, economies of scope would be achieved, further maximising the profitability of existing capital (Chandler & Hikino, 2004).

The first producer to develop innovative or greatly improved products or manufacturing processes would gain a considerable competitive advantage by being an early adopter, as, through the re-investment of initial high profits, it would be possible to gain even further sales or profit margins by enlisting the help of marketing or further research and development activities (Chandler & Hikino, 2004). Those who were later to adopt the new technologies would then face potential penalties if they invested in expensive capital machinery only to find they were producing for an already saturated market. The modern enterprise was created as a result, which included three key elements. The first was the exploitation of economies of scale or scope to increase production and reduce unit costs. To ensure that the products produced would be met with higher demand, the companies invested in national and international marketing and distribution networks. Finally, to coordinate both of these processes, it was necessary to invest in management to bring everything together. These new enterprises gained competitive advantage over other players and effectively became an oligopoly. As such, early adopters and front-runners would no longer compete on product price alone, but rather on strategy and functionality. The strategy would include identifying and moving into new markets, while the functionality may include things like improving the product offering, manufacturing processes, increasing the effectiveness of their marketing campaigns or improving their supply chain relationships. This emphasis on strategic advantage saw companies diversify, both into international markets and to include a wider variety of products (Chandler & Hikino, 2004).

The adoption of a capitalist model of industrialisation naturally had a significant impact on the design of consumer products. In his review of the role of marketing in the 'production era', (Fullerton, 1988) highlights the fact that production and supply alone were not sufficient to drive consumption to necessary levels. Instead, he notes that the 'production era' was typified by rapidly changing social and technological conditions. As urbanisation reduced peoples' self-sufficiency it created a new type of consumer. Competition was fierce. Overproduction was an issue, especially as manufacturing technology-encouraged production during good and bad times, so as not to lose out on interest and returns on capital investments. Companies faced dips in demand due to downturns in the business cycle (Fullerton, 1988). Economies of scale led to the production of increasingly standardised products, the most famous example being Henry Ford's Model T automobile. Dividing production processes into discreet tasks to be carried out by a combination of specialist mechanised machinery and unskilled labour, enabled Ford to achieve high volume, low unit cost production of the standardised vehicle. As such, the design involved consideration of the production processes and the creation of individual standardised parts, with high levels of accuracy to ensure compatibility between components (Doll & Vonderembse, 1991). However, whilst the adherence to a standard design afforded great economies of scale and enabled competitive prices to be offered to consumers, this could only continue for so long. As consumer tastes changed and Ford sort to enter new international markets, it became apparent that the one size fits all model and a reliance on price competitiveness was not be sufficient. As Ford attempted to expand the same process in Britain, he came across several obstacles. The first was the fact that the British labour force was less accepting of simplified, unskilled roles than that of the United States (McDermott, 2007).

Additionally, upon recognising that British consumers weren't interested in the same large cars as American consumers, Ford realised the need to adapt products to the specific needs of different markets (McDermott, 2007) As such, the importance of design as a driver of product success and alignment with consumer tastes and desires began to be recognised.

**6.5 The Emergence of 'Design'**

Various design schools and initiatives emerged in the early 1900's, focused on the intersection between industry and creativity. As argued by (Fullerton, 1988), design was increasingly viewed as a means of purposely stimulating consumption and demand for products. Design schools were therefore set up with the intention of training designers who would be able to create increasingly appealing products. Additionally, with the development of new manufacturing technologies, it became possible to devise new types of consumer products, further helping to create demand and achieve business success (Fullerton, 1988). The introduction of electricity within the home made possible a whole range of new product types that didn't exist before, providing more design freedom and the ability to create products that met consumers' expectations and desires (Woodham, 1997). As explained by (Sparke, 2013), design was therefore also involved in making new products more appealing, as familiar surface patterns and shapes were incorporated to alleviate some of the anxieties consumers felt towards the new and unfamiliar. These included concerns about the safety of new materials and technologies. The design of packaging and promotional assets also helped to market these products and paint modernity and the consumption of mass-produced goods in a positive, progressive light using imagery evocative of a pleasant and beautiful life. As explained by (Friel & Santagata, 2008), design at the beginning of the twentieth century could therefore be separated into four key categories: 'Traditional handicrafts', which had diminished substantially, leaving low quality products made by individual craftsmen, 'art works' created by artisans and artists drawing on material culture, 'serial utilitarian products', which were cheap, low quality and mass produced products resulting from early industrialisation, and 'functional industrial design objects' drawing on mechanical production techniques and fusing these with new conceptual, aesthetic and technological developments. Design was therefore caught up in friction between the interests of industry and manufacturers and those advocating for creativity and artistic expression in everyday consumer products. The former valued standardisation and design features that would be compatible with mass production. The latter argued that the value of products would suffer by being restricted by economic, political and industrial concerns (Woodham, 1997).

Important to the development of design, the Deutscher Werkbund was founded in Germany in 1907 with the aim of promoting a new industrial culture combining traditional craftmanship with manufacturing in an industrial context. As such, the idea was that quality products would become affordable and available to everyday people. It was suggested that adopting such a focus would help to establish and reinforce Germany's competitive advantage within the market, helping to differentiate their products from the competition. Whilst the ideas of craftmanship and the importance of quality were reminiscent of the views of the British Arts and Crafts Movement, the Werkbund differed in that it was not opposed to capitalist industrialisation. Instead, it sought to find a balance between factory production and quality, crafted goods (Giaccio, et al., 2013). They also advocated for improving worker satisfaction by increasing their importance and pride in the quality products produced and by bringing the craftsman and industrial workers closer together (Giaccio, et al., 2013). The Werkbund therefore set about promoting quality as a key foundational feature of products through educational activities and publications aimed at shop owners, consumers and manufacturers.

As it rapidly industrialised, Germany adopted this progressive design approach in the design of new products, for which existing examples and traditions did not exist, such as electrical products. In turn they established their version of German 'good taste', incorporating appreciation for quality, functionality and forward thinking, which would provide them with a competitive edge on the international market. Companies, such as AEG and Siemens were early examples. Behrens was appointed to AEG having trained as an architect. He worked on graphic design, but his role then extended to buildings, appliances and shops, creating a modern corporate identity for the company (Woodham, 1997). Behrens is considered one of the first true designers as he designed mass produced products for the general consumer, concentrating on economic manufacturing and developing products that were easy to operate and straightforward to service. As explained by (Styles, 1988), an example of manufacturing-oriented design, as demonstrated by Behrens whilst at AEG, was the creation of a kettle that utilised interchangeable, standardised components to enable the production of 30 different variations of the kettle. As such, this demonstrated the benefits of using standardised components to achieve economies of scope.

The advent of the First World War saw an increase in the efficiency of factory production, standardisation and a focus on manufacturing 'useful' items. Rationing, labour shortages and the use of many factories to produce armaments and war related supplies had a significant impact on industry, production and consumption (Woodham, 1997). After World War I, when imports from Germany were limited, Britain attempted to emulate the principles of the German Werkbund with the establishment of the English Design and Industries Association in 1915, working towards achieving a better fit between the goals of industry and design (Bürdek, 2007). Modernism followed in the 1920s and 1930s, however, rather than being one unifying style, aesthetically it differed between countries, but the styles were all more focused on the future, machines and products, which leant themselves to manufacture. As explained in (Dorrestijn & Verkbeek, 2013)'s review of design and social wellbeing, the key was the reverence for machines and for mass-produced products that could be produced for all and the relationship between design and society. The De Stijl Group in the Netherlands, which was formed in 1917 and included Doesburg, Mondrian & Rietveld, exemplified this when they put forward futuristic social and aesthetic utopias with reductionist, mechanical aesthetics. 'Less design is more design' can be traced back to this movement (Bürdek, 2007). These modernist movements, such as 'New Objectivity' or 'Functionalism', aimed to show the societal benefits from the production of products to improve the lives of the masses. Whilst (Dorrestijn & Verkbeek, 2013) point out that the novel processes employed to create futuristic shapes. An example of this is the cantilevered chair by Mart Stam, which is made from a single piece of metal tubing. Whilst the novel processes employed meant that the products produced could not be cheaply produced using the existing industrial technology, they did present a vision for a future social utopia (Dorrestijn & Verkbeek, 2013).

Following on from the Deutscher Werkbund, the Bauhaus art school was established in Germany in 1919 with the aim of uniting art and technology. Its activities focused increasingly on teaching and producing prototypes for products that could be manufactured industrially. As such, it signified the early stages of forming design into a profession, turning the craftsman into an industrial designer (Bürdek, 2007). Many of the designers in Western Europe were socialists and the Bauhaus became an important convening point for the discussion and sharing of new ideas (Dorrestijn & Verkbeek, 2013). 'Function' became a central theme for designers at the Bauhaus, alongside maintaining affordability and accessibility for the general population. Thus, there was a move away from artistic exploration and a move towards applied design, which in turn afforded the school many industrial commissions (Bürdek, 2007). There was also a social element to the design process at the Bauhaus, where it was believed that influencing the living environments surrounding everyday people, through the design of products, would help to anchor art within society and help people to adopt new ways of living (Bürdek, 2007). As explained by (Friel & Santagata, 2008), products designed at the Bauhaus tended to have certain qualities and features, including suitability for serial, industrial production, an embodied intellectual component influencing aesthetics, form and functionality, the intensification of shared symbolic meaning leading to a consumer culture and the breaking away from incremental or cumulative design innovation and tradition. Later, Meyer was appointed head and focused more on art and social subjects, e.g. sculpture, psychology, photography. Gained a stronger focus on design serving people. The Bauhaus disintegrated in the thirties as a result of increasing pressures from the looming WWII. (Bürdek, 2007) explains that the Bauhaus had a limited direct and immediate impact on the design of mass-produced products of the time, as the works were largely only purchased by a select, intellectual customer. However, the Bauhaus was most influential through the emigration of many of its students as a result of WWII, which helped to spread its principles and concepts internationally, influencing design for many years following its dissolution.

These developments began to give shape to design as a profession, as necessitated by industrialization and factory production. Rather than taking aesthetic direction from the decorative arts, designers began to anticipate the consequences of technological development and innovation, arriving at original design directions.

**6.6 Design and Consumerism**

From the 1930's onwards, the 'Production Era' was replaced by the 'Sales Era', during which a more aggressive and targeted selling approach was adopted as a result of the economic pressures of the Great Depression (Styles, 1988). Social marketing was coined by (Kotler & Zaltman, 1971), which can be defined as,

> *'[...] a process that leads towards influencing or changing public behaviour through the systematic use of commercial marketing and communication techniques, with the intent of delivering a positive benefit to society.'* (Muratovski, 2015, p. 179).

However, this was not a new concept, but one based on ideas that were present in the 50's and even as far back as the original works of Edward Bernays. Generally regarded as the pioneer of public relations, Bernays laid the foundations for mass consumerism from the 1930's (Muratovski, 2015). Up until 1920's, most products were purchased on the basis of functional needs, fashionability or material quality. However, businesses worried that this would come to an end when people believed they had accumulated enough products; a belief that seemed to come to fruition in the economic depression that followed the end of the First World War

(Muratovski, 2015). Paul Mazer from the Lehman Brothers responded to this threat by recommending America transition away, from a need, to a ‘desire’ based culture. He suggested that consumers should be trained to seek the accumulation of new products in advance of the point at which the old products fail (Muratovski, 2015). In a bid to win over the public following WWI in America, Bernays drew on psychology, sociology and design with significant financial and logistical support from corporations to transform American society into a consumerist one (Muratovski, 2015). This led to the creation of ‘public relations’, the ‘advertising industry’ and ‘industrial design’ to promote the accumulation of goods by society (Muratovski, 2015). Strategies employed included linking social issues with consumerism, celebrity endorsement and product placement within popular culture and media, such as magazines and films (Muratovski, 2015). By doing so, this helped to create a massive campaign to promote the ‘American way of life’, selling people on the idea that they needed newer and better products. In contrast to the early days of industrialisation when advertising merely highlighted the product, its features and functionality, the advent of social marketing saw products transcend their physical form, being purchased instead on their symbolic meanings and the fantasies they projected (Muratovski, 2015). Additionally, consumerism was promoted as, and considered by many, to be a patriotic duty important for the survival and prosperity of the economy, which is something that continues today (Muratovski, 2015). As a result of marketing and advertising, design became responsible for bestowing meaning upon products, beyond their form and function. As a result, the role of the designer changed. Not only did it involve designing products that were aesthetically pleasing and functional, but also appealing on a deeper level, tapping into consumers’ desires.

The 1930’s became a golden era for industrial design as designers were tasked with shaping and forming products that people would want to purchase. As explained by (McCracken, 1986), it was through design that a product could be imbued with cultural meaning, which would then be recognised by consumers as having certain symbolic properties as projected by its physical form. Advertising agencies saw themselves as ‘apostles of modernity’, with the goal of pushing consumerism into the conscience of the masses, similar to a religion (Muratovski, 2015). This created the idea that fulfilling needs, whether basic, like hunger and safety, or more ephemeral, such as love and self-actualisation, could be obtained through the purchase of a product. Whatever the need or desire, everything could be acquired for a price religion (Muratovski, 2015). As such, this gave rise to the belief that an individual’s success could be measured by their ability to accumulate material goods. However, this would not be a simple, permanent exchange as, despite selling consumers on the idea that material consumption equated to happiness and fulfilment by association, the accumulation of material objects would only provide short-term happiness, leading to a continual cycle of consumption, referred to as 'retail therapy' (Muratovski, 2015). Further shortening the happiness generated by the accumulation of products was the ability for the cultural meaning associated with a product to change rapidly. An object that once represented wealth and social standing would rapidly become a symbol for being behind the curve, despite the product remaining the same, as fashions changed (McCracken, 1986). Constant, deliberate and rapid change in cultural meanings associated with products was achieved by employing high-esteemed members of society with considerable fame, beauty or wealth, or fringe sub-cultures (e.g. punk culture), to re-invent the values projected by products and which products represent the qualities desired by consumers (McCracken, 1986). These changing values and qualities were then incorporated into products by industrial designers and promoted by fashion journalists and social observers. As explained by (McCracken, 1986) a positive feedback loop was created as the journalists would inform designers of the cultural meanings desired by consumers, designers would then create a product with those meanings embedded and projected by the object's form. The link between the product and these cultural meanings would then be reconfirmed through advertising. Whilst there had long been changes in fashion, the speed and extent of which the embedded cultural meaning of products would change in the western industrial societies was and still is an ethnographic anomaly (McCracken, 1986). With global expansion, American companies then brought these ideas and strategies to other countries (Muratovski, 2015). The main changes to industrial design brought about by social marketing, was that designers were tasked with designing not only the physical properties of a product, but also the symbolic meanings they embodied.

### 6.7 The Changing Value of Products

In addition to advances in engineering technologies, material innovations have also had a significant impact on manufacturing and, in turn, product design, consumption patterns and the perceived value of products. One of the most significant developments in materials was the invention of plastics. This was not a sudden development, but rather one that began in the late 1800s and continued throughout the 20th century (Freinkel, 2011).

John Wesley Hyatt is credited as being the inventor of the first commercial plastic material, celluloid. Its development in 1851 was in response to a competition, which was launched to find a replacement for ivory in order to continue to manufacture billiard balls. Manufacturers of billiard balls, as well as other consumer products and home furnishing made from unevenly distributed and increasingly scarce natural resources were facing an impending crisis. Stocks were being consumed faster than they could be replaced and there was concern that elephant populations would dwindle past the point of return. Celluloid, a mouldable thermoset plastic derived from cellulose and other easily obtained chemicals offered a cheaper and far more accessible means of producing everyday products. In turn this resulted in the democratization of objects previously made from rare and difficult to source materials. Additionally, moulding proved intriguing for manufacturers who had previously relied on subtractive fabrication techniques (Freinkel, 2011).

However, the production of celluloid was problematic due to its volatility and propensity to ignite and result in explosions, making manufacture dangerous. There were also problems with shrinkage as the solvent evaporated. Having witnessed the potential of a plastic material but wishing to avoid the problems associated with celluloid production, many set to work developing new and improved alternatives (Freinkel, 2011). One of those developed was Bakelite, regarded as resembling shellac, a substance made from the secretions of the shellac beetle, it was the first true synthetic, derived from coal tar. Bakelite proved to be a good electrical insulator and became popular in the 1930s. Products made from Bakelite achieved a distinctly new, smooth and 'plastic' aesthetic due to its inherent properties and new design possibilities available as a result of injection moulding and curing process (Freinkel, 2011). These early plastics played an important role in World War II and were used in an array of applications, including aircraft and vehicle interiors, helmet liners and even weaponry. The demands of the war resulted in considerable research and development of both new forms of plastics as well as new production and moulding processes. Once the war came to an end, factories that had been enlisted to produce plastics used in the military switched to consumer products and the number of plastic consumer goods proliferated (Freinkel, 2011).

With the advent of thermoplastics, such as polystyrene, nylon and polyethylene, as well as new advances in injection moulding, production processes became significantly faster, cheaper and able to produce far greater quantities than ever before (Freinkel, 2011). With the proliferation and availability of household goods and electrical appliances following the war, plastic found many applications and became a widely consumed commodity. This had the effect of democratizing consumption, ushering in a new era, or 'material utopia', characterised by social mobility and the emergence of consumer culture. However, the widespread availability of plastics and their increasingly competitive prices also had the negative impact of affecting consumers' perception that plastic was a cheap, low-value material. This is something that the industry has since attempted to counteract, however, consumer perceptions today still reflect these values with our disposable culture (Freinkel, 2011). However, as plastics technology improved, the focus shifted to not only finding replacements for rare or difficult to obtain natural materials, but to developing plastics that were significantly superior to anything that existed within nature. As a result, technical polymers were invented, including non-stick Teflon surfaces and ultra-strong heat-resistant Kevlar fibres.

Another way in which plastics impacted on consumption was by changing access to cultural media. As (Freinkel, 2011) explains, celluloid was used to produce photographic film in the late 1800s. This created a new mode of consumption in the form of entertainment, such as early cinema and photography. This trend continued and by the 1980's the technical capabilities of more advanced forms of plastic gave rise to new product possibilities and new means of consumption in the form of multimedia storage, sharing, viewing and listening, including cassette tapes, film and discs. As such, consumption became less about the physical product and more about creating new experiences for the consumer (Meikle, 1997).

### 6.8 The Formalization of the Design Profession

The Second World War saw the rapid advancement of mass manufacturing technology as national production of armaments and standardised military supplies accelerated industrialisation. During this period, consumption was limited by the rationing of resources, with clothing and other products becoming increasingly utilitarian (McDermott, 2007). As a result, post war initiatives in France, Britain and across Western Europe aimed to promote the design of products with a simple, practical aesthetic and a relevance to everyday life (Woodham, 1997). It was suggested by Keynes that state-level intervention by liberally minded intellectuals could help to foster economic recovery. The US followed this line of thinking, creating employment for American artists, designers and architects who were hit by the depression and WWII. This application of modernist ideals therefore formed part of the post-war regeneration, with industrial designers gaining a prominent role in the rebuilding of the economy (McDermott, 2007).

In Germany, the Ulm School of Design carried on many of the traditions of the Bauhaus, but with less of a focus on art and free creativity. The focus instead was on educating students in design practices that would help to set them up for careers through which they would need to meet industrial design briefs. As such, teachings were interdisciplinary, drawing on a wide variety of subjects, including ergonomics, mathematical techniques, economics, physics, politics, psychology, semiotics, sociology and science. The aim was to design products that would be both mass-produced and used regularly by everyday people. The process of designing that was taught was stripped back, focusing on individual, physical objects, rather than systems or the bigger picture, and attention was almost solely reserved for functionality and not decoration, craft or art. Industrial projects were increasingly taken on, with the aim of realising successful manufacturing concepts that would be able to be met by the technologies available at the time (Bürdek, 2007). Unlike earlier modernist designs, the useful and highly functional products created using the Ulm School approach could be successfully manufactured by mass production means, becoming available to the masses. As argued by (Dorrestijn & Verkbeek, 2013), the key differences compared to early modernism was the growing consideration of real consumer needs, as opposed to obvious universal market assumptions, with scientific research into the users of products becoming increasingly important. As such, the Ulm School was instrumental in starting design methodology, analysis and synthesis, and the justification of design decisions in the face of multiple options.

This new direction manifested itself in the 1960's as 'design methods', launched at The Conference on Design Methods in London in 1962. The aim was to establish a rigorous process for ensuring that design decisions were based on objective and rational evaluation. Technologist, Buckminster Fuller declared a design science revolution in which science and technology, rather than politics and economics, could be drawn upon to promote design for social and environmental wellbeing (Cross, 2001). This was followed by Herbert A. Simon's seminal work 'The Sciences of the Artificial' which suggested that design should be reducible to an optimised, universal and logical framework that could be easily taught (Bayazit, 2004). As a result, the study of design moved into academia as a formal, systematised and teachable course that became common throughout the US and Europe during the 1960's (Cross, 2001). However, these design methods came under criticism as they were considered too positivist and rigid, lacking consideration of the softer elements of design. It was argued that the machine focus meant that creativity and the human aspect of products were ignored and that the emotional and meaning potential of objects were not fully realised (McDermott, 2007). As explained by (Bayazit, 2004), the inability for these initial design methods to accommodate complex real-world challenges resulted in narrowly defined product designs, which were rarely successful. Considering this, some came to think of design methods as an academic sub-culture.

In contrast to the functional, austere and long-lasting goals of modernist design, pop culture of the 1960's brought about a change of thought, incorporating emotions, desires and the needs of the consumer into the design process. In addition to this, the higher living standards of the 1960's led to an increase in demand for consumer goods, particularly amongst the younger generations who hadn't been subject to war rations (McDermott, 2007). Cheaper and increasingly transient products emerged, particularly across furniture and clothing; their visual appeal often enhanced by surface pattern designs and the growing phenomenon of 'Pop Culture', whereby designers drew upon cultural references, from sports and entertainment to publishing and advertising to inform these surface designs. Ultimately it was recognised that design values weren't necessarily absolute or indefinite (McDermott, 2007). Design had therefore become rooted in consumerism.

By the 1970's there was a change in mood, with a move away from the ephemeral, disposable and novel aspects of pop culture and a growing awareness of environmental issues. This gave way to post-modernist design. As explained by (McDermott, 2007, p. 181), the term 'post-modernism' came to refer to both *'... major cultural developments in the late 20th century as well as a design style'*. However, as a relatively imprecise term, post modernism has become a reference to any design that is novel or new.

This new era of consumption saw the development of a new generation of design methods. The main difference being the concept of user involvement in which the identification of consumer needs and the development of design solutions involved user participation and a new, democratic approach in line with the existing political atmosphere (Bayazit, 2004). Rather than being prescriptive, as in the case of the original design methods, second generation methods aimed to provide a process through which designers could focus on the user to uncover key objectives, encouraging collaboration with social scientists and anthropologists (Bayazit, 2004). The focus of design shifted towards the individual rather than on society as a collective whole, which was embedded in the concept of 'lifestyle' and based on the material surroundings of an individual being an extension of self and a reflection of personal identity. As such, design became more of an adaptive problem solving and decision-making activity as opposed to something that could be reduced to a scientific formula. The success of a design was therefore determined by the designer's ability to comprehend and understand consumers and to translate their needs into a product design (Bayazit, 2004). The environmental impacts of design and production also began to be recognized in the 1970's and 1980's, challenging prevailing notions about fashion and disposability. A more detailed discussion of these developments is provided in Chapter 3.

An example of postmodernist design was the Italian 'Memphis' movement in the 1980's, which saw mixed materials, from plastics to expensive wood finishes simultaneously integrated into designs. As such, designers were afforded a new freedom, allowing them to break rules exemplified by features, such as non-identical table legs and non-horizontal wall shelves, through which they challenged existing preconceptions (McDermott, 2007). The concept of 'semiotics' and theories about society and culture gave design a broader role, going from problem solving and practical decision making to forming part of a larger world of intellectual ideas (McDermott, 2007). Throughout the 1980's and 1990's governmental investment in design research increased and design became established as an academic subject (Bayazit, 2004). The development of professional university training courses in design placed new demands on designers, with the restructuring of knowledge and new philosophies and theories of design. The relationship between design practice and research has since become an increasingly important focus amongst academic and professional communities (Bayazit, 2004).

The relationship between design and manufacturing also changed considerably in the 1990's. Previously, these two activities had tended to be carried out in separate teams, with designers passing their designs to engineers and manufacturers to materialise effectively and efficiently their visions (Mansour & Hague, 2003). However, in recognition that approximately 70% of the costs of a product are determined during the design stage, new concepts began to emerge. Design for Manufacturing (DfM) from the initial stages of product development (Mansour & Hague, 2003). As explained by (Mansour & Hague, 2003), DfM encouraged designers to employ strategies, including making products that comprise standardised, modular and interchangeable components with compatible interfaces, making parts multifunctional and multi-use and designing products that would be easy and cost-effective to produce. As such, design options were limited by the most readily available or most profitable manufacturing processes to hand, with designers encouraged to use standardised parts.

The optimisation of product design for manufacturing efficiency and cost effectiveness was further influenced by the development of telecommunications, information technologies (IT) and, later, internet connectivity. As explored by (Kraft & Truex, 1994), cross-border communication and information sharing enabled new post-modern organisational forms to emerge, in which different business activities could be carried out in disparate geographic locations. This afforded companies the ability to seek out services, processes and materials from countries in which labour and resource costs were cheaper. Rather than being defined by local markets and materials, products resulting from such postmodern organisations instead reflected the sharing of knowledge and innovation (Kraft & Truex, 1994). This enabled companies to be more responsive to change as it became possible to continually evolve by bundling and unbundling various subcontracted services, materials and workforces. The success of a product was therefore less limited by in-house manufacturing capabilities and production limitations, as had been the case in the past, and had more to do with intellectual property and the conceptual ideas promoted by the company (Kraft & Truex, 1994). Describing the 'virtual organisation', (Kraft & Truex, 1994, p. 116) explain,

> *'It learns and accepts change as the norm. It cooperates as well as competes and creates as well as responds to markets'.*

However, despite the amorphous nature of these modern organisations, consumers still perceived them as a unified whole, achieved through branding and marketing. Towards the end of the twentieth century there was a move towards integrated quality, serving as a key strategic element of businesses with quality controls embedded at each step of the process, with trends such as 'Total Quality Management' (TQM) (Giaccio, et al., 2013).

**6.9 The Globalization of Production and Consumption**

From the turn of the millennium, globalisation became an increasingly prominent force, with many Western companies outsourcing their production to countries that began to establish themselves as manufacturing powerhouses, such as China (Sparke, 2013). However, globalisation was not a goal in itself, but the manifestation of the conditions, incentives and opportunities experienced by companies at the time. As explained by (Rehsteiner, 2003), the underlying rule of all commercial manufacturers (i.e. excluding not-for-profit and state-sponsored operations) is to generate profit. Crudely speaking, this can be achieved in two ways, by increasing the price at which products are sold, or by reducing the cost of their production. Globalisation therefore presented an opportunity to minimise production costs by sourcing raw materials, labour and supporting services from countries with lower prices. As explained by (Sparke, 2013), companies' ability to take advantage of this opportunity was facilitated by two key earlier developments. Firstly, the advancement of information and communication technologies enabled formulation of 'virtual' organisations, made up of dispersed sub-contracted operations that function together effectively and simultaneously as a whole.

Secondly, the standardisation of components as part of design for manufacturing efforts meant that manufacturers could benefit from economies of scale, producing many of the same components for many international companies. As globalisation progressed, it had the impact of homogenising products, technologies, industries and patterns of consumption through the increased mobility of objects and people globally, as well as the international sharing of information, innovation and media (Sparke, 2013). This enabled the opening up and expansion of new markets and a move away from class-based aspirational consumption to the regrouping of consumers around other cultural identity indicators (Sparke, 2013).

The advent of computing and its application in manufacturing afforded new benefits associated with growing integration within companies towards the end of the twentieth century, with advancements continuing into the new millennium. Computing had an impact on every stage of the product lifecycle. Within design, sketches and plans for products were created using 'computer aided design' (CAD) systems, which could be used to inform manufacturing processes. Computer aided process planning (CAPP) then configured the necessary, sequenced steps and operations for manufacturing, optimising for efficiency, cost, quality and production rate. Computer aided manufacturing (CAM), incorporating numerically controlled machines, material management and process coordination programs improved coordination and efficiency, whilst automated storage and retrieval (ASR) systems helped to manage the inventory of raw materials, components and finished products (Kusiak, 2000). These new technologies have increased competitiveness between organisations, with an increase in the number and variety of products being introduced to the market. This has also resulted in rapid obsolescence of products, as products with higher quality and improved performance take over. This has seen a shortening of the lifecycle of products, particularly those with a technological element (Kusiak, 2000). Writing in 1997, (Meikle, 1997) explained that the freeing of possibilities that plastic had achieved for physical objects in the 20th century was what the development of computing and digital was beginning to do for the consumer experience towards the turn of the millennium with the advent of digital photography, computer animation and interactive displays.

Today, individuals categorised as 'Generation Z' (digital natives) are using the internet and social media to express themselves through consumption and association with certain products. However, unlike previous generations that would have tended to be influenced by a select group of popular culture references (celebrities, tv-shows etc), trends are much less centralised, with peer-to-peer networks, such as social media. There is more individuality with smaller sub groups and sub cultures (Saravanan & Nithyaprakash, 2015).

In a commercial sense, design has been described as following a process that,

> *'[...] starts with the brief, which combines research from marketing about consumer need, specifications for manufacturing and finally sales planning and profit potential. Ideas for the new product then follow initially as drawings or simple models- a stage called concept design - after which the process of concept development will test the product. At the subsequent design development stage the designer works with a team including experts in sales and marketing. This team produces the final model for manufacture.'* (McDermott, 2007, p. 186)

Throughout the 21st century, design culture has become more fluid and ephemeral and has formed an integrated component of wider business activities, alongside marketing, advertising and customer service.

To summarise, this chapter has outlined the key technological, social and economic developments that have occurred since the first industrial revolution, which have given rise to design and shaped it into the activity that it is today. As such, it has identified several key points. Firstly, whilst humans have designed products throughout history, design, in its current form, situated within an industrial context, is a relatively recent development. Secondly, design and industry are not separate entities, but closely interrelated. Design has become what it is today as a result of several defining industrial transformations, from the centralization of production, product standardization and the economies of scale principle, to advertising, marketing the emergence of consumerism. This goes some way towards explaining the difficulty in implementing DfCE against the existing industrial paradigm, which has given rise to design that supports a linear economic model. It also suggests that further industrial transformation, such as in the case of Industry 4.0, is likely to lead to changes to design.

## Chapter 7. Existing Barriers to Design for a Circular Economy (DfCE) Implementation

This chapter explores the barriers currently limiting the effective implementation of design for a circular economy (DfCE) practices with a focus on consumer products. As highlighted in Chapter 3, design forms an important contributing factor in realising a circular economy (CE) and achieving a more sustainable pattern of production and consumption. This is due to the fact that the design of a product, along with any associated business models and supporting services, determines the potential for its embodied energy and material value to be continually recirculated within the economy and, ultimately, within wider biogeochemical cycles. However, despite a long-established link between design and sustainability and a growing awareness of the relationship between design and the CE in particular (De los Rios & Charnley, 2017) (den Hollander, et al., 2017) (Bocken, et al., 2016) (Andrews, 2015), the transition towards a sustainable, CE remains fragmented and at an early stage of development (Korhonen, et al., 2018) (Ritzén & Sandström, 2017) (Ghisellini, et al., 2015), suggesting DfCE practices are not yet widespread.

Following an initial review of the literature (Chapter 3) it was determined that a comprehensive analysis of the barriers limiting DfCE implementation had not yet been conducted. In order to fill this gap in knowledge, an integrative literature review was employed in combination with a series of semi-structured qualitative interviews. As explained in Chapter 5.4.2, an integrative literature review was selected as a means of overcoming the lack of existing material dedicated to the specific topic of focus. This was conducted by searching for mention of DfCE barriers in articles generally concerned with design and the CE. The scope was also broadened to take into consideration barriers identified in articles on related concepts (e.g. sustainable design, eco-design, cradle-to-cradle design) where those barriers were likely to be shared in the case of DfCE. The series of semi-structured qualitative interviews with six practicing designers and three representatives from entrepreneurial CE companies (Table 7.1) supported the integrative literature review by providing detailed contextual accounts of how and why design decisions are made, helping to better understand the barriers to DfCE in practice (Appendix B). The results are presented thematically, divided into four main categories ranging from the micro to macro level; task barriers, designer barriers, organisational barriers and external barriers.

| Interview Participants | | |
|---|---|---|
| **Designers** | DESIGNER 1 (Anonymised) | In-house fashion designer |
| | DESIGNER 2 (Anonymised) | Design consultancy furniture designer / Freelance furniture designer / Entrepreneur jewellery designer |
| | DESIGNER 3 (Anonymised) | Design consultancy product designer |
| | DESIGNER 4 (Anonymised) | Freelance product designer / Design educator |
| | DESIGNER 5 (Anonymised) | In-house footwear designer |
| | DESIGNER 6 (Anonymised) | Design consultancy product designer |
| **Entrepreneurial CE Companies** | FAIRPHONE | A technology start-up specializing in ethical and modular smartphone devices optimized for repair and upgrade. |
| | MUD JEANS | A fashion brand specializing in the repair, resale and leasing of denim garments. |
| | THE LIBRARY OF THINGS | A social enterprise specializing in using community spaces to lease products in line with the sharing economy |

**Table 7.1** List of interview participants.

### 7.1 Task Barriers

Whilst many of the barriers to DfCE implementation share commonalities with several of the preceding and alternative approaches to designing for a more sustainable model of production and consumption, there exist several challenges specific to the DfCE task itself. These can be summarised as the need for innovation, investment and risk taking; the extension and expansion of the scope of design; the increased complexity of design and the limitations of available tools and methods. Each of these are discussed in more detail below.

#### 7.1.1 Innovation, Investment and Risk Taking

The first barrier associated with DfCE is the degree of disruptive innovation and up-front investment its implementation demands in order to bring successful, new circular products to fruition. This is in contrast to the incremental, eco-efficiency approaches to sustainable design commonly employed within organisations. As these involve relatively minor adjustments to existing products and manufacturing processes in an attempt to gradually reduce negative environmental externalities, they benefit from minimal disruption and the continuation of business-as-usual (Menoni & Morgavi, 2014). DfCE on the other hand, requires designers to fundamentally rethink the way in which value is delivered to consumers in order to facilitate the closing, slowing and narrowing of resource loops (Bocken, et al., 2016).

The need for product innovation in DfCE was demonstrated in the interviews conducted with representatives from entrepreneurial CE companies. These highlighted the need to foreground CE at the earliest point in the design process, orienting the design of products around CE principles by embedding elements such as durability, disassembly, repairability, maintainability, upgradability and recyclability. The jeans of MUD JEANS, for example, were designed around the principle of closing loops by adhering to the use of renewable and recyclable mono-materials and avoiding the addition of unnecessary embellishments. The adoption of a classic design aesthetic also facilitated the extension of loops by encouraging long-term wear irrespective of changing fashion trends and enabling take-back and resale initiative. In the case of FAIRPHONE, the extension of loops was prioritised in the design of the FAIRPHONE 2 smartphone device, which was optimised for ease of repair and maintenance, whilst other criteria, such as aesthetics, were addressed subsequently.

> *"Normally you design smartphones the other way around, so you design the outside and then you try to cram in all of the insides [...] we wanted to make sure that it was repairable so we made sure there was space to build-in all of the repairability and then we tried to wrap it as beautifully as possible and as aesthetically as possible."* (FAIRPHONE)

Although THE LIBRARY OF THINGS was not directly involved in the design of products, instead providing a pay-per-use product rental service, they highlighted a number of product innovations necessary to facilitate the extension of loops through product-service-systems. These included the design of products optimised for ease of cleaning, compact storage, convenient transport and intuitive use by unfamiliar users. Through the formation of partnerships, THE LIBRARY OF THINGS was involved in feeding this information back to Original Equipment Manufacturers (OEMs), for consideration in the design process. Practical examples such as these therefore serve to highlight the need for innovation at a product level when implementing DfCE.

However, whilst essential, product innovation also presents additional challenges for organisations. As explained by (Baxter, 1995), new product development (NPD) activities require considerable outlay in terms of both time and resources. These are necessary to facilitate the key stages of the process, which include research, ideation, development, prototyping and testing. Additionally, whilst NPD is generally carried out with the intention of bringing about additional revenue, there is no guarantee of success (Baxter, 1995). As such, the design and development of innovative products for a circular economy demands both additional up-front investment and the acceptance of an added element of risk, both of which may represent barriers to DfCE implementation (Ritzén & Sandström, 2017).

It should also be noted that the innovation requirement in DfCE, is not limited to products, as this alone is insufficient to realise the transition to a CE. Whilst the design and development of new circular products may make a CE *possible*, it is also necessary to ensure such measures are *profitable*. This is especially the case as many of the features of circular products, such as optimisation for disassembly and product life extension, don't make sense in terms of the linear economic principles that underpin traditional business models (Bocken, et al., 2016). As such, DfCE also necessitates business model innovation in order to capture the potential value of circular products (Lewandowski, 2016).

Examples of this were evidenced in the interviews conducted with entrepreneurial CE companies. For example, MUD JEANS described their take-back and re-sale initiative, 'Lease-A-Jeans', in which consumers pay to rent a pair of jeans for a number of months, after which they have the option to keep or return them in exchange for a discount on a new pair. This enabled MUD JEANS to resell the returned garments potentially many times before they were recycled. Further to this, FAIRPHONE highlighted their recent research report 'Circular Phones' through which the company had begun exploring the benefits of business models whereby ownership of physical assets is retained by the manufacturer. In the case of THE LIBRARY OF THINGS, their pay-per-use product rental service served as an example of an innovative CE business model, which had already gained interest from the OEMs of the products they were renting to consumers. As these examples illustrate, CE business model innovation is not only a necessary component of DfCE, but also one that has the potential to present new economic opportunities, providing incentives for organisations. These include previously unexplored revenue streams, increased customer loyalty, added customer insights, synergistic partnerships along the value-chain and the various benefits of internal resource management (Lewandowski, 2016).

Nevertheless, as in the case of product innovation, business model innovation also presents some challenges. As Bocken, et al. (2016) note, the more radical a product innovation, the more disruptive the change required of the associated business model. Such disruption can call for the fundamental reorganisation of a company's structure and changes to core business operations (Cumming, 2018) (Ritzén & Sandström, 2017) (Preston, 2012). As such, the validation of radically innovative circular business models incurs a greater level of risk than that of proven, linear business models (Ritzén & Sandström, 2017) (Lewandowski, 2016). This risk is compounded by the up-front investment required to transform core business operations and to put in place necessary supporting mechanisms, such as new manufacturing equipment, restructured supply chains and reverse logistics capabilities (Preston, 2012). As explained by DESIGNER 6,

> *"[…] it takes a lot for a designer to want to say – 'Right, we're going to have to stand up to the current paradigm and create something new' – and perhaps be bashing their head against a wall for a long time trying to get something to stick and it's able to cross over and there's the right kind of media backing and the right sort of support."* (DESIGNER 6)

The added disruption, risk and investment requirements associated with the innovation of circular business models may therefore represent a further barrier to DfCE implementation.

Beyond the organisation itself, DfCE may also necessitate innovation on behalf of stakeholders (Ritzén & Sandström, 2017). For example, in the case of MUD JEANS, the expansion of the Lease-A-Jeans initiative from their website to concession stores was limited by the organisation and technological infrastructure of retailers. Other examples of external innovation required to successfully implement DfCE, include new material development and the creation of new technologies and processes, as well as social innovation and the application of innovative policy instruments. Each of these external aspects are discussed in more detail in Chapter 7.4.

It therefore becomes evident that DfCE requires a considerable degree of innovation, not only in terms of the products designed, but also the business models and external developments necessary to capture their value and ensure their feasibility and success. Associated with this level of innovation is an increased degree of risk and up-front investment. Each of these factors represent additional considerations above and beyond what would be required for design within a traditional, linear economy context. As such, they may be considered potential barriers to DfCE implementation.

### 7.1.2 The Extension and Expansion of the Scope of Design

Another potential task-based barrier associated with DfCE is the extension and expansion of the scope of the design task. DfCE innovation at a product level requires additional, CE design criteria to be considered. Designers must not only consider the narrowing of resource loops, as in the case of eco-efficiency approaches, but also their closure and extension (Bocken, et al., 2016). As such, DfCE requires design solutions that simultaneously address energy and material efficiency, disassembly and recyclability, whilst also optimising products for multiple use cycles and life extension strategies (Mestre & Cooper, 2017). Such strategies are diverse and may require consideration of both the emotional durability of products, encouraging consumers to engage with and use products for longer, and products' functional durability, facilitating maintenance, repair, upgrade, reconditioning, remanufacturing, resale and redistribution (Mestre & Cooper, 2017) (den Hollander, et al., 2017). In doing so, DfCE represents an *extension* of the scope of the design task, adding numerous CE design criteria to those already considered as part of the traditional product design process, such as aesthetics, ergonomics, manufacturability and cost.

Additionally, CE product solutions must be adequately supported and facilitated in order to realise their full potential. Beyond determining the physical embodiment of products, DfCE therefore also involves the design and development of complementary processes, business models and services, as well as potential partnerships with third party providers (De los Rios & Charnley, 2017) (den Hollander, et al., 2017). As explained by (Lacy & Rutqvist, 2015, p. 199), when a company transitions to a circular economy model,

> *'[...] it's often expanding its scope upstream or downstream in the value chain from where it currently sits.'*

This in turn can require the redesign of core business activities, presenting implications for organisational strategy, structure and management (Ritzén & Sandström, 2017). An illustrative example of this was provided in the interview with DESIGNER 3, who described a situation whereby an organisation was considering redesigning a product to provide ease of access for repair. It was highlighted that such an initiative would be of little consequence if the organisation did not have the necessary services in place to facilitate take back and repair activities. Decisions to redesign products according to DfCE principles on a physical, product level can therefore require more fundamental organisational changes in order to facilitate them and to capture their value.

> *"So the redesign has to be a conscious decision and has to be a decision taken by the person paying for the whole thing. It's more fundamental."* (DESIGNER 3)

As such, DfCE also represents an expansion of the scope of the design task into new areas, addressing not only the physical embodiment of products, but also the design of supporting measures, such as services, which span a variety of business areas, including marketing, logistics, after sales services and third party partnerships. This expansion may be accommodated by a devolution of design decisions to other stakeholders in the value chain or the diversification and augmentation of the responsibilities of the designer (De los Rios & Charnley, 2017). Either option represents a transformation of the role of design within an organisation.

It is therefore evident that DfCE represents an extension and expansion of the scope of the design task, requiring both the consideration of additional CE criteria and the adoption of a wider, systems perspective. This in turn makes DfCE a greater undertaking, necessitating additional time and resources, as well as the potential training and upskilling of designers or other stakeholders within the value chain. This may therefore be considered a further potential barrier to DfCE implementation.

### 7.1.3 The Increased Complexity of Design

A further barrier to DfCE implementation is the increased complexity of the design task. Design is already a complex, iterative process involving the assimilation of various design objectives and the simultaneous navigation of constraints (Bloch, 1995). These include the need to meet aesthetic and performance objectives, match users' ergonomic requirements, achieve a feasible and cost effective means of production and comply with any necessary legal and regulatory requirements (Bloch, 1995). A successful design is therefore one that integrates solutions to a variety of issues simultaneously (Lawson, 2006). As a result, designers must grapple with multiple, interrelated and at times conflicting requirements (Byggeth & Hochschorner, 2006). The introduction of added environmental considerations into the design process therefore requires the implications of each to be balanced against all other design criteria (Knight & Jenkins, 2009). As a result, the design process becomes exponentially more complicated. As DfCE introduces many additional CE criteria as a result of the extension and expansion of the scope of the design task (7.1.2) it increases the complexity, with each CE criteria needing to be balanced against each other and all other design criteria (Andrews, 2015).

The evaluation of CE criteria can also prove to be challenging. Further to the need to source additional information in order to support design decision making, the metrics by which CE criteria are measured can be difficult to establish. This is particularly the case for qualitative CE metrics, such as the subjective aspect of emotional durability (den Hollander, et al., 2017). This ambiguity in terms of metrics can also make the comparative analysis of CE criteria and the justification of design decisions a somewhat ill-defined process (den Hollander, et al., 2017). DfCE is then further complicated by the fact that bringing the perspectives of different stakeholders from the value chain into the design process may introduce multiple, differing evaluations of individual criteria (Byggeth & Hochschorner, 2006). For example, material innovations that improve product durability, seen as beneficial by the core organisation, may represent problems for third parties tasked with disassembling and recycling end of life products. Further, the evaluation of certain criteria can also vary according to timescale, which is important to consider when optimising products for multiple lifecycles. For example, strategies extending product life may represent the most circular solution available at one point in time, but as technological developments afford newer solutions that make more efficient use of resources in the future, this may no longer be the case further down the line (den Hollander, et al., 2017). Complications such as these all add to the complexity of the design task when implementing DfCE.

#### 7.1.4 Design Trade-offs

Another design task challenge associated DfCE is the fact that optimised solutions satisfying all criteria may not always be realised or, in some cases, may not even be possible. This can be due to several reasons, including limitations associated with the designer (Chapter 7.2), potential organisational constraints (Chapter 7.3) and even a lack of external enabling factors (Chapter 7.4). When this occurs, designers must compromise and make a sacrifice in one area in order to accommodate another, which inevitably results in trade-offs. Tensions can arise between a variety of criteria, including between individual CE strategies (Mestre & Cooper, 2017). How these are navigated in the design process depends on the prioritisation of criteria and which elements are considered essential to the success of the product. Situations such as these were reflected in the interviews with designers and representatives of entrepreneurial CE companies, in which several trade-offs limiting DfCE implementation were highlighted.

One of the criteria most commonly emphasised as being essential, whilst at the same time incompatible with more sustainable CE design solutions, was product quality. DESIGNER 1 provided an illustrative example, explaining how compromising on product quality in order to implement DfCE could damage a brand's reputation, preventing such initiatives from being adopted.

> *"So if we're going to make a sustainable product, we never want to compromise our quality, because that's where we stand as a brand. That's why sometimes with what we do… we can't use a complete 100% recycled plastic yarn… because if the performance is not great, then we wouldn't put the product out in the first place."* (DESIGNER 1)

This finding is corroborated by the results of designer interviews conducted by Singh & Ordoñez (2016), who found quality and performance trade-offs associated with recycled or reused materials, components and products to be a significant potential limiting factor for transitioning to a CE. Even in the case of entrepreneurial CE company, MUD JEANS, the CE benefits of a completely closed-loop supply chain for their cotton fabric could not be justified in light of the inescapable quality trade-offs.

> *"We cannot go up… 40% post-consumer waste and 60% new, organic cotton… the techniques now allow us to make the same quality of fabric, otherwise it would of course not be possible to deliver a quality product. We cannot, by using recycled cotton, make a less good quality jean."* (MUD JEANS)

These findings suggest that, in instances where it requires a trade-off in terms of product quality, DfCE is unlikely to be implemented.

Another trade-off highlighted in the interviews with the potential to limit DfCE implementation was increased costs associated with CE strategies. Cost related trade-offs were raised by all of the interviewees with some reinforcing it multiple times throughout the interview. In some cases, such as DESIGNER 4 and DESIGNER 2, cost related trade-offs associated with DfCE manifested as higher prices charged to consumers and the potential to exceed that which the consumer would be able or willing to spend.

> *"[…] you can't offer a good, high-quality toaster that can be broken down for disassembly to someone who's only got, say a tenner to spend on it."* (DESIGNER 4)

Supporting this observation, THE LIBRARY OF THINGS, having implemented a pay-per-use product rental system, had found high prices to be a limiting factor preventing consumers from renting certain products. In other cases, such as DESIGNER 1, DESIGNER 5, DESIGNER 3, DESIGNER 4 and DESIGNER 6, cost related DfCE trade-offs manifested as reductions in profit margins.

> *"If we can't get a certain margin that we need to hit, then it doesn't work for us… because in the end, every business or company wants to make business."* (DESIGNER 1)

These findings are reflective of the literature, which suggests that, generally, companies are only willing to make significant changes to their products and operations if they stand to gain significant commercial success (Preston, 2012). The interviews with representatives of entrepreneurial CE companies demonstrated that they too faced similar cost related conflicts and were forced to make trade-offs between profitability and the extent of DfCE implementation. FAIRPHONE, for example explained that it was necessary to adopt a step-by-step approach whereby different aspects of the business were transitioned to more sustainable and circular solutions as and when the company could afford to do so.

> *"[…] we are quite opportunistic with how we approach the solutions to these issues. So some of the issues we highlight and we know we can tackle […] but there are other issues that we cannot tackle yet."* (FAIRPHONE)

In the case of THE LIBRARY OF THINGS, it was explained that their pay-per-use rental model was not yet financially sustainable, requiring additional funding and supplementary income gained through speaking events to remain operational, even as a not-for-profit organisation. Further to this, MUD JEANS described a situation where additional costs arising as a result of their in-house repair service had to be borne by the company. These findings suggest that in the case of cost related trade-offs, it can be difficult to find solutions, with companies facing a choice between DfCE implementation and profitability and even viability.

Other DfCE conflicts highlighted included those associated with manufacturability, lead-times and legal requirements and regulations. However, interviewees placed less emphasis on these in terms of their potential to limit DfCE implementation. Instead, they tended to be framed less as inevitable trade-offs and more as potential considerations that needed to be factored into the design process. For example, DESIGNER 1 described a situation where the legal requirement to have uniformity between products presented a challenge for CE innovations that resulted in a variable finish. However, it was explained that a trade-off situation was avoided through the addition of supplementary communication devices advising consumers of the reasons behind the observed variability.

> "*It's almost like those legal things that come in, because usually we have to check that every single piece is exactly the same… unless we communicate it on a separate hang tag that – 'Hey, because of the process we want to keep that unfinished or imperfect look'.*" (DESIGNER 1)

This suggests that, in some instances, trade-offs may be averted should additional, reconciliatory measures be taken.

It is therefore evident that DfCE criteria can conflict with other, traditional design criteria. This may require the development of additional solutions, however, should such solutions fail to be identified or remain unavailable, designers will inevitably be presented with a decision between implementing DfCE and the criteria considered essential for commercial success. Depending on the prioritisation of these other criteria, DfCE may be sacrificed, representing another potential limitation on its implementation.

### 7.1.5 The Limitations of Available DfCE Tools and Methods

A further challenge in implementing DfCE, as highlighted in the literature, is the limitations of the tools and methods aimed at helping guide its implementation. To date, attempts to address sustainability through the design of products have tended to follow an Ecodesign approach. As discussed in Chapter 3, Ecodesign refers to the integration of environmental considerations into the design process to address impacts at each stage of a product's lifecycle. Ecodesign typically employs some form of systematic measurement and analysis of environmental aspects and impacts associated with an existing product's design, such as a Life Cycle Assessment (LCA), to highlight areas requiring improvement. The application of Ecodesign and LCA therefore helps to shift the consideration of sustainability from end-of-pipe to the earlier product design stages, supporting design decision making through the collection, analysis, weighting and interpretation of data on a product's environmental performance (Bhander, et al., 2003). These tools were originally promoted as a means of addressing the energy and material efficiency of products under the Ecodesign Directive. In order to better accommodate DfCE, The European Commission has since called for the scope of Ecodesign to be expanded in order to better accommodate CE thinking as part of its Circular Economy Package (Hughes, 2017).When it comes to DfCE, there are a number of factors that can limit the suitability of an LCA-centred approach.

The first is the stage of the design process at which an LCA is conducted. Typically, an existing product is assessed in order to provide the data needed to identify the most environmentally impactful aspects. As a result, designers may focus on changes that can be made to the existing product, as opposed to a more conceptual re-evaluation of how consumer needs are fulfilled and whether these could be better met through an entirely different product or service approach (Bhander, et al., 2003). An LCA may therefore encourage incremental improvements to existing products as opposed to the radical innovations required for DfCE. Product service systems (PSS), for example, may necessitate a re-evaluation of consumer needs and behaviours, requiring consideration at a much earlier stage in the design process (Widgren & Sakao, 2016). A further factor is the reductive, quantitative nature of the LCA process. As explained by De los Rios & Charnley (2017), even if the scope of LCA were to be expanded, it is unclear how such an approach would aid in the identification of alternative business models or support the evaluation of more qualitative aspects, such as emotional durability. This is because DfCE aspects such as these necessitate a shift in perspective from physical products to systems of value delivery, which can be more difficult to quantify. Additionally, by reducing aspects and impacts to data, the LCA process can obscure complexities, preventing designers from gaining anything more than a superficial understanding of the reasons behind results (Bhander, et al., 2003). An LCA approach is therefore unlikely to support the sort of deeper comprehension necessary for solution ideation and the development of alternatives. It has also been suggested that the rigid and analytical LCA process is difficult to integrate into the spontaneous, creative process of design (Brones & de Carvalho, 2015). This results in it becoming an additional, isolated task that designers must contend with (Knight & Jenkins, 2009). Adding to the inconvenience is the amount of time and resources that conducting an LCA requires in what is a already a complex and time-sensitive process (Allione, et al., 2012). This may be further compounded by the challenge of gathering the necessary data, which can prove to be a difficult and lengthy task itself (Dekoninck, et al., 2016). It has also been argued that DfCE and LCA differ on a deeper, ideological level, with LCA incorporating the waste hierarchy[11], which encourages gradual improvement in waste management practices, whilst the

[11] The ‘waste hierarchy’ is an ordered list of end of life processes, ranging from ‘refuse’ to ‘rethink’, ‘reduce’, ‘reuse’, ‘repair’, ‘refurbish’, ‘remanufacture’, ‘repurpose’, ‘recycle’ and ‘recover’ (Kirchherr, et al., 2017).

CE concept aims for the elimination of waste through the re-framing of end of life products, components and materials as the resources for new products (Dieterle, et al., 2018). This further brings into question the suitability of an LCA approach in DfCE. Therefore, whilst existing LCA-centred Ecodesign approaches provide a well defined method for the evaluation of products' environmental aspects and impacts, they are of limited use with respect to supporting the implementation of DfCE.

Considering the limitations of existing Ecodesign approaches, several frameworks, tools and methods aimed specifically at supporting DfCE have emerged with the subject remaining a very live area of research and development. Whilst there are nuanced differences between each one, they generally follow one of two approaches. The first is a reductive, analytical approach akin to an LCA, through which an existing product's circularity performance is quantified using a questionnaire. Examples include (Cayzer, et al., 2017)'s Circular Economy Indicator Prototype and (Evans & Bocken, 2013)'s Circular Economy Toolkit. These benefit from being simple to navigate for non-CE-experts and their provision of a succinct summary of a product's CE performance, which can be easily shared and quickly understood by other stakeholders. However, approaches such as these share many of the shortcomings associated with LCA as outlined above. Additionally, where simplicity is gained, detail is lost, and the tools therefore tend to rely on assumptions. As a result, these tools can be quite rigid, with the questions, variables and weightings needing to be adjusted to accommodate different industries, products and contexts, which may represent a barrier to implementation (Cayzer, et al., 2017). This was reflected in the experiences of DESIGNER 6, having used similar approaches.

> *"A lot of the outputs of those things often end up with – 'You should use a different material' – and the challenge with that is that the material is either not suitable for the product that that company makes or the company is not yet set up to be able to change its operations to take on that material."* (DESIGNER 6)

The alternative is high-level, strategic approaches, which tend to outline key CE principles and business models and list potential Design for 'X' (DfX) strategies to achieve them. Examples include the (Ellen MacArthur Foundation & IDEO, 2017)'s Circular Design Guide, (Mestre & Cooper, 2017)'s framework for slowing, closing, bio-inspired and bio-based loops, (Bocken, et al., 2016)'s product design and business models for a circular economy, (Moreno, et al., 2016)'s framework linking DfX strategies to CE business models and (van den Berg & Bakker, 2015)'s framework combining CE visioning, DfCE guidelines and spider diagrams for comparing design outcomes. These approaches benefit from being applicable to the earlier stages of the design process, and from their flexibility and capacity to accommodate different product types. Additionally, adopting a high-level approach can help to transform DfCE from a solution-development activity to a more strategic process, considering business models, wider systems and operations. However, a limitation is that they require those using them to be sufficiently knowledgeable in DfCE to know which strategies to apply in which contexts. A criticism of these high-level frameworks is therefore that they don't provide adequate support for designers faced with evaluating a range of potential solutions and making difficult design decisions. The spider diagrams in (van den Berg & Bakker, 2015), for example, frame DfCE strategies as being independent and of equal value, even though there may be interactions between them, and some may be of greater importance than others with respect to circularity. For these reasons, the high-level, strategic visions generated by such approaches may be difficult to integrate with practical design tasks, which was a point highlighted by DESIGNER 6.

> *"I think what you get a lot of in the conversation around circular economy products at the moment is very beautiful diagrams and top-level systems, models, which are great and you can see that value is kicked back into the system here and here it is again, and here it is again. But the actual practical application of those are very difficult [...]"* (DESIGNER 6)

Considering the challenges of both systematic, LCA-inspired tools and strategic, high-level frameworks, some attempts have been made to merge the two as part of a more extensive approach. (Mendoza, et al., 2017) for example employs back-casting[12] to facilitate CE strategy development and DfCE ideation, followed by a CE adjusted LCA to assess the possible designs put forward. However, whilst this combined framework is comprehensive, with the potential to counteract the limitations of either approach in isolation, (Mendoza, et al., 2017) admit that its implementation can prove challenging. This is due to the level of detail and complexity inherenet in the process, which demands considerable time, resources and commitment at various levels of an organisation. Nevertheless, this top-down, bottom-up approach, combining high-level visioning and LCA to evaluate potential solutions is largely what entrepreneurial CE companies described in their interviews. The reprepresentatives from both FAIRPHONE

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[12] 'Back-casting' may be defined as a process of looking back from a desirable or unavoidable future (Vergragt, 2005).

and MUD JEANS recalled enlisting DfX strategies in line with CE business models followed by an LCA to assess the success of their designs. However, it is interetsting in that they claimed that they didn't follow any particular method or tool.

> *"So I couldn't remember a design strategy as such that we have followed, but of course there are principles of a lot of design strategies embedded in the FAIRPHONE 2. So there are elements of design for longevity and emotional design as well, with some elements that we have created into the device to make that strong bond with the customer. There are elements, of course, of design for repairability and design for recycling as well, but further than those, I wouldn't say we follow a very methodological process […]"* (FAIRPHONE).

It may be drawn from this that the guiding tool or method is subordinate and perhaps superfluous to what is a logical, albeit challenging, process of embedding DfCE practices within a company. Upon reflection, a complete lack of available tools and methods is unlikely to be a limiting factor. Whilst some approaches may be less suitable and effectual for facilitating DfCE, more suitable methods have emerged. However, the challenge with these is that they do little to alleviate the task-based barriers identified in chapters 7.1 to 7.4. Irrespective of the tools and methods used, DfCE remains a large, complex and time and resource intensive process. Similar observations have been made with respect to sustainable design tools and methods more generally, with (Brones & de Carvalho, 2015, p. 49) stating,

> *"[…] there is an excess of tool development and a lack of consideration given to strategic intent and content, i.e. the 'broader context of product development.'"*

It may therefore be concluded that it is the challenging process of implementing DfCE that is a barrier, as opposed a lack of available tools and methods, which inherit rather than ameliorate such difficulties.

It is therefore evident from the review of the literature and interview responses that the DfCE task presents several challenges. The first is the disruptive innovation required to redesign products, business models and operations and the associated upfront costs and risks. The next is an expansion and extension of the scope of the design task, necessitating a systems perspective beyond the physical product and requiring additional time and resources. The addition of CE and wider systems considerations makes the task exponentially more complex, as the consequences of each additional criteria must be evaluated in terms of all of the other criteria necessary for a successful product. Identifying and resolving potential trade-offs may then require yet further time and resources. Finally, whilst DfCE specific tools and methods are beginning to emerge, they do little to resolve these challenges and instead assimilate many of them. All of these task-based barriers may therefore limit implementation of DfCE.

## 7.2 Designer Barriers

There are also a number of DfCE barriers associated with the designer. These include designers' awareness and knowledge of CE, their values and beliefs, and the extent of their autonomy and freedom to implement DfCE. Each of these barriers are discussed in more detail below.

### 7.2.1. Awareness and Values

In recognition of the role of design in achieving a CE (Chapter 3), many publications have framed the designer as an instigator for change (Ellen MacArthur Foundation, 2017) (De los Rios & Charnley, 2017) (Celades, et al., 2017) (Moreno, et al., 2016) (Boehnert, 2015) (Andrews, 2015). As a result, an emphasis has been placed on raising awareness of CE amongst designers in order to bring this change to fruition.

The interviews also suggested that DfCE awareness itself may not be the only limiting factor. Whilst all of the designers interviewed displayed some level of awareness of sustainability issues and DfCE, this alone did not guarantee implementation. That's not to say that awareness is ubiquitous throughout the wider population of designers, as those with an existing interest in sustainability may have been more likely to respond to the call for participants in this study. However, what is interesting is that despite their awareness, those interviewed still struggled to apply DfCE principles in their day to day design practices. This suggests awareness doesn't necessarily lead to action, implying the existence of other limiting factors.

Further analysis of the designer interviews and the literature suggested values may also play an important role. As research by (Coles, 2003, p. 123) explains, design decisions are influenced by designers' *"[...] preferences, priorities, options, convictions and emotions"*. It is therefore important that designers are not only aware, but also value CE principles if they are to become instigators of DfCE. That being said, an awareness of sustainability issues is obviously still a prerequisite for holding such values, which was a point highlighted by DESIGNER 1,

> *"[...] you only care about what you love, and you only love what you know, but if you don't know about something then obviously you're not going to care about it as much."* (DESIGNER 1)

However, the interviews revealed that CE values can be compromised should they conflict with other values held by designers. For example, DESIGNER 3, DESIGNER 5 and DESIGNER 4 emphasised the conflict between CE values and those associated with success, career progression and the ability to support themselves and dependents financially. As DESIGNER 4 explains,

> *"In fact I had one student who was in a sort of moral dilemma with the kind of work he wanted to go into after university, because they would have him working on things that really go against his values and then, at the same time, he does understand he does have to make a living"* (DESIGNER 4)

It was also evident throughout the interview with DESIGNER 1 that product performance was valued highly by them on a personal level, as they themselves were a user of the product and expected a certain level of performance. Further, in the case of DESIGNER 4, a conflict emerged between personal values related to designing affordable and accessible products and the potential for sustainable products to become elitist due to increased costs and higher prices. This suggests that even within designer's own personal values there can exist conflicts and potential trade-offs. However, as identified by (Trimmington, 2009)'s research on the role values play in the design process, designers' personal values are not the only values that influence design decision making (Figure 7.2).

This figure has been removed as the copyright is owned by another organisation or individual.

**Figure 7.2** Values influencing the design process. Adapted from (Trimmington, 2009).

Internally, designers may be guided by abstract meta-values, such as artistic preferences, the values they embed within their designs, and those that they perceive to exist within wider systems or to be held by stakeholders. These internal values add to a range of external values that drive and constrain the design task, such as consumer expectations, market trends and business targets (Trimmington, 2009). As with product design criteria, values may conflict and compete, requiring solutions to be sought or trade-offs to be made. Therefore, whilst awareness of sustainability issues is essential for designers to value CE principles, the challenge is more complicated than simply acting on this awareness. The balancing of CE values against all other values involved in design decision making adds further complexity.

### 7.2.2 Knowledge and Training

Additionally, it has been suggested that a failure to equip designers with the knowledge and skills necessary to carry out DfCE may be a limiting factor. Andrews (2015) for example, suggests that not all designers are 'sustainability literate' causing some to avoid engaging with circular design. Similarly, (Boehnert, 2015) highlights the need for designers to develop an 'ecological literacy' including an understanding of alternatives to existing models of production and consumption, such as CE. This sentiment is shared by (De los Rios & Charnley, 2017) and (Celades, et al., 2017), who emphasise the role of formal education institutions in promoting DfCE awareness and knowledge amongst designers. The proposed solution is therefore the embedding of CE principles within the design curriculum to ensure that this awareness and knowledge becomes implicit in design education (Andrews, 2015). The challenges associated with achieving this are highlighted by (Celades, et al., 2017), including a lack of commitment from educational institutions, a lack of time and resources available and the fact that the topic of CE crosses multiple disciplines, when academic subjects tend to be disciplinarily constrained. The literature therefore suggests that a key barrier to DfCE implementation is a failure or inability on behalf of education providers to impart the knowledge and skills necessary to implement DfCE to designers.

However, in reality, the situation may be less straightforward. Firstly, the interviews revealed that formal design education routes represent just one of many possible means through which designers may gain an understanding of DfCE. Participants described additional or alternative avenues, including extra-curricular reading, self-motivated study, industry events, in-work initiatives and informal connections with colleagues in other departments, such as dedicated sustainability teams. This suggests that a lack of DfCE training via formal design education may not be a limiting factor for DfCE implementation. It also demonstrates that there exists an opportunity to diversify the delivery of DfCE training, which is of particular relevance to practicing designers who have since left education.

The results of the designer interviews also question the need for designers to possess an in-depth knowledge of DfCE prior to taking on DfCE design tasks. Designer DESIGNER 5, for example, explained that they had not received any formal DfCE training as a student or vocationally, acknowledging the limitations of their knowledge with respect to topics, such as manufacturing externalities. Despite this, they described a situation where they felt confident and willing to take on a circular product design side project, which they proposed to their manager.

> *"[…] maybe a year and a half ago, I actually started talking to my head of technical about developing a range of fully circular, sustainable lingerie and I said – 'Look, it could be a side project. I'd do it with [Company] and we could do it as a sort of experiment just to see where we could get to and then present it to the directors,*

> *like this is what it's going to look like, this is how much it would cost and this is the margin you would have to take.'"* (DESIGNER 5)

This is reflective of the nature of the design task, which goes beyond the simple application of existing knowledge. As noted by (Coles, 2003), designers employ a combination of knowledge and skill as part of the design process. Such skills include investigation, invention, implementation and evaluation, which help them to tackle ill-defined design problems that involve missing information and often conflicting requirements. This is evidenced by DESIGNER 3's experience designing a healthcare product, where unknowns were tackled through a process of research, experimentation, prototyping and seeking expert advice and evaluation.

> *"There was a project that we worked on for healthcare […] we had to basically do some initial testing in the studio, very rough tests, to then submit our proposal to the regulator and the associations that take care of the full scientific process."* (DESIGNER 3)

Designers are therefore used to seeking out new knowledge and advice from a variety of sources, including experts, to help gather the level of detail necessary to generate, critique and refine design solutions. It may therefore be proposed that the skills inherent in design are conducive to implementing DfCE, even if designers don't have specific knowledge of the topic prior to commencing the task. However, it's important to acknowledge that this is dependent on the quality and reliability of available sources of information. As highlighted by DESIGNER 4,

> *"There're a lot of common misconceptions and it's amazing, actually, how much of the stuff we think is getting recycled is going to actually eventually reach landfill."* (DESIGNER 4)

It therefore appears that prior knowledge of, and training in, DfCE may not necessarily be required in order for designers to attempt DfCE tasks, however, the quality of outcomes may be affected by the accuracy of the information that they are able to obtain in support of the design process.

Beyond designers' ability to design products for a CE, the research highlighted another potential barrier in their capacity to promote disruptive change. This is a necessary component if designers are to assume their role as instigators and promoters of DfCE. As such, designers may need to develop additional skills that enable them to critique existing operations and systems and convince decision makers to bring their CE designs to market, replacing existing, unsustainable products. (Boehnert, 2015, p. 6) touches on this when they suggest designers require,

*"[...] critical skills in order to analyse the political problems and societal dynamics that keep sustainable practices marginal."*

This is corroborated by the findings of (Brass & Mazzarella, 2015), which suggest designers must develop more strategic and collaborative capabilities, enabling them to facilitate change and mediate between stakeholders, driving the transition towards a more sustainable future. Business acumen was also highlighted as an important skill for designers to possess if they are to change the opinions of  other stakeholders and win over management (Balkenende, et al., 2017). As DESIGNER 6 explains,

> *"I think a better understanding of design, but design for business, within the circular economy would be fundamentally important to have any impact on those major, major companies."* (DESIGNER 6)

It makes sense that lobbying skills such as these, which go beyond a traditional, product design focus, may represent a more significant challenge for the average designer, compared to incorporating CE requirements into a familiar design process.

### 7.2.3 Designer Autonomy

A further limiting factor affecting DfCE implementation is a lack of designer autonomy. Whilst the literature promotes designers as those responsible for making design decisions and therefore having the power to affect change (Celades, et al., 2017) (Andrews, 2015) (Boehnert, 2015), the results of the designer interviews suggest that this is not always the case. This is because decisions that affect the circularity of product designs are often made or influenced by other stakeholders in the value chain.

One way in which this occurs is through the stipulation of design criteria by managers and clients in the form of a design brief. This can limit the creative freedom of designers and their capacity to come up with new, circular product alternatives (Bocken, et al., 2016). The experiences of the designers interviewed suggest that the degree of specificity can vary between briefs, depending on the goals of those devising them, with some more restrictive in terms of designer freedom than others. DESIGNER 1, for example, describes price limitations as being particularly limiting.

> *"I think there are projects where we're quite constrained. Like, let's say a project with a really low price point. We can't really do much."* (DESIGNER 1)

This is corroborated by research by Byggeth & Hochschorner (2006), who note that criteria, such as cost restrictions, have a limiting impact on design, narrowing the scope of product possibilities by constraining elements, such as form, material selection and manufacturing and assembly options. It was also found that design briefs within established businesses may also make significant reference to existing, successful products upon which future products are to be based. This was reflected in DESIGNER 1's explanation of the need for new designs to fit within an existing product range and DESIGNER 5's description of the way in which new designs are modelled on existing templates.

> *"For example, the collections side of things, so what I had been working on, we had almost like templates, like shapes that we work towards every season that we don't really update an awful lot, but we update the overall aesthetic of that shape."* (DESIGNER 5)

Where this is a requirement or expectation, the focus of design becomes rather more about styling. Criteria specified in design briefs therefore have the potential to effectively limit designers to the later stages of design (Behirsch, et al., 2011). This may in turn restrict their involvement in strategic decision making and obscure opportunities for innovation, such as DfCE.

Employers may also make decisions regarding the allocation of time and resources to particular design tasks, which can limit opportunities for conducting the additional research and experimentation necessary for product innovation and DfCE (Mendoza, et al., 2017). This was highlighted by DESIGNER 3, who explains,

> *"[…] most companies looking for innovation don't allow budget for innovation, they just allow budget for execution […]"* (DESIGNER 3)

Another aspect that can restrict the autonomy of designers is the division of labour. In some instances, designers are given a very specific, isolated tasks with very little insight and input into wider design and production processes. DESIGNER 2, for example, describes being tasked with producing furniture designs for a company on a freelance basis with very little insight into the final product outcome.

> *"I've done these designs for this company. They produce them, but I don't know really what they do. That's sort of out of my hands, like, I'm not overseeing production […]"* (DESIGNER 2)

Working as a design consultant, DESIGNER 3 described working on projects in which they were tasked with realising clients' pre-existing product concepts, with little opportunity to contribute to more strategic, systems-level decisions.

> *"So, basically, I work as a consultant. So I work on other people's ideas. When people want to actually create something out in the market, they come to me and say – 'Can we develop this?'"* (DESIGNER 3)

As a systems perspective is integral to DfCE, this division of labour into compartmentalised design tasks can limit the potential for designers to adopt a more strategic role and to push forward comprehensive CE solutions.

In addition to the limitations placed on their autonomy throughout the design task, designers may also find that their final design outputs are subject to the approval of other decision makers. An example is provided by DESIGNER 5, who explains that the progression of their designs to market is at the discretion of senior management.

> *"So, although I will have developed a product and fed into it, ultimately, I won't be there when they finally get it signed off by the directors, but that's because I'm just a small fish."* (DESIGNER 5)

Likewise, DESIGNER 2 describes making adjustments and changes to designs as directed by the client.

> *"So, whenever you're designing for a client, you're always going to have to change things for the client… you will have some clients that will be very hands-off and you'll have other clients that will be very hands-on." (DESIGNER 2)*

This has previously been identified as a limiting factor in Ecodesign, which remains of relevance to DfCE, with (Bhamra, 2004, p. 565) concluding,

> *"One might presume that the design decision process is taking place at a management level within the company or client."*

In addition to these more explicit restrictions on designer autonomy, social and cultural influences can also impede the freedom of designers when making design decisions. One example evident in the designer interviews is the social dynamics associated with employment. DESIGNER 2, for example, describes the difficulty in challenging clients on their practices when employed as a designer.

> *"It would be quite hard to go in to someone else as a creative, like – 'I want to know how you do all these things' – because you would probably burn some bridges. You have the power where you… I think you make the choices you can where you can, I guess."* (DESIGNER 2)

Likewise, DESIGNER 6 highlights the need to conform to the requirements of employers in order to gain work and generate income.

> *"Designers at the end of the day need to make some kind of profit themselves, such is the way the world is shaped, and it's really hard for a lot of people to do the type of work that they want to do when the pressure is coming from production."* (DESIGNER 6)

These responses suggest that employment entails differences in authority between employer and employee and an expectation that designers will conform to the requirements of their employer or client. Failure to do so may result in a damaged reputation, as highlighted by DESIGNER 2, or a loss of income as explained by DESIGNER 6. DESIGNER 6 does make the point that designers retain the ability to decline work that they disagree with.

> *"And also it's important for designers to be a little bit more particular about who they work with and not just accept jobs because they're fee paying, because that sort of attitude won't actually lead to any form of long-term change."* (DESIGNER 6)

However, this may prove a challenging course of action for designers to take, as DESIGNER 5, DESIGNER 3 and DESIGNER 4 all described the ability to support oneself financially as being of high importance.

Further to this, the division of labour, as previously mentioned, can also have social and cultural impacts on designer autonomy. In addition to designers being restricted to specific, isolated tasks, it can also limit their sense of responsibility and accountability with regards to wider operations, limiting their capacity for affecting change (Bandura, 1999).

> *"Most enterprises require the services of many people, each performing subdivided jobs that seem harmless in themselves. After activities become routinized into*

> *detached subfunctions, people shift their attention from the morality of what they are doing to the operational details and efficiency of their specific job."* (Bandura, 1999, p. 198)

Working as part of a team can also result in a degree of moral disengagement as, when decision making is shared, no one person assumes full responsibility (Bandura, 1999). This was reflected in DESIGNER 1's description of design as a process of negotiation.

> *"So it's almost like… you learn so much about this negotiation with your counterpart… to give and also to like… you have to sacrifice certain things in order to make the product work because you can't just do everything for yourself… thinking that – 'This is the best for me' – you have to think – 'What is the best for the team?' – and it almost taught me a lot… that sometimes you have to sacrifice certain designs… in order to build trust within your team.. to progress together as a team."* (DESIGNER 1)

When designers publicly assume sole responsibility for a design and outputs are directly attributable to them, it's possible they would be more likely to assert control over design decisions, with DESIGNER 2 explaining,

> *"I think if you are putting your name on it and It's going to go out there and everyone… It's going to be like – 'Such and such lamp by…' – and the person's name is on it. In those sorts of situations I would be much more inclined to be much more strict with them about changes they could make to it."* (DESIGNER 2)

However, it's also important to note that designing independently may also limit the diversity of knowledge and perspectives informing the design process (Widgren & Sakao, 2016). This was noted by DESIGNER 4, who described having greater freedom, yet missing the input and ideas gained through collaboration. Therefore, designing independently may make the process of acting on CE values more straightforward if the designer has them, but at the same time, lower the likelihood of someone in the process having CE values and reducing the information and ideas contributing to design solutions.

Interestingly, the interviews revealed instances where designers had, or were planning to develop, individual design projects in line with their own personal values. For example, DESIGNER 4 explains,

> *"I think that's where I'm at the moment and I'm hoping to do a lot more humanitarian design. I've got a few projects that I've got to get out of the way first, but that's sort of where I'm at. So, something that's a lot more meaningful to myself and my own design values and personal values."* (DESIGNER 4).

This was also the case for DESIGNER 2, who was self-educated on DfCE and had set up an independent jewellery design business with an ethical and sustainable angle as a personal side project, having faced barriers to do so in their other freelance and in-house design roles. These results therefore suggest that a lack of designer autonomy may be a limiting factor preventing designers from instigating DfCE within organisations or on behalf of clients.

To summarise, it appears there is a difference between the ability of designers to navigate DfCE tasks and their capacity to instigate DfCE within organisations or client projects in the face of contextual barriers. With respect to the former, the need for designers to have prior knowledge of and training in DfCE, whilst beneficial, may be over exaggerated, as it was demonstrated that designers possess skills that lend themselves to dealing with unknowns and seeking out information and advice to fill knowledge gaps. A range of DfCE information sources consulted by designers were identified, however, the quality, reliability and availability of that information remains an important factor. With respect to designers' capacity to act as instigators of DfCE, awareness was found to be essential for designers to hold CE values and prompt action. However, such action may be compromised as a result of contextual barriers that limit designers' autonomy. These include direct barriers associated with the design brief, the restriction of resources, the boundaries of designers' roles and the need to obtain approval from management. Added to these are indirect limitations, such as the need to balance CE values against all others influencing the design process and the navigation of social and cultural factors associated with employment and collaboration. A lack of critical and persuasive skills and CE-specific business acumen were highlighted as potential shortcomings preventing designers from overcoming these contextual barriers.

### 7.3 Organisational Barriers

The limitations on designers' autonomy suggest barriers to DfCE implementation also exist at a wider, organisational level. These can generally be categorised as; awareness and leadership, organisational structure, and business viability and profitability. Each of these are discussed in more detail below.

### 7.3.1 Organisation-wide Awareness and Leadership

One of the organisational barriers limiting designers from implementing sustainable design initiatives, is a lack of awareness amongst other stakeholders who are either directly involved in design decision making or who have an influential role. This is especially the case for DfCE as its implementation requires systemic change, whereby circular product innovations are facilitated by supportive business models, processes and services. As such, the alignment and cooperation of stakeholders across all levels of an organisation are required in order to facilitate such a transition (Behirsch, et al., 2011) (Boks, 2006) (Bhamra, 2004). This includes those with indirect involvement in design, such as human resources, IT and data management who may act as enablers of DfCE adoption (Lewandowski, 2016). An example is provided by DESIGNER 1, who highlights the need for better support from their marketing department as a barrier in realising DfCE design solutions and bringing them to market.

> *"I'm more than happy to design some more sustainable products, but then I also need my marketing team to help me to validate this point and to present it and to get it at the right price point."* (DESIGNER 1)

This was also evidenced by the fact that widespread awareness of CE values formed an essential component of the entrepreneurial CE companies interviewed. Representatives from FAIRPHONE, for example, describe how their procurement and communications departments embrace CE principles.

> *"[…] the sourcing department, when we do the procurement, instead of only caring about the quality and cost, we also look into the social and environmental performance of the suppliers. And also in the communication department, instead of only doing the branding communication, we would also try to create a lot of awareness on different sustainability topics."* (FAIRPHONE)

Whilst some of the designers interviewed, such as DESIGNER 1 and DESIGNER 5, also described sustainability and CE awareness raising initiatives within their organisations, they both noted challenges associated with implementation.

> *"[…] we have been a bit frustrated as designers, saying – 'We understand that we have these commitments, but as a design team, they're not actually integrating that into the design process.'"* (DESIGNER 5)

> *"Sometimes it looks like corporate doesn't care, but we just haven't had that proper system yet. Sometimes it just takes time to make it work globally."* (DESIGNER 1)

This suggests that, in addition to widespread awareness, there is also a need for leadership and strategic direction. This is necessary to support the coordinated embedding of CE principles within organisations at the earliest stages of decision making. As explained by (Lewandowski, 2016), it is important for business leaders and decision makers to navigate potential CE benefits and risks, setting out a clear strategic direction and establishing a common understanding within organisations. This includes the development of circular business models as well as high-level visionary statements and goals (Bocken, et al., 2016). (den Hollander, et al., 2017) suggests that high-level developments, such as changes to business models, inevitably filter down to designers through radically different design briefs. This proved to be a recurring theme throughout the interviews with designers. DESIGNER 5, for example, explains,

> *"Yeah. I guess implementation, but also the buy-in from the top leadership level to actually make it a priority to actually achieve it."* (DESIGNER 5)

Likewise, DESIGNER 6 makes the following statement with regards to DfCE implementation,

> *"So it's important, I think, for designers to get that high-level buy-in with companies."* (DESIGNER 6)

A similar situation was found with regards to clients of freelance designers, with DESIGNER 3 estimating that only about two percent stipulate sustainability or CE requirements, limiting the scope for DfCE implementation by the designer.

The need for CE leadership was corroborated by the fact that the entrepreneurial CE companies interviewed all described having CE principles as a core part of their business strategy. Interestingly, in the case of MUD JEANS, strong CE leadership was even credited for encouraging skilled, CE-minded employees to join the company, suggesting it may also go some way towards overcoming CE awareness challenges.

> *"I must admit that I didn't realise it upfront, that being a social enterprise and B-corp, it attracts a lot of young, talented people that are very motivated to join this movement and put their power, knowledge and energy into it. That's a great factor in doing this kind of thing."* (MUD JEANS)

These results suggest that company-wide awareness of CE principles and strong, strategic CE leadership are two essential and interrelated requirements for DfCE implementation. Awareness is key for ensuring those in other business functions are able to work with and support designers in achieving DfCE, whilst commitment and leadership from those in positions of authority empower employees to put DfCE solutions and ideas into action (De los Rios & Charnley, 2017). A lack thereof is therefore likely to represent a key barrier.

### 7.3.2 Organisational Structure

As DfCE is a complex task that requires innovation and considerable change across products offerings, business models, operations and processes (Chapter 7.1) organisational structure may also represent a barrier by increasing the difficulty of implementing such changes.

Firstly, companies may face challenges associated with diversification, as DfCE demands the setting up of new business functions and capabilities, such as repair, maintenance and reverse logistics. As noted by (Balkenende & Bakker, 2015), switching from a business model based on product sales to one focused on product services, for example, can require significant changes across the entire value chain. Such developments may also represent unfamiliar and untested ways of doing business, bringing new challenges. Further to this, significant changes to business operations may impact on relationships with existing suppliers. For example, (Dalhammar, 2016) notes that the incorporation of initiatives such as repair and recycling may be viewed unfavourably by manufacturers as they represent a reduction in consumption and therefore production and sales. Challenges such as these highlight the difficulty of diversifying core business functions in order to accommodate DfCE.

There are also a number of barriers specific to large and complex organisations, as a result of the number and variety of operations, business functions and departments that they encompass. As explained by DESIGNER 6, implementing change in one area of a large organisation can have implications for others, resulting in conflicts of interest, which may require mitigating measures (Asif, et al., 2016). Further, the rolling out of DfCE initiatives within large organisations can require the investment of considerable time and resources. This was a challenge highlighted by DESIGNER 1, who explained,

> *"Because we have so many employees and how are we going to spend budget here and there and this is something we didn't put aside. It's something we are slowly progressing and developing to make it work"* (DESIGNER 1)

Within large organisations, there can also be a disconnect between high-level decision makers and those that are tasked with implementing such initiatives (Boks, 2006). As there exists an array of contextual, as well as technical, challenges to DfCE implementation, failure to identify and take these into account may result in inappropriate or ineffectual initiatives being proposed. This is reflected by DESIGNER 5 stating,

> *"A large gap exists between the proponents and those that have to make it [DfCE] operational"* (DESIGNER 5)

Another challenge in large organisations is the potential for knowledge and information to become siloed as operations are compartmentalised in an effort to streamline and simplify business activities. Rather than being integrated throughout all departments, sustainability initiatives, such as DfCE, may therefore be delegated to separate, dedicated departments, such as CSR and sustainability teams, preventing integration. This is reflected in DESIGNER 1's comments regarding the company's sustainability team,

> *"I think every team wants to push sustainable things, but I think it's… the strategy and the system and how… those teams are poorly integrated and the system is not… not there yet."* (DESIGNER 1)

Additionally, the division of labour can make it difficult to implement DfCE initiatives in a coordinated way, with the potential for ideas to become diluted without a shared understanding and unifying goal or the appointment of a high-level decision maker with oversight of such projects at large. This was highlighted by DESIGNER 6, who states,

> *"[…] it's really sad to see that often those most innovative and interesting elements to that business plan get sort of ironed out as more and more and more people get involved in that process and more people get involved in that process and more people who have a small part of one job to do […] And you start to see that a lot of people in those industries have one small job to do and slowly start to engineer out that ambition and it's an incredibly frustrating part of the business"* (DESIGNER 6)

In contrast, smaller companies, such as start-ups and SMEs[13] are typically more agile, *"In short, it is much easier to create a green SME than to make an already existing company greener"* (Rizos, et al., 2015) As a result, they are able to incorporate changes, such as those required by DfCE, more readily, which was a point highlighted by DESIGNER 6. However, they then face other barriers, most notably a lack of resources to invest in DfCE initiatives, which was evidenced by the experiences of the entrepreneurial CE companies interviewed. FAIRPHONE, for example, explains,

> *"[…] as a start-up we are faster to change, but we very often lack the resources to support that change. And probably for bigger organisations it's the other way round, right? They are slower to change, but they have all of the resources available."* (FAIRPHONE)

With respect to this, DESIGNER 6, highlighted the fact that there exist opportunities for larger organisations to learn from or to partner with smaller start-ups, whilst providing the resources for exploration as part of a mutually beneficial arrangement. Such partnerships were also highlighted by FAIRPHONE as a necessary means of achieving DfCE as a start-up.

> *"So we cannot do it alone, because we need to partner and that's what we do. So for every project we look for the right partnerships."* (FAIRPHONE)

Challenges associated with organisational structure can therefore be summarised as difficulties implementing change in the case of larger corporations, a lack of available resources for smaller companies and, more generally, the need to diversify business functions and develop new partnerships, with knock on impacts for existing operations and business relationships.

### 7.3.3 Business Viability & Profitability

A further organisational-level barrier that can have a limiting effect on DfCE implementation is the need to achieve business viability and profitability. This is essential if circular solutions are to gain market success and displace existing, less sustainable products. Additionally, generating profits represents a driving force for companies, with consumer satisfaction, sales and selling price taken into consideration from the outset of product development processes (De Souza & Borsato, 2015).

[13] An 'SME' may be defined as a small to medium sized enterprise.

However, new innovations as demanded by DfCE often require initial investment and high upfront costs, which may represent a risk that organisations are reluctant to take without a guarantee of returns. As explained by DESIGNER 6,

> *"All of those things scare companies because they sound like cost. They sound like new ways of doing things and while they might love to do them for all sorts of reasons, they might represent a ten, twenty percent material increase… they might represent more. So for them, where they have very, very entrenched manufacturing and supply chains, they feel that they can't afford to make those moves."* (DESIGNER 6)

In some cases, particularly for established organisations, it can be difficult to incur these costs without passing them onto the consumer in the form of higher prices. As DESIGNER 2 notes,

> *"So, for a company that already produces at a certain price point and has a certain method of production… For them to suddenly… it's hard for them to kind of incorporate those values and not massively change their prices."* (DESIGNER 2)

However, doing so can prove difficult as DfCE solutions still have to compete with the traditional, linear products on the market, which benefit from high economic performance (Baltrusaitis, 2015). Where raising prices is not an option, companies may have to absorb these higher costs, forfeiting a proportion of profits or recouping costs by cutting back in other business activities. An example of this was provided by entrepreneurial CE company, MUD JEANS, who described having to streamline business operations in order to make DfCE solutions economically feasible.

> *"A lot of the time a lot of money is wasted in making new collections, travelling, and high costs for ridiculous things. And if you do a circular denim brand and you buy at a fair price, the margins are lower. So your whole business model must be very sharp and minimal, otherwise it's not possible to do this."* (MUD JEANS).

Even where companies are committed to implementing DfCE and are willing to compromise to some extent on profitability, there can still be challenges with cash flow and raising the necessary capital to bring DfCE solutions to market. Such issues were raised for all three of the entrepreneurial CE companies interviewed. For example, representatives from FAIRPHONE explain,

> *"So I think for us the main bottleneck has been, very often, the lack of cash, like any start-up company. So being able to have the right financing at the right moment, has always been difficult and has, I would say, the biggest limiting factor that we have had."* (FAIRPHONE)

Barriers such as these can see DfCE solutions relegated to smaller projects, where they lack the potential to gain significant market share and challenge existing linear products. As noted by (Lacy & Rutqvist, 2015) the added challenges, investment risks and upfront costs associated with CE initiatives are often mitigated through a reduction in scale. This was also evidenced in the interview with DESIGNER 6 who explained that sustainable innovations, such as DfCE solutions, are often regarded as an 'experiment', 'marketing activation' or 'exploration', going on to ask the question,

> *"[...] at what point would their work cross over into the mainstream?"* (DESIGNER 6).

A focus on business success was also eschewed by the designers interviewed who described having or planning personal design projects that better reflected their personal values. It was evident from their responses that these endeavours weren't or wouldn't be their main source of income. DESIGNER 2, for example, described being free to make design decisions for their jewellery business, irrespective of whether the products sold, as they relied on other sources of design employment to support themselves. Likewise, DESIGNER 4 explained that their personal design projects wouldn't need to be for profit as they were fortunate enough to be able to sustain themselves through other work. This reinforces the fact that, whilst possible, DfCE solutions may not necessarily be viable from a financial sustainability perspective. As such, one of the key barriers to DfCE implementation is in transitioning from proof-of-concept to mainstream adoption and disruption of the status quo (Ellen MacArthur Foundation, 2015).

However, even where challenges to the business viability of DfCE solutions are not insurmountable, implementation may still be limited by the extent to which businesses are willing to accept a reduction in profitability. It has been suggested that there exists a tendency for companies to prioritise profitability above all else (Murray, et al., 2017) (Ceschin & Gaziulusoy, 2016) (Byggeth & Hochschorner, 2006). This may come down to the decisions made by senior management, although for some organisations, there may also be significant influence from shareholders. As explained by DESIGNER 6,

> *"And it's sad to have to sometimes play into the role, but ultimately companies are answering to their shareholders and they need to be able to show that they can create value by doing this."* (DESIGNER 6)

Where this is the case, even a relatively conservative reduction in profits may result in DfCE solutions being deemed unacceptable. The responses of the designers interviewed suggest this is often the case, with DESIGNER 5 stating,

> *"I mean, they want our number one focus to be selling as much product as we can and that… I mean, in my heart I know that I don't agree with that, but it's such a huge business and that's their motivation. […] So making sustainable or circular design appealing or economic to big businesses… that hasn't happened yet."* (DESIGNER 5)

In the case of DfCE, this is further complicated by the fact that it's not only the core company's economic interests that must be considered, but also those of the service providers and facilitators necessary to support multiple product lifecycle loops throughout the value chain. Such partnerships may also require compromises that are viewed unfavourably by business decision makers. The need for collaboration, for example, can raise issues associated with the sharing of intellectual property, ownership rights and, in the case of repaired, refurbished or remanufactured products, responsibility for guarantees and product warrantees (den Hollander, et al., 2017).

Therefore, the evidence suggests that for many companies, economic considerations are of paramount importance making it difficult to act against their own financial interests. Further to this, the autonomy of business managers and their freedom to make difficult decisions in the name of DfCE may also be limited by the influence of shareholders and their expectations with regards to profits. Even in cases where decision makers are able to accept a reduction in profitability to accomodate DfCE implementation, they may still face challenges associated with business viability. As a result, DfCE innitiatives may be rendered untenable or reduced to smaller scale projects, limiting their capacity to challenge unsustainable linear products in the market. Even designers operating individually, free from autonomy restrictions, are not immune to these challenges.

### 7.4 External Barriers

Many of the barriers to DfCE implementation discussed thus far are influenced by wider, external barriers, which determine the feasibility and profitability of transitioning to a CE

(Lewandowski, 2016). These include those related to the market, law and policy, consumer behaviour, technology and infrastructure, and the availability and accessibility of information. Each of these are discussed in more detail below.

### 7.4.1 Economic and Market Conditions

Economic and market barriers represent an important external challenge limiting DfCE implementation. Beyond achieving a more sustainable model of production and consumption, the Circular Economy has also been widely promoted as a means of improving competitiveness, securing resources, reducing costs and boosting innovation, growth and jobs (European Parliamentary Research Service (EPRS), 2016). However, as (Pitt & Heinemeyer, 2015) question, if this is the case then why has CE not yet achieved mass adoption? The answer appears to be that, whilst DfCE has the potential to afford economic benefits, there exist barriers to realising these due to existing market conditions preventing the transition from a linear to a circular economy. Within this context, the business viability and profitability of DfCE solutions may be compromised, as evidenced in Chapter 7.3.3. As explained by the (Ellen MacArthur Foundation, 2015, p. 18),

> *'Our economy is currently locked into a system in which everything from production economics and contracts to regulation and the way people behave favours the linear model of production and consumption.'*

It may be for this reason that eco-efficiency strategies, which continue to follow linear economy logic, have been more readily implemented (Rizos, et al., 2016). DESIGNER 1, for example, describes the immediate financial benefits afforded by simply adjusting the layout of patterns to minimise material waste during manufacture, stating,

> *"So firstly, it saves us money and secondly, it makes less trash"* (DESIGNER 1).

In contrast, the financial benefits of DfCE can be more difficult to realise as they must first overcome prevailing economic principles and structures. As representatives of FAIRPHONE explain,

> *"So we are not yet in a circular economy, we live in an economy that is very traditional, with many stakeholders that are still very traditional in their thinking. So there are definitely benefits and they are quantified as well, but they are very difficult to see and to make other stakehodlers see in the short term in the current system."* (FAIRPHONE)

One influential principle that follows linear economy thinking is the economies of scale principle, which has emerged as a result of industrialisation (Chapter 6). As DfCE requires innovation, such as new materials, manufacturing processes and supporting infrastructure, costs tend to be higher compared to existing products, which are manufactured at scale in well established, highly efficient value chains (Singh & Ordoñez, 2016). An example of this was provided by designer DESIGNER 5, who described how designers had proposed to use a novel recycled fabric, but faced a no decision from management due to its hier costs compared to existing material that they bought in bulk for use across a variety of product ranges.

> *"But, unfortunately, they have one major fabric; because it's swimwear you don't really need that many fabric sources. I think they have a couple that they use from different regions and, because they buy so much of this one fabric, they get such a good cost price on it that they're not prepared to diverge into something different for a smaller part of their business [...]"* (DESIGNER 5)

As environmental externalities are not currently incorporated into the cost of products and reflected in their pricing, it can be dificult for new DfCE solutions to compete with cheaper, traditional products that are mass manufactured, benefitting from economies of scale (Baltrusaitis, 2015). CE business models may also incur higher costs where complex processes are needed to facilitate them. Although used products may be acquired for free, the heterogeneity of waste streams, comprising various products of differing quality and purity, can prevent the standardisation of processes, such as sorting, disassembly and reprocessing (Singh & Ordoñez, 2016). As a result, they do not achieve the same economies of scale as in the production of new products. This was reflected in the comments of DESIGNER 6, who stated,

> *"And I think that it's a really sort of tragic situation for the world that we're in at the moment, that making something new is often normally cheaper for these companies than repurposing something."* (DESIGNER 6)

A further market disincentive for implementing DfCE is the increasingly rapid turnover of products. As explained by DESIGNER 3, this can make investing in specialist production processes more difficult as the period during which benefits are reaped may be reduced, in turn encouraging short-termism.

> *"I think these days it's hard because the lifespan of production is reducing so much. Back in the day [...] the same product would be around thirty or forty years so that*

> *perhaps the company or the brand could invest in their own factory and probably a designer would be involved in planning that factory […] that happens less and less because of the lifespan of products and the speed of consumption and the speed of how trends change and everything"* (DESIGNER 3)

Additionally, investing in life extension strategies with the intention of circulating products for a long period of time can prove unsustainable if those products fall out of use more quickly than intended due to changes in consumer needs or fashion trends.

In addition to the existence of real market barriers, the implementation of DfCE may also be limited by perceived barriers that stem from a deep-seated linear economy mindset. One example is the belief that remanufactured and refurbished product lines will undercut and cannibalize sales of new, premium products. However, in a study of the mobile phone industry, van Weelden, et al. (2016) demonstrated that this was unlikely to be the case, as refurbished products tend to appeal to different consumer demographics than those purchasing the latest product offerings. Their results therefore suggested that DfCE solutions, such as take back and resale schemes, could infact increase, rather than reduce, market share. Nevertheless, well established beliefs such as these can prove resistant to change and may also represent a barrier to DfCE.

These results suggest that DfCE can be limited by both real and perceived market conditions associated with the current, linear economic model. These in turn set the scene for many other barriers identified in this chapter, such as economic design trade-offs, business viability and profitability.

### 7.4.2 Law and Policy

A lack of appropriate law and policy represents a further external barrier to DfCE implementation. Addressing this is essential for two reasons. The first is the ability for legal provisions, policy instruments and taxes to correct existing market and regulatory failures that currently favour the linear economy. An example was provided by entrepreneurial CE company, MUD JEANS, who had encountered laws precluding them from importing waste materials to recycle into new products.

> *"The factory, for instance, in Turkey, is difficult, because they do not accept raw materials, post-consumer waste, coming into their country."* (MUD JEANS)

The second is their potential for law and policy to guide and incentivise the transition to a CE (Lewandowski, 2016). This point was highlighted, again by MUD JEANS, who explained that, when applied to the resale of used garments, existing tax laws act as a punitive measure, when tax breaks could instead incentivise DfCE.

> *"The jeans that come back to us after leasing are sometimes very beautiful and we sell them as a vintage pair of jeans. That means I sell the same pair of jeans twice, which I think is a great business model and also not so bad for the environment, but I have to pay VAT again […] if you really want to push for a circular economy, like what they are saying, then repair should be free of TVA [VAT] as well."* (MUD JEANS)

The importance of effective laws and policies was also highlighted by designer, DESIGNER 6, stating,

> *"So I think that the world of governance in the design of the next phase of products that we use and love is so important […] it's only when governance comes into play that the hand of the manufacturers is forced to take some sort of responsibility."* (DESIGNER 6)

However, putting such measures in place can prove challenging. In some cases, there may be a conflict of interest between the law and policy demanded by DfCE and that which serves other important interests. An example is the need for increased collaboration and sharing of information in order to facilitate the transition to a CE and the creation of circular value chains, and competition laws intended to prevent collusion and the formation of cartels (Rizos, et al., 2016). Additionally, legal measures taken to enforce or promote one course of action can result in unintended outcomes. (Ghisellini, et al., 2015) provides an example, describing efforts to eliminate waste in the Netherlands, which resulted in the winding down of the landfilling industry and the sudden loss of employment. Trade-offs such as these, which have negative consequences for businesses and individuals, are likely to be politically unfavourable; something which may be considered when considering which legal and policy directions to take.

The effective implementation and application of law and policy instruments can also prove challenging. For example, the degree of specificity and subsequent interpretation of directives and regulations can result in divergent or insufficient actions being taken. As highlighted by DESIGNER 4,

> *"For instance, what the government are proposing for 2024, where all avoidable plastics will be against the law. Well, again, there's a little, kind of, opportunity there for that word 'avoidable'. What does that mean? People will use that as leverage. That's the problem, that's just reform, it's not the reconstruction that's actually needed."* (DESIGNER 4)

Enforcing laws can also present difficulties. Some companies may outsource their production to distant manufacturing centres and countries in which environmental legislation and law enforcement are lacking (Rizos, et al., 2016). Further, where complex supply chains cross international borders, multiple and potentially conflicting laws may apply, each overseen by different governing bodies (Govindan & Hasanagic, 2018).

As these results suggest, appropriate law and policy instruments are essential to incentivise DfCE and to provide a competitive advantage over traditional, linear economy. A lack thereof can have the opposite effect, acting as a disincentive. However, there exist several challenges to implementing such measures, which must be successfully navigated.

### 7.4.3 Consumer Behaviour

A further barrier that can affect the market success of DfCE solutions is consumer behaviour. The responses of designers interviewed suggest consumers are not averse to circular products, and that consumer interest in sustainability initiatives, such as DfCE may be growing. For example, DESIGNER 1 explains,

> *"I think that the consumer response is amazing. Like, a lot of the [campaign] shoes have been selling really well, because I think there's a purpose and I think now the trend is not just – "Oh you just want to be that person who cares about sustainability" – but it's just… like, being sustainable is becoming like a cool thing."* (DESIGNER 1)

Likewise, FAIRPHONE described experiencing a positive sales response to their disassemblable and repairable mobile phone handsets.

> *"I wouldn't even say sales* [were a limiting factor]*, because I think we've always proved that when we have stock, when we have running production, we sell out pretty well* […]*"* (FAIRPHONE)

However, as DESIGNER 2 admits, this could be limited to a niche market, having not yet crossed over to the mainstream.

> *"I think there's a huge market for that kind of mentality I guess… sustainability in design, but I think it's still kind of in pockets, if that makes sense?"* (DESIGNER 2)

This may be due in part to consumer awareness, which De los Rios & Charnley (2017) promote as being essential, regarding consumers as key stakeholders in the value chain. Due to their geographical disconnect, Europeans generally fail to recognise the full impact of their fashion purchases (Rizos, et al., 2015). Sharing this sentiment, representatives from FAIRPHONE described consumer engagement and education as a key objective of their marketing department.

Despite this, consumer awareness may not always translate into action due to the presence of an 'attitude-behaviour gap'. The term refers to the difference between intentions, as expressed by consumers, to purchase more sustainable or circular products and their actual practices (Camacho-Otero, et al., 2018). Such differences may result when other criteria, such as price and quality, take precedence in consumer decision making (Camacho-Otero, et al., 2018). This suggests that CE credentials alone are insufficient and cannot be relied upon to persuade consumers. In order to compete with traditional, linear products, DfCE solutions must achieve comparable or superior status across a range of criteria. This was reflected in the case of FAIRPHONE, whose representatives point out that circular products must still meet consumer expectations.

> *"So the first one I wrote down was about following design trends in the market versus having a repairable phone […] You don't want to end up with a very weird smartphone that nobody buys because it's too chunky."* (FAIRPHONE)

Additionally, as DESIGNER 5 notes, it is also important that such products remain competitive in terms of price.

> *"Because I think there is some nervousness that, if you put a product into store at that higher price, even though the customer sees that it's sustainable, you know, or that they've used recycled fabric, she then sees another swimsuit that's then a third of the price. You know, is she really going to spend her money there?"* (DESIGNER 5)

The issue of price is also raised by DESIGNER 4 who notes that some consumers may simply not be able to afford circular products should they be priced at a premium, excluding them from opportunities to make purchasing decisions according to their values.

In addition to real differences between circular and traditional, linear products, consumers' purchasing behaviours may also be influenced by perceptions, misconceptions and an unfamiliarity with CE concepts. A lack of understanding surrounding refurbished products, for example, can reduce consumers' willingness to pay, even if they are of comparable quality to new products (van Weelden, et al., 2016). Additionally, where consumers are used to making purchasing decisions based on initial retail price, they may opt against DfCE solutions where the upfront cost is greater, even though they offer considerable savings in the long-term (Preston, 2012). In some situations, psychological factors may also come into play. For example, in the case of sharing models and product service systems (PSS), (Lewandowski, 2016) suggests that consumers may be more reluctant to relinquish full ownership of a product if they share an emotional attachment with it or if it imparts important, intangible value, such as social status. Fears regarding a loss of freedom and control have also been highlighted as potential barriers to the adoption of PSS in line with CE principles (Tukker, 2015). Additionally, the experiences of entrepreneurial CE company, THE LIBRARY OF THINGS, highlighted a number of concerns consumers had when borrowing products as part of a sharing model, stating,

> *"So either – 'I've got it already', 'I'm scared of breaking it' or 'It's too expensive' – one of which we can very easily do something about, of course, which is to lower the prices."* (THE LIBRARY OF THINGS)

These findings suggest that, whilst consumer awareness and interest in CE is an important factor, it cannot be taken for granted that this alone will result in the successful sale of DfCE solutions. It is also essential that such offerings meet consumer expectations and compete effectively with other products in the market on criteria, such as quality and price. It may also be necessary to improve consumer understanding of DfCE business models, particularly where they require changes to deep-set beliefs and behaviours. Failure to do so may limit DfCE implementation.

### 7.4.4 Technology and Infrastructure

Another potential barrier to DfCE implementation is a lack of supporting technology and infrastructure. Technological advancements are essential for realising new product possibilities optimised for a CE (Preston, 2012). Such developments afford innovative product solutions incorporating DfCE strategies, such as product life extension, sharing and utility based business models and the closing of resource loops (de Jesus & Mendonça, 2018). An example of this was the technological innovations developed by FAIRPHONE to create a modular, disassemblable, repairable and upgradable mobile phone handset.

> *"The driving force was to show that it was possible, using the phone and our operations again as a trigger project to convince people and to talk about the durability and modularity of devices."* (FAIRPHONE)

Further to this, technological innovations can also afford improvements to existing circular products, such as enhanced quality and performance, reduced costs or new material options, with the potential to improve market performance (Ritzén & Sandström, 2017). For example, the representative from MUD JEANS described in their interview a new material technology to improve the cyclability of their garments.

> "We're working now on a cellulose-based yarn, so this will also dissolve when you recycle it or when you compost it, but that's not done yet." (MUD JEANS)

Developments such as these may therefore help designers to overcome common DfCE trade-offs as highlighted in Chapter 7.1.

Beyond products themselves, technology also plays an important role in determining the business feasibility and profitability of DfCE solutions through improvements to supporting infrastructure. For example, ICT developments may help facilitate product service systems for a CE, whilst biological, chemical and mechanical engineering innovations can provide new, commercially viable resource cycling options. Technological developments in supporting infrastructure therefore play a key role in addressing gaps and delays between product invention and implementation (de Jesus & Mendonça, 2018). An example of this was identified in the interview with THE LIBRARY OF THINGS, who described developing a bespoke security system to allow their self-service product rental model to operate effectively.

> *"Yeah, so the lock system was something we developed with some design-engineers who were pretty experienced in electronics. They are obviously prototype locks, they're not super visually appealing, but they've helped us understand what a smart-lock needs to do."* (THE LIBRARY OF THINGS)

Technology therefore plays a crucial role, not only in the development of circular products and their refinement but also in creation of the necessary infrastructure to support market success. It is perhaps for this reason that the emergence of technical solutions for a CE, tend to be accompanied by the need for further technological innovation (de Jesus & Mendonça, 2018).

However, as a key enabler of DfCE, technology can also be a limiting factor in terms of the pace of new discoveries and advancements. This can be impacted by challenges, such as the upfront costs and financial risks associated with technological research and development. For example, technology developers may be reluctant to explore new avenues without a proven end-use case to guarantee a return on investment (Ritzén & Sandström, 2017). In light of this, (De los Rios & Charnley, 2017) suggest designers should take a more active role in R&D activities, such as scientific materials development, so that new technologies and DfCE applications can evolve together. Additionally, there can be issues due to the fact that those developing new technologies for a CE are not necessarily the ones that will benefit from it. For example, the development of technologies that make product disassembly easier and more efficient may be a cost borne by producers, whilst cost savings are afforded for those carrying out remanufacturing and resource recovery operations. As a result, there may be insufficient incentives for producers to invest in technological innovation (Dalhammar, 2016). Additionally, where lead times and costs are critical for producers, long and costly research and development activities may be eschewed in favour of existing off-the-shelf solutions, resulting in technological lock-in and stalling the transition from a linear to a circular economy (Byggeth & Hochschorner, 2006).

As demonstrated by these findings, the implementation of DfCE and the success of circular products is somewhat determined by the degree of technological advancement, which can in turn be limited by a range of economic factors that can act as disincentives to technological research and development.

### 7.4.5 Information Availability and Accessibility

A further barrier to DfCE implementation is the unavailability or inaccessibility of information. There are several ways in Firstly, in the case of products, the ability of designers to identify and evaluate circular alternatives, such as materials and components, is dependent on access to the necessary information. As highlighted by DESIGNER 5, such information can prove difficult to get hold of, with that associated with more traditional options being more prevalent.

> *"[...] those materials and those solutions that are out there that are more sustainable, but I think just the fact that the mainstream options are much more accessible and do much more work to reach out to us, it ends up being quite hard to see the alternatives."* (DESIGNER 3)

The quality and format of data and information can also present barriers in the design process. As noted by (Lawson, 2006, p. 81),

> *"Just as it is increasingly difficult to know what is safe and healthy to eat, so designing in an ecologically sound way is surrounded by myths, campaigns and, sometimes, deliberately misleading data. In all this confusion, however, designers cannot usually procrastinate […] They simply must get on and make the decision in as integrated and sensible a way as they can."*

It is therefore evident that the information necessary to support designers in implementing DfCE must not only be made available, but also be of high quality, easy to access and be compatible with the day to day design task.

Beyond the design process itself, there is also a need for top-level business decision makers to have access to information about DfCE and the opportunities available for transitioning from a linear to a circular economy. Not only can information about the potential financial benefits help to incentivise and promote the adoption of CE principles, but accurate information can also help to combat assumptions and misconceptions (Rizos, et al., 2015). From a wider, systems perspective, there is also the need for information sharing between stakeholders. As a CE involves complex systems and collaboration between various stakeholders to facilitate multiple product lifecycles, the sharing of information becomes essential. This was highlighted in the interview with entrepreneurial CE company, THE LIBRARY OF THINGS, who had begun sharing customer feedback and insights gathered through their product sharing model with original equipment manufacturers (OEMs) to inform product design and development. In return, THE LIBRARY OF THINGS required information on how to operate, maintain and repair products effectively from producers.

> *"We cannot disassemble that carpet cleaner and do that process of repair once it's reached that stage. What we keep saying to Karcher is can we please come for a day at your HQ where we learn all of the troubleshooting tricks and all of the preventative tricks, which we can pass onto our borrowers before it gets to the real repair stage. They've been good at sending us that advice via email, but they haven't yet invited us to their HQ, but we will persevere."* (THE LIBRARY OF THINGS)

This example demonstrates the importance of effective transfer and sharing of knowledge, information and innovation between stakeholders throughout the value chain, from design and development and manufacturing, to service providers and remanufacturers. However, this may be limited for a variety of reasons. Firstly, much information is considered sensitive by organisations, which they tend to keep closely guarded (Rizos, et al., 2015). As (Kurilova-Palisaitiene, et al., 2015) explains, this is often due to fear of competition, such as the potential for remanufacturing firms to become competitors, undercutting new product sales. The sharing of information can also be further hampered by a lack of shared understanding, which makes communicating and disseminating information between different stakeholders difficult (Rizos, et al., 2015). Further to this, there may also be a lack of established sharing platforms and mechanisms for transferring information, which means that it's not an integrated function, but something that must be consciously requested or actioned (Kurilova-Palisaitiene, et al., 2015). Finally, as there is a tendency for each stakeholder to focus only on the information that is relevant to their own business activities, there is a lack of motivation for them to manage, store and pass information between stakeholders further up and down the value chain, where it is of no direct use to them (Kurilova-Palisaitiene, et al., 2015). Information is subsequently lost as the product moves along the value chain, from product development to manufacturing, use, service, remanufacturing and secondary use. As a result, those at the later stages, such as remanufacturing and second use must compensate by trying to rediscover and duplicate the same information from further up. (Kurilova-Palisaitiene, et al., 2015). Obstacles, such as these must therefore be overcome if DfCE is to be successfully implemented.

From a consumer perspective, it is also necessary to have access to information about the circularity of products to help them to make accurate and informed decisions. Without traceability and transparency, consumers may be vulnerable to greenwashing campaigns, where companies make exaggerated or misleading claims about the CE credentials of their products. This was highlighted by MUD JEANS as something they were tackling with a transparency initiative,

> *"So every product there is a QR code where you can see where the recycled material comes from and where the new denim has been made. So we try to be fully transparent in that."* (MUD JEANS)

As these results suggest, the availability and accessibility of information is an essential, facilitating component of DfCE throughout every stage of the value chain. Any factors limiting this is therefore likely to present barriers to DfCE implementation.

In summary, this chapter has identified key barriers limiting the adoption and successful application of DfCE, combining a review of the literature with insights from designers and entrepreneurial CE companies. From the results it is evident that barriers to DfCE implementation exist at various levels and are not confined to the role, responsibility or control of the designer (See Figure 7.3). Despite the categorisation of the barriers, the results of the research suggest that there is overlap and interaction between them. For instance, it makes logical sense that technological innovation that renders a circular product offering commercially viable could help to eliminate barriers associated with business viability and profitability. As such, the interaction between barriers would prove an interesting avenue for further study. However, what this research achieves is a clear, high-level overview of the key barriers affecting DfCE implementation, which can then be used to assess the contribution that Industry 4.0 developments and their impact on design may make to overcoming them. The research has therefore met the aims and objectives that it set out to achieve, making a clear contribution to this emerging field.

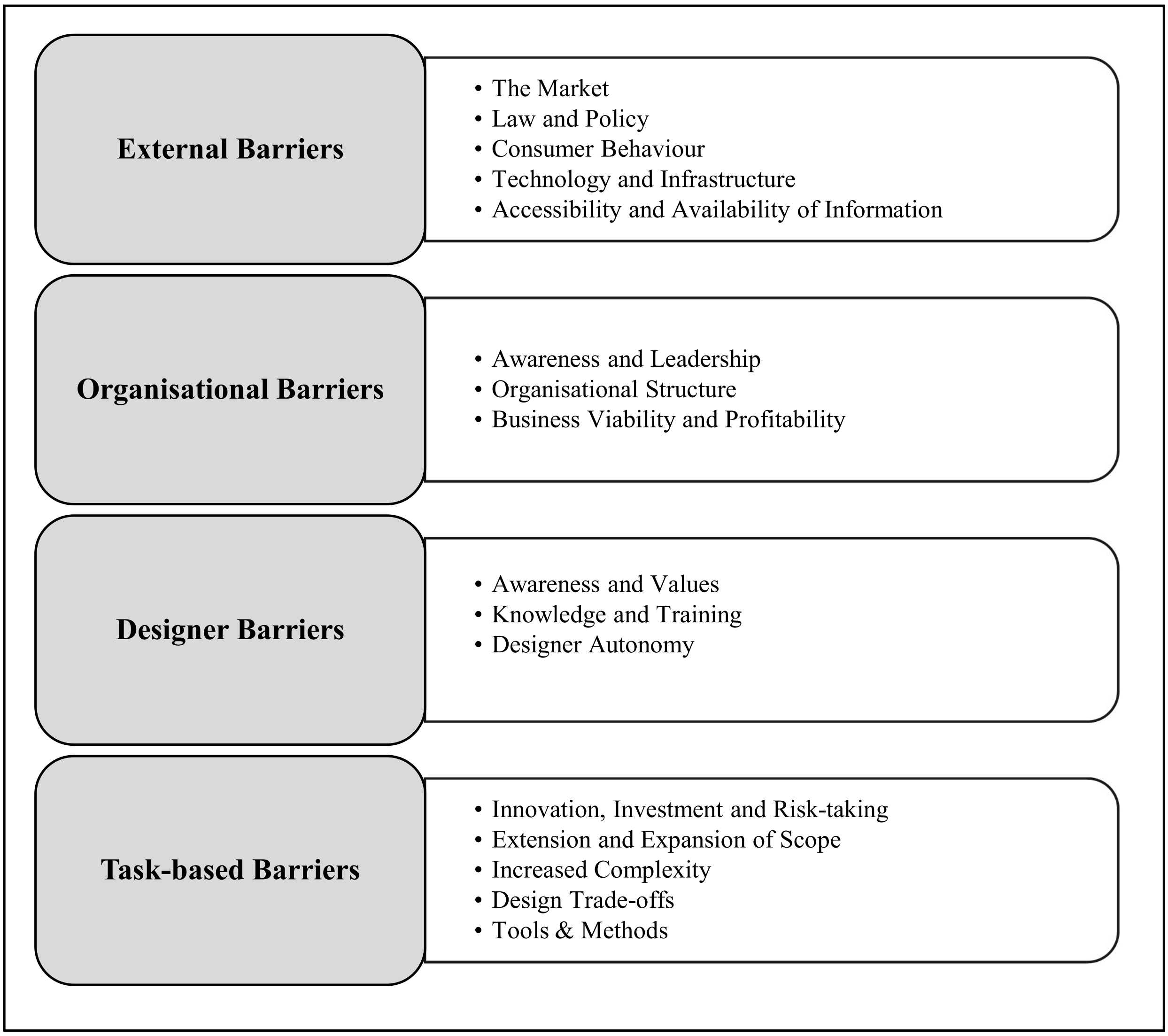


**Figure 7.3** Framework of DfCE barriers.

# Chapter 8. Design Implications of Industry 4.0

This chapter explores the potential impacts that Industry 4.0 may have on design, with a focus on consumer products. As set out in Chapter 4, Industry 4.0 comprises a range of digital technologies which are expected to have a significant transformative impact on manufacturing, leading to a fourth industrial revolution. Having highlighted the close relationship between industrial transformation and design in Chapter 6, reviewing key examples from the past, it follows that Industry 4.0 will also lead to changes in the design of consumer products. A lack of existing literature exploring this particular topic, suggested a gap in knowledge requiring further investigation. As noted by (Gerlitz, 2015, p. 181)

> "*Research on design integration within the industry 4.0 or "internet of things" phenomena from [a] strategic management perspective is still marginalised."*

In order to fill this, an integrative literature review was employed in combination with a series of instrumental case studies. As explained in Chapter 5.4.2, an integrative literature review was selected as a means of overcoming the lack of existing material dedicated to the specific topic of focus. This was conducted by searching for mention of design in articles generally concerned with Industry 4.0. The scope was also broadened to search articles on design and the specific technologies associated with Industry 4.0, as identified in Chapter 4. The series of instrumental case studies, focused on early adopters of Industry 4.0 technologies, then supported the integrative literature review by providing detailed contextual examples of how these were transforming design in practice. The results are presented thematically, organised around four key avenues by which Industry 4.0 is influencing the design of consumer products;

- The transformation of manufacturing
- New product possibilities,
- The evolution of the design process
- New business model possibilities

The purpose of this chapter is therefore to map the ways in which Industry 4.0 may impact the design of products, so as to compare these findings to the DfCE barriers previously identified in Chapter 7. This will enable a comparative analysis to be conducted, helping to build an understanding of how Industry 4.0 may aid or further limit the implementation of DfCE (Chapter 9).

## 8.1 Transformation of Manufacturing

As explored in Chapter 6, since the industrial revolution, the design of consumer products has evolved according to the economic principles of the linear economic model; centralisation of production, standardisation of products and mass production following the economies of scale principle. However, as noted in Chapter 4, Industry 4.0 is expected to see a reversal of these principles as technologies, such as digital fabrication and self-guided, automated assembly facilitate decentralised production, mass customisation and economically feasible batches of one. It is therefore evident that fundamental changes to manufacturing capabilities, as a result of Industry 4.0, have the potential to transform, not only the physical means by which products are fabricated, but also the economic dynamics of production, which ultimately determine what is feasible and profitable to produce (Figure 8.1).

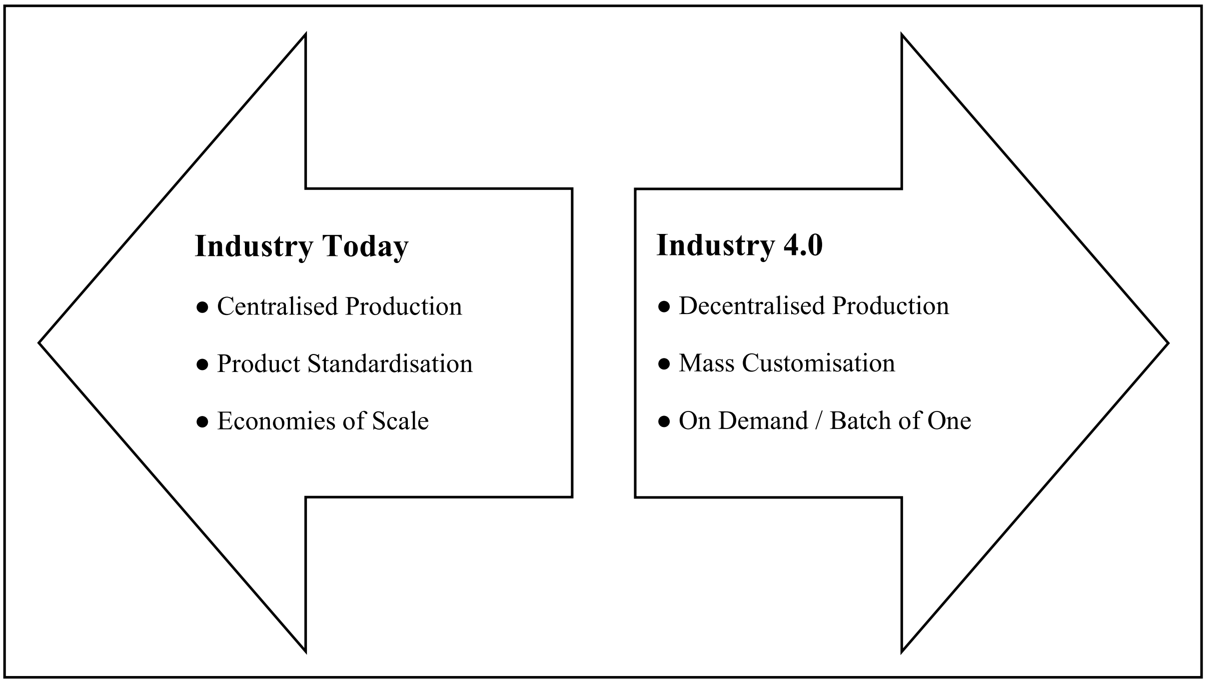


**Figure 8.1** The dynamics of production in industry today and Industry 4.0.

Developments in digital fabrication technologies, including 3D printing, laser cutting, CNC[14] machining and robotic assembly are beginning to facilitate the direct and automated translation of data into physical objects, components and products. This is achieved through cyber physical systems (CPS) in which digital information instructs the movement of fabrication equipment, such as a printing nozzle, laser beam, router or robotic arm, in patterns according to individual

[14] CNC is an acronym for Computer Numerical Control whereby the physical movement of machines follow pre-programmed sequences according to digital instructions (Newman, et al., 2008).

product specifications. This enables extensive variation of outputs at the individual process level. The ability to store this information in embedded readable devices, such as RFID[15] chips is also being further developed to allow products to guide themselves through production (Azizi, et al., 2018). This not only allows each fabrication process to be tailored to the requirements of each product, but it also enables the coordination of different combinations of manufacturing processes and the automated navigation of products-in-progress between them (Zhong, et al., 2017) (Gilchrist, 2016). The success of such integration is dependent on key factors, such as the compatibility and interoperability of communication devices and machinery, however, if achieved, manufacturing becomes significantly more flexible, agile and reconfigurable (Zhong, et al., 2017).

One of the outcomes of these changes to manufacturing in Industry 4.0, is that the low-cost and timely production of custom products, known as mass customization, becomes a real possibility (Zawadzki & Zywicki, 2016). Mass customization presents several implications for economic dynamics, which are likely to influence business decisions and, ultimately, the design of products. Firstly, it eliminates the need for tooling and the setting up of rigid production processes, as required in traditional manufacturing, avoiding the associated high overheads and long lead times (Bahrin, et al., 2016). As a result, it is no longer necessary to produce large quantities of products in advance in order to spread these costs across more units, as per the economies of scale principle. Digital fabrication therefore makes the production of small batches of products both technically and economically feasible Figure 8.2.

[15] RFID is an acronym for Radio Frequency Identification, which is a means of conveying readable information like a barcode, but without the need for visibility (Pio Di Monte, 2016).

**Figure 8.2** Economies of scale in mass production and digital fabrication[16]. Adapted from (Yao & Lin, 2015).

This could in turn help to encourage innovation (Bahrin, et al., 2016). Early digital fabrication technologies, such as 3D printing have been in use for several years to facilitate rapid prototyping, allowing designers to test and evaluate new innovations quickly and cost-effectively before investing in mass manufacturing. However, as these technologies improve and are able to create market-quality products, companies may be able to test innovations in the market in small batches or even on an individual product basis before investing in their mass manufacture (Gerlitz, 2015). In such circumstances, product innovation becomes achievable with minimal initial outlay and risk, avoiding not only tooling and set-up costs, but also the need to meet production minimums. Beyond rapid prototyping and supporting the production and testing of new product innovations in the market, digital fabrication enabled mass customisation may also be adopted as a main means of production. As demonstrated by Figure 8.2, this is advantageous for short production runs of niche products or those with a high degree of variability, with cost per unit remaining constant irrespective of how many are

[16] This model assumes that core factory facilities are already in existence.

produced (Yao & Lin, 2015). A further benefit of digital fabrication is that it enables custom products to be manufactured on demand, eliminating the need for companies to hold stock of finished products, as would be required in the case of mass production. The sequence of events therefore changes, from design, production and then sales to design, sales and then production. This not only further reduces the up-front investment required for manufacture, which can prove prohibitive for the production of smaller batches using traditional means, but it also reduces the risks associated with mass producing stock of a new product without the guarantee that it will sell. As such, digital fabrication enabled mass customisation may further drive product innovation and differentiation by providing a cost effective means of producing small batches of custom products with minimal risk (Flores Salvidar, et al., 2016). In addition to generating greater interest in innovation from existing companies, this may also lower barriers to market entry for smaller enterprises and even design entrepreneurs.

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**Plate 8.3** A robotic arm operates a stack of 3D printers at Voodoo Manufacturing (Voodoo Manufacturing, Inc., 2018).

An early provider of this manufacturing model is Voodoo Manufacturing, a New York based company that aims to make fabrication *"as fast, affordable and scalable as software"* (Voodoo Manufacturing, Inc., 2018). They achieve this through a warehouse filled with more than 200 3D printers manned by robotic arms to enable the automated removal of completed prints and restocking of materials (Plate 8.3) (Schwartz, 2017). As a result, they are able to reduce costs and offer competitive prices for batches of 1 up to 10,000 units when compared to traditional mass manufacture using injection moulding. Voodoo Manufacturing therefore provide a means of manufacturing products that is not only economically feasible for a new wave of custom and niche products, but also accessible to a wider range of designers and even individuals (Schwartz, 2017). Voodoo Manufacturing's services are then made even more convenient through the provision of a Voodoo Manufacturing app that facilitates the intuitive design and development of 3D products, which designers can list on their online store via the Shopify marketplace. From here, customers can order a product, which Voodoo Manufacturing will then automatically fabricate on demand, packaging and delivering the order direct to the customer (Mustin, 2018). This provides a one-stop-shop for anyone to have their products made with minimal up-front costs and financial risks in what can be described as 'manufacturing as a service' (Plate 8.3). As such, the Voodoo Manufacturing's services are currently limited to the fabrication of products that can be manufactured by Fused Deposition Modelling (FDM)[17] 3D printers, however, the company envisions further developments in digital manufacturing revolutionising the whole industry, as a more diverse range of products and those of greater complexity are able to be materialised following a similar model.

> *"Beyond 3D printing specifically, we believe in a digital future for manufacturing where lead times are short, iteration cycles are fast, products can be customized, and runs can start small and scale instantly."* (Voodoo Manufacturing, Inc. In: (Schwartz, 2017).

[17] Fused Deposition Modelling is a form of 3D printing in which layers of (usually a melted) material are deposited and fused to lower layers successively to form a three-dimensional object (Novakova-Marcincinova & Kuric, 2012).

**Figure 8.4** Voodoo Manufacturing's 'manufacturing as a service' offering (Voodoo Manufacturing, Inc., 2018).

In addition to improving the affordability and accessibility of manufacturing, Industry 4.0 technologies, may also allow for greater flexibility in design. This is because in traditional manufacturing, there are economic benefits to be gained from incorporating standardised components and optimising designs for rigid sequences of mass production processes in order to gain economies of scale. In contrast, Industry 4.0 is expected to see the networking of digital fabrication processes enabling each product to navigate its own production pathway (Gilchrist, 2016). This is made possible with the embedding of detailed instructions within products-in-progress using technologies, such as RFID chips, QR codes[18] and NFC[19] devices (Azizi, et al., 2018). These instructions are then able to be read by smart manufacturing equipment, to assist in the recognition of diverse in-coming products-in-progress, carry out the specific fabrication process required and then direct the product-in-progress to the next appropriate stage of its manufacture (Makris, et al., 2012). As a result, the design of products is not as constrained by rigid production and assembly lines, providing a greater variety of flexible options for product materialisation.

The embedding of instructions for product manufacture within products themselves may also result in changes beyond simply controlling the production process, with further implications for design. Supply chains in a traditional, linear economy are often complex and opaque due to the centralised, globalised and multi-tiered nature of production. This can hinder traceability and transparency in relation to product provenance (Francisco & Swanson, 2018).

Digital fabrication may therefore present an opportunity for improvement, as it enables a detailed account of a product's manufacturing history to be recorded as digital information. In instances where trust is lacking and objectivity is required, as in the case of auditing or proving the authenticity of a product, these digital records can be further verified using Blockchain[20] to generate smart contracts[21] (Francisco & Swanson, 2018).

An early adopter of Blockchain technology for these purposes is London based company, Provenance. They provide a track and trace service to manufacturers and producers to automatically capture and document the digital chain-of-custody of their products as they move through the production process, using technologies, such as embedded RFID chips and QR codes (Plate 8.5) (Project Provenance Ltd, 2015). Information collected ranges from the sourcing of raw materials through to product attributes and impacts of fabrication, with Blockchain employed to ensure these records are immutable, unchangeable and auditable. Provenance then provides a platform through which the digital chain-of-custody for each

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[18] A 'Quick Response (QR) code' may be described as a 2-dimensional barcode used to rapidly encode and decode data using a reading device (Rouillard, 2008).

[19] 'Near Field Communication (NFC)' may be defined as communication *'between two compatible devices over a very short communication range'* (Coskun, et al., 2012).

[20] 'Blockchain' may be defined as a *'[…] distributed ledger technology managed in a decentralized manner (often autonomously)'* (Cong & He, 2019).

[21] 'Smart contracts' may be defined as *'a computerised transaction that executes the terms of a contract'* (Cong & He, 2019).

product can be retrieved and viewed by other stakeholders in the value chain as well as regulators, auditors and consumers (Project Provenance Ltd, 2015).

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**Plate 8.5.** Blockchain and QR code technologies implemented by Provenance (Project Provenance Ltd, 2016).

By gaining visibility of this information, designers may be better equipped to make informed design decisions. Additionally, granting consumers access may also influence their purchasing decisions, which could in turn lead to companies adjusting their design briefs and supply chains.

The potential to capture additional product information, as facilitated by Industry 4.0 technologies, may also present opportunities for smart remanufacture and repair services at later stages of the product lifecycle. The embedded RFID chips or QR codes used to direct initial smart manufacturing processes, for example, provide a means of retaining product-specific construction information, such as product specifications, materials and components, with products throughout their life cycle. Additionally, in the case of smart, connected products, embedded sensors can facilitate the gathering of information related to products during the use phase, including condition, functionality and service or repair history (Fang, et al., 2014). As a key challenge associated with the provision of remanufacturing services is dealing with the heterogeneity of products in terms of both type and quality, this added information could significantly improve the efficiency of assessing incoming products and identifying the reparatory processes required (Fang, et al., 2014). Further, as this information is machine readable, there is the potential to support automated remanufacture and repair services, utilising agile and flexible digital fabrication technologies. This may in turn improve the economic feasibility of such activities by reducing manual labour costs (Yang, et al., 2018). Efforts to develop these technologies have already begun in the case of high-value products, such as in the automotive and aerospace industries (Yeo, et al., 2017). An example of an early adopter of smart remanufacturing technologies is German company, Hamuel Reichenbacher, who have developed the world's first hybrid turbine blade and turbo fan remanufacturing machine. By combining both additive and subtractive smart manufacturing , the machine is able to automatically and accurately restore parts to their original form through a coordinated process of assessment, deposition and milling (HAMUEL Maschinenbau GmbH & Co. KG , 2018). Developments such as these suggest that Industry 4.0 will see manufacturing transition from a descrete activity solely for the purpose of fabricating products, to an ongoing process that extends throughout the product lifecycle (Porter & Heppelmann, 2015). This may in turn present opportunities for retrofitting existing products with custom upgrades, adjustments and improvements facilitated by agile digital fabrication processes. This concept is explored by Terzioglu (2019), who explored the application of 3D printing technology to repair, improve and alter consumer products, including apparel, homewares and toys, through the creation of custom parts and components. Whilst these were applied to products manually, it is possible that this process could be automated following the remanufacturing example above. This suggests that in Industry 4.0, design may no longer be concerned solely with the development of original products, but also with the design of upgrades, adjustments and improvements that can be applied to existing products retrospectively.

A further transformation of manufacturing resulting from the integration of Industry 4.0 technologies is the reorganisation of value chains. As identified in Chapter 6, historically, the trend has been for manufacturing to become increasingly centralised, owing to the economies of scale principle. The advent of ICT has then enabled companies to outsource production to distant, low-wage economies in order to achieve further cost savings. With manufacturing becoming increasingly automated in Industry 4.0, there exists the potential for digital fabrication to present a more cost effective means of production compared to traditional manufacturing processes, even in low-wage economies (Strange & Zucchella, 2017). An example of this is Sewbo, a Seattle-based start-up that has pioneered the automation of garment construction. Through the application of a dissolvable fabric treatment, pre-cut textile pattern pieces are able to be temporarily stiffened into sheets. This then enables digitally controlled robotic arms to position and sew them together into a finished product (Plate 8.6), automating the sewing process and opening new possibilities for garment customisation (Sewbo, Inc., 2016).

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**Plate 8.6** Sewbo's robotic arm sewing a garment from stiffened textiles (Sewbo, Inc., 2016).

Where automation of production out-competes labour from low-wage economies in terms of cost, there exists a strong economic incentive for companies to re-shore[22] manufacturing processes (Strange & Zucchella, 2017). In addition to financial gains, this could also offer further benefits. Relocating production closer to the point of consumption, for example, may eliminate the need to ship components and products between distant locations, shortening lead times (Moradlou, et al., 2017). This could help companies to be more responsive to changing consumer preferences and to meet consumer delivery expectations in the case of customized products, which must be produced on-demand (Sodhi & Tang, 2017). There may also be organisational benefits to be gained from simplifying supply chains, increasing the

[22] Re-shore: The process of moving manufacturing operations to the location in which the parent company is situated (Moradlou, et al., 2017).

dependability of manufacturing and increasing the extent to which companies have control over production (Moradlou, et al., 2017). An example of an early adopter of digital fabrication for the purposes of re-shoring production is German sportswear company, Adidas' SPEEDFACTORY facility (Plate 8.7). Through the implementation of digital fabrication technologies, they have begun to revolutionize the way in which their products are manufactured, starting with a range of footwear customised for the needs of consumers in different cities around the world. As a result of the cost savings afforded by automation, they have been able to bring manufacturing back to Germany whilst providing consumers with customised products achieving greater speed, precision and responsiveness (Adidas AG, 2017). The SPEEDFACTORY facility is also being used as a means of developing and testing new product co-creation models and design innovations (Adidas AG, 2017).

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**Plate 8.7** Adidas' SPEEDFACTORY, incorporating robotics and digital fabrication (Adidas AG, 2018).

In addition to the re-shoring of production, Industry 4.0 technologies are also resulting in further changes to the structure and arrangement of manufacturing processes. The ability to digitally fabricate products from digital information, without the need for tooling and the setting up of rigid production lines could see manufacturing become increasingly decentralised and flexible. As a result, product designs are no longer confined to being produced by a specified manufacturer and can instead be produced anywhere. An example of a company transitioning to such a model is London-based Opendesk. Through their online platform and market place, designers upload digital furniture designs from which consumers can choose. For some designs this also includes an option to customise dimensions with the help of an augmented reality app that allows consumers to visualise the furniture in situ by superimposing a 3D rendering over a camera image using a phone or tablet (Worley, 2018). The consumer then selects a local manufacturer from a geographically diverse range of options listed on the platform, who fulfils the order on demand using CNC milling to cut component parts from sheet material before assembling and delivering the finished product to the consumer. This method of connecting designers, manufacturers and consumers via a platform provides consumers greater control over when and where their products are produced (Plate 8.8) (Opendesk, 2019).

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**Plate 8.8** Assembly of CNC milled components of an Opendesk table (Opendesk, 2018).

In addition to formalised platforms and marketplaces, like Opendesk, peer-to-peer production facilities are also beginning to emerge where anyone with a digital design file can fabricate products on demand. These include Makerspaces and Fab Labs, which are workshops equipped with both traditional and digital fabrication equipment available for individuals to hire and use (Browder, et al., 2019). Whilst manual tools and machines have long been available for the purposes of self-fabrication, the introduction of shared spaces and digital fabrication technologies are helping to overcome barriers by cutting down the time and labour involved in fabricating a product, reducing the need for specialist, artisanal skills and lowering machinery costs through shared access models (Browder, et al., 2019). As a result, consumers are becoming producers themselves in a phenomenon referred to as *'pro-sumption'*[23]. In addition to accessing facilities, such as Makerspaces and Fab Labs, in person, prosumers can also have their designs produced remotely by accessing automated, digital fabrication technologies and submitting digital design files online. For example, Netherlands-based start-up, 3D Hubs has become the world's largest network of manufacturing services, hosting individuals and companies with machinery, such as 3D printers and CNC milling machines, that individuals can enlist to manufacture and deliver small batches of products on demand (3D Hubs, 2019). These peer-to-peer production facilities offer prosumers the freedom and flexibility to produce any digital design imaginable, without being restricted to designs offered on a particular platform, in turn, opening the design and fabrication of bespoke products to virtually anyone.

It is therefore evident that Industry 4.0 and associated developments are already beginning to have significant transformational impacts on the manufacture of consumer products, which in turn present implications for design. Digital fabrication is enabling the direct translation of digital information into physical objects, which makes on-demand, small batch production and mass customisation, not only technically possible, but also economically feasible. By doing so, financial, scale, time and skills-based barriers that previously limited manufacturing to companies able to place large orders for standardised products are being eliminated. This may have the impact of encouraging innovation by reducing associated costs and risks and providing the opportunity to design and manufacture to a wider array of individuals and entities. Further, smart manufacturing, whereby each product's progression through the production process is tracked and recorded may present opportunities for greater transparency and traceability in value chains, generating insights that can help to inform designers and consumers alike. This information may in turn influence design and purchasing decisions, respectively. Finally, the capture and retention of product information from both smart manufacturing processes and smart products in use may also support the extension of manufacturing beyond the initial production of products to later stages of products' lifecycles, to include remanufacture, repair and upgrade (Lopez de Sousa Jabbour, et al., 2018). As a result, design may include tasks, such as the development of improvements to be retrofitted to existing products, in the future.

[23] 'Pro-sumption' occurs as consumers take an increasingly active role in production processes, including design, manufacture and distribution (Rayna & Striukova, 2016).

## 8.2 New Product Possibilities

With Industry 4.0 technologies affording new manufacturing capabilities, new product possibilities are also emerging, presenting new avenues for design. One of these is the ability to create new structures and geometries using additive manufacturing technologies, such as 3D printing. As the process involves creating products from the bottom-up, layer by layer, there is the possibility to nest parts within one another; something that wouldn't be possible using traditional manufacturing techniques, such as injection moulding or subtractive methods (Thompson, et al., 2016). This opens up opportunities for consolidating parts, which would otherwise need to be assembled from multiple components. As a result, functional, moving mechanisms can be created in a single process, simplifying manufacturing considerably (Thompson, et al., 2016). An example is provided by Ion, et al. (2016) who developed a number of operational products, ranging from a door handle to a set of pliers (Plate 8.9), which are created using a 3D printer to deposit a matrix structure. By varying the pattern they are able to adjust the thickness and rigidity of different sections of the print, which enables the single part to behave as a machine.

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**Plate 8.9.** Functional 3D printed pliers formed of a single component (Hasso Plattner Institut, 2019).

Another technological development with the potential to realise new product possibilities is multimaterial 3D printing (Thompson, et al., 2016). This may enable electronic components and products comprising functional circuitry to be created layer by layer using a 3D printer with the capacity to deposit different materials (MacDonald, et al., 2014). Whilst there exist some technical limitations given current 3D printing technology, it is expected that further technological advancement will eventually enable the creation of suitably high-quality, market-ready products (MacDonald, et al., 2014). A further development in terms of new product possibilities in Industry 4.0 is the potential for individualised and customized products. As explained in Chapter 8.1, 'batch of one' production is becoming both technically and economically feasible with the advent of smart manufacturing, digital fabrication technologies and robotic assembly. This could see niche product designs that weren't previously viable in terms of mass manufacture enter the market, freeing designers from many existing mass manufacturing constraints (Tsakiris, et al., 2018). It is therefore evident that, just as the advent of plastic and injection moulding gave rise to new product possibilities in the past (Chapter 6), the manufacturing capabilites afforded by Industry 4.0 technologies are making new avenues for product design available.

In addition to affording new manufacturing capabilities, technologies associated with Industry 4.0 are also bringing about new product possibilities by being directly incorporated into products themselves. The merging of cyber physical systems with consumer products through the embedding of sensors, chips, actuators, computational capabilities and internet connectivity is giving rise to a new generation of 'smart products' (Schmidt, et al., 2015). These smart products are able to capture information about themselves and the physical world around them through various onboard sensors (Schmidt, et al., 2015). This information can include product location, identity, composition and condition, as well as use and service history (Schmidt, et al., 2015). By being connected to the internet, smart products become part of the Internet of Things (IoT) and are able to relay these insights in real time to consumers, manufacturers, and other stakeholders in the value chain, including service providers, as well as being able to receive information in return (McKnight, 2017). These developments have several implications for design.

Firstly, by providing visibility past the point of sale, during the product use phase, designers gain valuable insights, helping to identify issues and opportunities for improvement, as well as develop appropriate solutions and future upgrades. Further to this, it also becomes possible to adjust products remotely and post-purchase via software updates and the download of digital applications (McKnight, 2017). This is significant as it enables the continual improvement of existing products already in circulation by providing advantages, such as additional functionality, interface customisation and improved user experience. An example of a company already implementing this concept is US based electric vehicle manufacturer, Tesla. After an issue was identified with the emergency breaking system in their Model 3 vehicle (Plate 8.10), which led to poor safety reviews, Tesla was able to deliver a solution remotely and instantaneously for all vehicles, including those already sold, with an over-the-air software update (Marshall, 2018). As a result, a 19 feet reduction in vehicle stopping distance was achieved without the need for any physical, mechanical adjustment at all (Marshall, 2018). Developments such as these could enable smart products to actually improve over time, rather than depreciating in value or becoming obsolete (Porter & Heppelmann, 2015).

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**Plate 8.10** Tesla Model 3 electric vehicle (Tesla, 2019).

In addition to software updates that improve performance and functionality, smart products may also enable the ongoing transformation and customisation product aesthetics. An example of early innovators in this area are New York based start-up, ShiftWear. They are in the process of developing a range of footwear with embedded flexible screens, which will allow consumers to upload custom imagery and effectively change the look of their shoes on-demand (Plate 8.11) (ShiftWear (TM), 2018). This is facilitated by a smartphone application connected to the shoes via Bluetooth to provide an intuitive user interface (ShiftWear (TM), 2018). By controlling the aesthetics of products digitally, endless, ongoing customisation becomes a real possibility. A further benefit of this is that by controlling product adjustments remotely via another device, such as a tablet or smart phone, the products themselves can be simplified, by reducing the number of physical onboard controls (Porter & Heppelmann, 2015).

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**Plate 8.11** ShiftWear product prototype (Shiftwear (TM), 2017).

A further opportunity presented by smart products is the potential for value to be realised as a result of the connectivity and interactivity between them. Facilitated by machine-to-machine communication and the sharing of information in real time, product operations can be synchronised and coordinated to provide new functions using existing hardware. An example of this is an application created to link Phillips Hue lighting products, which allow consumers to adjust the colour scheme of their lighting at home, with Netflix, a video streaming service that plays on smart television sets (Clauser, 2014). As a result the hue of the lighting automatically changes in line with the dominant colour displayed on the screen to create a more immersive viewer experience (Plate 8.12) (Clauser, 2014).

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**Plate 8.12.** Philips Hue lighting and Netflix video streaming service (Hue Home Lighting, 2014).

In light of the opportunities for ongoing improvement, aesthetic customisation, and combined functionality that smart products present, it's possible that in future, product differentiation will increasingly focus on the digital level, with a simplification of rigid, physical attributes, as this affords greater freedom for changes and new product features to be implemented at a later stage (Tseng, et al., 2018). The value of products therefore increasingly shifts from their physical manifestation to their operating systems and their capacity to connect and interact with wider networks and systems of products and services (Sniderman, et al., 2016). As noted by Porter & Heppelmann (2015, p. 6),

> *"Smart, connected products require a rethinking of design. At the most basic level, product development shifts from largely mechanical engineering to true interdisciplinary systems engineering"*

It is therefore evident that the technologies associated with Industry 4.0 will not only impact on how products are manufactured but will also give rise to entirely new product possibilities. These include product geometries and assemblies facilitated by 3D printing that were not previously possible using traditional manufacturing techniques, as well as a new generation of smart products as Industry 4.0 technologies are incorporated into consumer products themselves. These changes present a range of new design avenues to be explored, which may result in new product designs emerging in the future.

**8.3 Evolution of the Design Process**

Another way in which Industry 4.0 technologies may influence product design is by transforming the actual process of designing products. Firstly, the expansion of the IoT and the development of smart products has the potential to provide designers with visibility of products past the point of sale. As explained in Chapter 8.2, smart products contain embedded sensors, which enable them to capture information about themselves and their environment. This information is then relayed to a computer or database via internet connectivity (Kiritsis, 2011). The information generated by smart products therefore extends beyond static, descriptive data about a product to include dynamic product data, such as how often a product is used and in what contexts, how efficiently it is functioning and operational diagnostics (Resatsch, et al., 2008). As a result, this may provide designers with greater insights into the later stages of the product life-cycle, including use and end of life phases (Figure 8.13). As noted by (Porter & Heppelmann, 2015, p. 10),

> *"The data from smart, connected products provides a much sharper picture of product use, showing, for example, which features customers prefer or fail to use. By comparing usage patterns, companies can do much finer customer segmentation - by industry, geography, organizational unit, and even more granular attributes."*

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**Figure 8.13** Informed design in Industry 4.0. Adapted from (Flores Salvidar, et al., 2016).

This information may be individualised, aiding in the identification of consumer-specific needs and requirements, useful for customisation (Flores Salvidar, et al., 2016). Alternatively, data generated by multiple smart and connected products may be combined and analysed together in order to provide more generalised information. Through the use of Big Data analytics and Cloud Computing[24], large volumes of data can be analysed in order to identify patterns, providing diagnostic, predictive and prescriptive insights (Porter & Heppelmann, 2015). This added information afforded by smart, connected products and the IoT may therefore result in better informed design processes and reduce the need for time and resource intensive manual data collection (Flores Salvidar, et al., 2016).

A further development involves changes to the way in which information and insights are delivered to designers. The outputs from Big Data analytics and cloud computing may be merged with computer-aided product development (CAD) software using artificial intelligence[25] to enable the consequences of design decisions to be determined instantaneously and automatically. As noted by (Sun & Zhao, 2017, p. 1),

> *"Unlike the traditional design approach where designers rely on intuition and tacit knowledge to solve problems, computational design enables encoding design*

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[24] Cloud Computing: See Chapter 4.3.5
[25] Artificial Intelligence: See Chapter 4.3.7

*decisions using computer language and predefines the steps needed to achieve a result."*

An example of this is AutoDesk's NETFABB software, which allows designers to digitally simulate designs of 3D printed parts. This enables potential faults and weaknesses to be identified and the performance properties of the final parts to be calculated automatically, prior to prototyping or fabrication (Autodesk Inc., 2019). As a result, designers have the advanced opportunity, as well as the information required, to make necessary adjustments and achieve a successful product. The information is also delivered in a convenient and accessible way, which is well integrated with the design process (Autodesk Inc., 2019). As it has been estimated that 80% of design time is currently spent completing routine tasks, simulation technologies such as these, which integrate information with CAD software, could free designers to concentrate on the more creative aspects of the design process (Zawadzki & Zywicki, 2016). Further to this, developments in virtual and augmented reality may also enable the consequences of design decisions to be conveyed in increasingly intuitive ways, whilst voice activated, and gestural controls help to simplify the design process and make it more accessible. In a collaboration between Nike, Dell, Ultrahaptics and Meta a near-future vision for design is presented, demonstrating the potential for industry 4.0 technologies to simplify and streamline the design process for creating footwear. The demonstrational video depicts designers using voice commands to retrieve consumer data, such as sizing, which is presented visually in augmented reality. Designs are simulated and changes are instantaneously visualised, including material selections and colour pallets. Product testing, in this case running, is carried out in virtual reality, complete with diagnostic data (Plate 8.14).

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**Plate 8.14** Future vision for smart, virtual design by Nike, Dell, Ultrahaptics and Meta (Ultrahaptics, 2018).

This vision is aligned with the suggestion by (Gerlitz, 2015) that the integration of Industry 4.0 technologies combined with on-demand, custom manufacture will see a shortening of product development cycles. As such, manually carrying out activities, such as planning, research, testing and prototyping may no longer be necessary for bringing new innovations to market. These developments suggest that the design process will become increasingly simplified, streamlined and intuitive.

Extending the role of technologies, such as artificial intelligence and simulation, within design is giving rise to new advances in generative design capabilities. Generative design involves setting certain design parameters required for a product and then using complex algorithms to generate potential designs that meet those parameters (Lobos, 2018). This approach can be used for both adjusting existing designs, such as reducing excess weight by incorporating lattice structures, or for creating entirely new forms. This provides two key benefits. The first is the automation of the design process, which enables magnitudes more potential design options to be explored than would be possible to achieve sketching them manually. This speed is something that (Zawadzki & Zywicki, 2016) suggest will be essential to handle mass customisation and individualised products with short turnaround times. The second is the way in which outputs tend to resemble natural forms, with the approach being similar to evolution in nature (Lobos, 2018). Both processes can be employed iteratively any number of times to further improve and revise designs. In such scenarios, the role of the designer is to determine the desired outcomes for the design and to set the necessary parameters, as well as evaluating the resulting designs and further refining parameters as required. An example of this is the Elbo Chair developed using Autodesk Research's generative design system, Project Dreamcatcher (Plate 8.15) (Autodesk Inc., 2016).

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**Plate 8.15** Elbo Chair developed using Autodesk Research's generative design system (Autodesk Inc., 2016).

To design this chair, creators, Arthur Harsuvanakit and Brittany Presten, began by uploading a digital design of an existing model for inspiration. Next, they determined the performance requirements of the chair, such as the minimum load and ergonomic requirements (Rhodes, 2016). From here, the generative design system developed hundreds of potential designs, improving aspects, such as material weight and joint strength with each iteration. At various points throughout the process, the creators would select a particular design and re-run the process, using it as the new baseline until they were happy with the results. Once the final design was chosen, the components were then able to be digitally fabricated using CNC milling, before being assembled (Rhodes, 2016). The design was therefore not generated by the designer, but by software, with the role of the designer to simply guide the process and evaluate outcomes. As noted by (Rhodes, 2016), such an intuitive approach to design may be carried out by designers or even consumers themselves.

In addition to automating the design process and significantly reducing development time, generative design may also produce designs that wouldn't be possible to conceive using traditional design methods. An example is presented by Michael Hansmeyer's 'Computational Architecture' where algorithms are used to create incredibly intricate geometric designs, which are then produced using digital fabrication technologies (Plate 8.16) (Michael Hansmeyer: Computational Architecture, 2018).

**Plate 8.16** Digital Grotesque II. Computation Architecture by Michael Hansmeyer (Michael Hansmeyer Computational Architecture, 2018).

Whilst Hansmeyer's designs have largely been confined to large scale applications, including interiors, set designs, and architectural structures, the same principles could be applied to consumer products (Michael Hansmeyer: Computational Architecture, 2018). As such, generative design is not only capable of simplifying and expediting the design process, but it may also present a means for navigating previously unexplored avenues for design.

Beyond changes to the design process itself, the integration of Industry 4.0 technologies may also transform who is involved in the design of products. Firstly, developments in digital design, simulation and augmented and virtual reality may facilitate greater collaboration (Arrighi & Mougenot, 2019). As previously highlighted, the increasingly intuitive nature of design could make the process more accessible to non-designers with different backgrounds and specialisms. This has the potential to introduce new and diverse perspectives into the design process and to help break down knowledge silos. The ability for digital simulations and visualisations to reflect design changes in real time may also facilitate remote collaboration between geographically dispersed individuals by enabling them to work on the same design iteration simultaneously (Arrighi & Mougenot, 2019).

Further to this, Industry 4.0 is expected to bring about greater involvement of consumers in the design process as a result of new mass customisation opportunities afforded by smart manufacturing, digital fabrication and robotic assembly. As mass customisation offers a point of differentiation for companies, they may increasingly seek to offer customisable products to consumers (Wang, et al., 2017). This could transform the goals of the design task, from amalgamating the needs of whole markets into a single product design, optimised for mass manufacturing to allowing individual consumers to guide the design process according to their specific needs and preferences. One way in which this can be achieved is for designers to develop modular products with interchangeable parts and components that consumers can select from (Rong, et al., 2017). Custom product assembly is then facilitated by Industry 4.0 technologies, such as RFID and robotic assembly with products guiding themselves through their own bespoke assembly process (ElMaraghy & ElMaraghy, 2016).

Taking customisation a step beyond the selection of pre-determined options, Industry 4.0 technologies such as simulation and digital fabrication may allow consumers direct control over product attributes (Arrighi & Mougenot, 2019). Designers would then be tasked with determining and defining the parameters within which adjustments could be made, whilst still achieving a successful product. An example of an early adopter of this technology is London based garment customisation start-up, UNMADE (Plate 8.17). In what they refer to as ‘curated customisation’, consumers are able to freely adjust the colour, scale and position of pattern designs on knitwear pieces using an online platform that displays their creation in real-time as they make changes to the design (UNMADE, 2018). This enables the consumer to create one-of-a-kind garments, which are then materialised using digital knitting machines (UNMADE, 2018).

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**Plate 8.17** UNMADE garment customisation platform (UNMADE, 2018) .

With Industry 4.0 technologies making the design process increasingly intuitive and accessible as well as enabling the economically feasible production of batches of one, consumers may even take control of the design process themselves, becoming 'prosumers'[26] (Tian, et al., 2017). Individuals may identify their own personal product needs, develop a suitable, custom design using digital CAD software and send this to a local manufacturer for automated, on-demand production (Tian, et al., 2017). A variety of publicly accessible digital fabrication services are already emerging, providing individuals with the ability to realise their own DIY designs. Currently, many of these are focussed on 3D printing, as in the examples provided by Voodoo Manufacturing and 3D Hubs. As (Jungnickel, 2015) notes, 3D printing technology has benefitted from a gradual reduction in the cost and size of printers, making them more accessible, a growth in distribution and marketing, raising public awareness and familiarity, as well as the development of more intuitive digital CAD software, eliminating the need for specialist skills, and digital libraries allowing for the peer-to-peer sharing of digital designs. However, should other digital fabrication technologies, as demonstrated by examples, such as

[26] Prosumer: '[…] value creation activities undertaken by the consumer that result in the production of products they eventually consume and that become their consumption experience' (Tian, et al., 2017, p. 2041).

Sewbo, Opendesk and UNMADE, follow a similar route as 3D printing, these may also become available to individual prosumers.

In the case of smart products, consumers may customise their products after the point of sale by selecting and downloading different apps and software to provide added functionality tailored to their needs (Hagel, et al., 2015). For example, Amazon's voice controlled virtual assistant, Alexa, and associated hardware accessories, including smart speakers, smart thermostats, smart lighting and tablet displays is now allowing consumers to design their own applications to customise the product's functionality (Rawes & Matthews, 2019). This is achieved via the Alexa Blueprints platform, which provides consumers with easy to use templates that allow them to code custom applications without the need for specialist computing skills (Plate 8.17). These applications can be adjusted, created and deleted at the will of the consumer in line with their changing needs and without the need for physical changes to the product (Rawes & Matthews, 2019).

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**Plate 8.18** A customisable Blueprint application for Amazon's Alexa virtual assistant (Amazon.com, Inc., 2019).

Further to this, as smart products gather vast volumes of data, artificial intelligence may enable them to learn and adapt to their environment and user preferences independently and automatically, no longer requiring the design input of formal designers or prosumers (Porter & Heppelmann, 2015). This may even allow consumers' needs to be predicted before they themselves identify them (Flores Salvidar, et al., 2016). As in the case of the generative design of physical products, the design of digital applications is fulfilled by algorithms, with designers or consumers adopting a confirmatory role.

The integration of Industry 4.0 technologies therefore has the potential to transform the design process. The data generated by smart, connected products and the IoT, as well as the analytical potential of Big Data and AI may lead to a better-informed design process. Developments in virtualisation, augmented reality and gestural control may also provide a more intuitive design process, automating routine tasks and freeing designers to concentrate more on creativity. Should the design process become increasingly automated through technologies, such as generative design, the role of the designer may be reduced to the setting of design parameters and the evaluation and selection of final designs. In addition to transforming the process of designing, there may also be changes to which stakeholders are involved in design. Technologies, such as virtual and augmented reality may support more collaboration, involving contributions from geographically dispersed stakeholders. The emergence of mass customisation and on-demand digital fabrication may also present opportunities for greater consumer involvement. In line with this, emerging phenomena, such as co-design and pro-sumption are signifying a shift from producer-led to consumer-led design. As such, it is evident that Industry 4.0 will impact on the design process which will, in turn, have implications for design outcomes and the products that are manufactured. With design and manufacture becoming increasingly accessible, collaborative and customisable, there is the potential for greater creativity and innovation.

### 8.4 New Business Models

The impacts of Industry 4.0 technologies on manufacturing, product possibilities and the process of designing, is also expected to change, not only what is technically feasible, but also what is economically profitable. As a result, business models will evolve in order to capture the potential value presented by these changes.

> *"The main function of the business model is to connect technical potential with realization of economic value."* (Andersson & Mattsson, 2015, p. 91)

Firstly, the ability to cost-effectively manufacture small batches of individualised products on demand using digital fabrication and robotic assembly will enable companies to offer consumers greater customisation and personalisation (Ramaswamy, 2011). This provides another means of differentiating product offering from the competition besides lowering prices

(Lasi, et al., 2014). Additionally, it allows companies to respond to changes in consumer needs and demands more quickly and effectively. As a result of this added flexibility and responsiveness, product design is expected to become increasingly consumer-led (Lasi, et al., 2014).

Additionally, as the economies of scale principle no longer applies in the case of digital fabrication, manufacturers benefit equally from producing many different products as they would many of the same product. This may result in manufacturers opening their services to a wider market by making individualised and small-batch production available to smaller companies, entrepreneurs, designers and pro-sumers. An early example of this is Voodoo Manufacturing (Chapter 8.1), whose services simplify both the fabrication and fulfilment process, providing an accessible means of production to virtually anyone, irrespective of their size and scale. With on-demand, digital fabrication also lowering the costs and risks associated with entering the market, by reducing overheads and eliminating production minimums, this could see more smaller businesses and independent innovators emerge, driving up competition and boosting innovation (Rayna & Striukova, 2016).

Further to this, the ability to fabricate digital designs anytime and anywhere, without the need for tooling and rigid production lines optimised for standardised products, may see design and manufacturing become increasingly independent activities. This opens opportunities for relocating these activities. For example, manufacturing may transition from centralised manufacturing centres in distant, overseas locations to distributed, digital fabrication points closer to points of consumption. This offers benefits, such as reduced logistics and delivery costs and shorter lead times. Whilst the re-shoring of production may have previously been prohibited in high wage countries due to labour costs, this is remedied in Industry 4.0 by an increase in automation. As a result, manufacturing is expected to become increasingly decentralised and distributed (Prause, 2015). With these developments, independent design and production activities become nodes in new, agile networks. An example of this is Opendesk (Chapter 8.1), which uses an online platform to connect consumers with designers and local fabricators. This may see a reorganisation of business models where manufacturing is sold as a service and designs are sold as digital files. An example of the latter is Netherlands based digital fashion start-up, The Post Couture Collective (Plate 8.18).

**Plate 8.19** The Post Couture Collective digital clothing designs for sale. (The Post Couture Collective, 2017).

In addition to ready-made garments, the company retails digital files of their fashion garment patterns, which consumers are able to download. These can be adjusted according to different size requirements and style preferences before being laser cut from non-woven fabrics and assembled by consumers by tying sections together (The Post Couture Collective, 2017). This represents a new format for business models, whereby designs are sold direct to consumers who then arrange digital fabrication via their own selected manufacturing service provider.

With the digitalisation of design and fabrication, a further potential disruption to existing business models is the ability for digital product design files to be replicated and shared at a negligible cost and then reproduced on demand by individuals (Tian, et al., 2017). In other sectors where there has been a transition from physical to digital products, such as in the music, film and gaming industries, this has given rise to piracy and peer-to-peer sharing (Rayna & Striukova, 2016). Whilst laws have traditionally acted as a deterrent to other companies counterfeiting products and infringing on intellectual property, in the case of distributed piracy where individuals were replicating files on a small scale for their own personal consumption, this becomes ineffectual (Depoorter, 2014). This is because it would require many individuals to be prosecuted for small scale infringements, rather than a more substantial charge being brought against a single company (Depoorter, 2014). As a result, existing market leaders that remained tied to traditional business models oriented around the sale of physical products have been undercut and outcompeted by more progressive and convenient alternatives. These include access models, such as Spotify's music streaming service, whereby consumers are charged a regular fee for the ability to listen to an extensive library of music on demand (Rayna

& Striukova, 2016). The same level of choice would be near impossible to achieve for the average consumer through the purchase and storage of physical CDs and the extra features and services provided by Spotify's interface provide added convenience and an improved user experience over pirating such an extensive library and navigating it manually. Should physical products follow a similar progression as a result of Industry 4.0, with consumers able to replicate company's retail offerings through digital design and fabrication, there could be a shift towards selling products as a service and providing more convenient access models.

The transition towards such service and access-based business models in Industry 4.0 may be further encouraged by new capabilities afforded by smart, connected products and the IoT. This is because these technologies have the potential to provide greater visibility, traceability and control of physical assets, allowing for remote monitoring and operation (Porter & Heppelmann, 2015). This can help companies to offer products as a service and to provide product access models by reducing operational costs. For example, US based car-sharing company, Zipcar, uses digital connectivity to manage their fleet of vehicles (Plate 8.19). Digital information is then conveyed to an easy to use application, allowing consumers to locate available, nearby vehicles in real time (Zipcar, Inc., 2018). The vehicles also operate a smart locking system to provide security, allowing only the correct customer to gain access to the correct vehicle by swiping a key card over a scanner located on the windshield. The length of time each vehicle is used for is also digitally monitored, enabling the correct fees to be applied. This eliminates many of the overheads associated with traditional car hire companies, such as shop fronts and staffing costs as transactions (Zipcar, Inc., 2018).

This image has been removed as the copyright is owned by another organisation or individual.

**Plate 8.20** Zipcar's digital car sharing application (Zipcar, 2019).

When selling products as a service and providing access models, the company retains ownership of the physical assets. As such, their storage, servicing and maintenance remain the responsibility of the company, rather than being shifted to the consumer as in traditional product sales and ownership models (Porter & Heppelmann, 2015). This is true for Zipcar, who take care of parking, maintenance and refuelling, providing added convenience for consumers (Zipcar, Inc., 2018). Digital connectivity can also help companies to reduce costs associated with these added services, by providing remote monitoring capabilities and predicting maintenance requirements (Blunck & Werthmann, 2017). Additionally, the production of spare replacement parts is simplified in Industry 4.0 as, rather than manufacturing them in advance and storing them until required, companies can fabricate the required parts as and when needed, using digital fabrication technologies and digital product data stored in embedded chips (Gerlitz, 2015). Other Industry 4.0 technologies such as Big Data, AI and simulation can help with the design of appropriate service models and predicting usage patterns, which can help companies to efficiently allocate resources in line with demand (Marilungo, et al., 2017). As such, the pressures placed on traditional product sales-based business models as a result of the digitalisation of design and manufacture, combined with the new opportunities provided by smart, connected products and the IoT, may see a transition towards product services and access-based business models in Industry 4.0.

However, in such a scenario, a conflict arises between the potential for truly customised products, as demanded by consumers and enabled by digital fabrication technologies and the potential to share existing products between multiple consumers as necessitated by product service and access business models. As a result, there exists potential for the physical construction of products to be standardised and instead customised through digital interfaces (Chapter 8.2) (Gandhi, et al., 2013). This would also help companies to keep their existing assets in use for longer periods of time, by enabling continual updates and improvements, reducing costs as a result (Chapter 8.2). Further to this, smart, connected products will provide companies with vast amounts of data, which they may be able to use to identify new service features and business opportunities (Porter & Heppelmann, 2015). The sale of this data to other companies and service providers may also serve as an additional source of revenue. New business models and service innovations may then arise by combining the data gathered from multiple, disparate products (Chapter 8.2).

It is therefore evident that Industry 4.0 will bring new ways of capturing value, giving rise to business model innovation, changed consumer expectations, which will in turn result in new products and services (Flores Salvidar, et al., 2016). Such developments will inevitably impact on the economic paradigm, which will in turn require a reconfiguration of the structure of companies as well as a reorganisation of industries and the relationships between different actors (Marilungo, et al., 2017).

In summary, this chapter has identified the key changes to design expected as a result of Industry 4.0, combining a review of the literature with demonstrative case studies exploring the early adoption of Industry 4.0 technologies. From the results it is evident that the impacts of Industry 4.0 will be far reaching, extending beyond the phenomenon's initial focus on manufacturing. The digitalisation and intelligentisation of product manufacture have the potential to realise on-demand mass customisation, increase automation and improve supply chain traceability and transparency as well as resulting in the decentralisation of production and the lowering of manufacturing set-up costs making manufacturing much more accessible. Industry 4.0 will also give rise to new product possibilities, including individualised and custom products, new product geometries and assemblies that weren't previously manufacturable, and smart and connected products with an increasingly digital component.

Further to this, the process of designing products will also change with new, digital design capabilities. Expected developments include the incorporation of data and insights gathered past the point of sale through smart, connected products, increased collaboration through virtual design platforms and greater involvement of consumers with the emergence of co-design and customisation platforms. With the increasing automation of design tasks, the process is also expected to become increasingly intuitive, opening new possibilities for pro-sumption and generative design, resulting in changes to who is actually making design decisions. In the case of connected, smart products there is also the possibility that design will extend beyond a one-time process at the beginning of the product life-cycle to become an ongoing activity, contributing to both physical and digital improvements and updates. All of these changes as a result of Industry 4.0 will in turn change the prevailing economic paradigm, providing new opportunities for capturing values and challenging the sustainability of traditional business models. New developments may include the emergence of many more, smaller designers, innovators and fabricators onto the market as the potential for decentralisation increases and initial cost and risk barriers are reduced. There may also be a division of value chains, separating tasks such as design, fabrication and fulfilment, which will instead become networked and reconfigurable. As design and production becomes increasingly accessible to consumers or 'pro-sumers', businesses may be forced to change their business approach. Early examples of Industry 4.0 technology adoption suggest this see a shift towards products as a service and access models. All of these developments are likely to have a significant impact on who is designing, what products are created and how they are used, which is of significant relevance to DfCE. As such, this chapter has provided a clear, high-level overview of the key developments in design expected as a result of Industry 4.0, which can be used to assess the contribution that Industry 4.0 will make to overcoming the barriers to DfCE implementation.

# Chapter 9. Design for a Circular Economy in Industry 4.0

This chapter brings together the findings from Chapters 6, 7 and 8 in a thematic analysis to explore the potential implications of Industry 4.0 for the implementation of DfCE practices. Chapter 6 examined the historical relationship between design and industry, demonstrating that the former has been significantly shaped by the latter. This suggested that industrial change, as a result of Industry 4.0, is likely to result in further transformation of design. Chapter 7 then identified existing barriers to DfCE implementation, categorised into task barriers, designer barriers, organisational barriers and external barriers. This provided a framework against which the design implications of Industry 4.0 could be assessed in terms of their potential for overcoming barriers to DfCE implementation. These were identified in Chapter 8, categorised as the transformation of manufacturing, new product possibilities, the evolution of the design process and new business models. The possibility for new DfCE barriers and opportunities to arise as a result of Industry 4.0 was also considered and included in the discussion. An iterative process of abductive reasoning and retroduction, supported by targeted literature, was employed to arrive at emergent themes and theories which are presented thematically. This chapter therefore serves to integrate the findings from previous chapters, providing an initial mapping of the research area created by the intersection between the circular economy, design and Industry 4.0. The chapter culminates in a design-centred circular economy agenda for Industry 4.0, which aims to lay the groundwork for future research in this important and evolving area.

## 9.1 Industry 4.0 and External Barriers

### 9.1.1 Technology and Infrastructure

As identified in Chapter 7.4.4, DfCE implementation may be constrained by the parameters of available technology, limiting the potential circular solutions available to designers. Additionally, even where facilitating technologies exist, these may not necessarily be implemented in such a way that they are readily available or accessible to designers, constituting a lack of supporting infrastructure for DfCE implementation. As the development of new technologies and supporting infrastructure requires upfront investment and incurs a level of risk due to uncertainties regarding return on investment, these barriers can prove difficult to overcome.

As outlined in Chapter 4, Industry 4.0 is beginning to introduce new technological capabilities and infrastructural developments, constituting a fourth industrial revolution. This transformation is characterised by increased automation, information, connectivity, and flexibility afforded by the integration of cyber-physical-systems (CPS). Originating as an industrial initiative aimed at advancing the competitiveness and profitability of the manufacturing sector, Industry 4.0 is focused on exploiting these developments to realise new opportunities for cost reduction, differentiation and value generation. Additionally, Industry 4.0 technologies are beginning to be applied beyond manufacturing, transforming products, design processes, business models and services. As these technologies become established, they give rise to new infrastructure, such as decentralized digital fabrication networks and the Internet of Things. Whilst the driving forces behind these developments may be economic in nature, the technologies and infrastructure introduced as a result of Industry 4.0 invariably present implications for DfCE implementation.

Firstly, Industry 4.0 technologies may provide designers with new product possibilities through which circularity may be achieved. For example, the case presented in Chapter 8.2 demonstrates the potential for 3D printing to make possible the production of a functional product as a single part in a uniform material, without the need for components or assembly. This could help designers to achieve designs that are optimised for material recovery and eliminate the need for disassembly, without compromising on utility. Another example provided in Chapter 8.2 was Tesla's Model 3 vehicle demonstrating the potential for products to become increasingly smart and digital. This could enable the remote application of product life extension strategies for a CE, for example, upgrades incorporating new digital functionalities and customisation to meet changing consumer tastes and needs as well as predictive and digitally-guided maintenance and repair services. This suggests that the new product possibilities offered by Industry 4.0 may include opportunities to realise circular products that were not previously technically achievable.

In addition to new CE product possibilities, technologies and infrastructure put in place to facilitate Industry 4.0 applications may also enable new circular processes to be realised. For example, the digital connectivity provided by smart products may help to facilitate product sharing models and product service systems. As demonstrated by the case of Zipcar, described in Chapter 8.4, the remote monitoring and control of smart products can enable processes, such as the granting of access, the tracking and location of physical assets, the logging and attribution of product usage to the appropriate consumer and the prediction of maintenance needs to be carried out automatically. Other circular processes facilitated by Industry 4.0 include smart, automated and flexible product disassembly. As described in Chapter 8.1, the transformation of manufacturing as a result of Industry 4.0 is expected to see smart products guide themselves through their own customised digital fabrication and robotic assembly using embedded chips and barcodes. When a product reaches the end of its functional life, these chips and barcodes may be read to retrieve information about the product's composition and construction. This in turn may enable automated robotic disassembly processes and the sorting of materials and components into homogenous streams, using the same smart and agile manufacturing equipment used for production, helping to close resource loops. As highlighted in the case of Hamuel Reichenbacher in Chapter 8.1, this automation may also extend to remanufacturing and repair processes, further supporting product life extension strategies. This demonstrates that the technologies and infrastructure implemented as part of Industry 4.0 also present opportunities for new processes that support the achievement of product circularity.

However, it should be noted that not all Industry 4.0 technologies and infrastructure developments will necessarily lend themselves to CE objectives, with some instead presenting new challenges. The development of smart, connected products, for example, requires the integration of electronics into products that would not have previously contained technical resources or complex components. Further, where the development of multi-material 3D printing enables different materials to be combined to create complex, integrated products requiring no assembly (Chapter 8.2), the separation of resources may become impossible. Both of these examples demonstrate how technologies and infrastructure developments associated with Industry 4.0 also have the potential to complicate material recovery operations and the closing of material loops.

These insights suggest that technological and infrastructural developments associated with Industry 4.0 have the potential to realise new product and process possibilities, which may be exploited by designers to extend and close resource loops, helping to achieve a CE. This presents an opportunity to overcome DfCE barriers associated with technological limitations and a lack of supporting infrastructure, as identified in Chapter 7.4.4. As Industry 4.0 is being implemented for other, economic purposes, DfCE opportunities may be realised without the costs and risks involved in developing new technologies and infrastructure specifically for a CE. However, by the same token, as DfCE is not currently a key driver of Industry 4.0, these benefits are not a given and must be actively sought out. Additionally, there exists the potential for new DfCE challenges to arise in Industry 4.0, which must be taken into consideration if they are to be resolved or avoided.

**9.1.2 Economic and Market Barriers**

As identified in Chapter 7.4.1, economic and market conditions represent a significant barrier to DfCE implementation, limiting the viability and profitability of circular products and business models (Chapter 7.3.3) and discouraging innovation, which is necessary for achieving a CE (Chapter 7.1.1). As a result, designers are faced with unavoidable trade-offs in which DfCE may be sacrificed in order to secure economic success (Chapter 7.1.4). This is due to the fact that, under the traditional, linear economic paradigm, DfCE strategies, such as the closing of resource loops, represent a cost for companies without a return on investment, or, in the case of product life extension, a reduction in sales and profitability. As evidenced by the findings in Chapter 6, economic and market conditions of the linear economy have evolved as a result of successive technological, industrial and social developments that have led to the current economic model. Since the first industrial revolution these have reinforced the centralisation of production, standardisation of products and mass production following the economies of scale principle. As highlighted in Chapter 8.1, Industry 4.0 has the potential to reverse these principles, leading to decentralised production, mass customisation and on-demand production in batches of one. As such, this may have a considerable impact on the economic and market barriers currently limiting DfCE implementation.

There exist several ways in which Industry 4.0 may optimise economic and market conditions for a CE. The first is the potential for digital fabrication and robotic assembly to challenge the economies of scale principle. As highlighted in Chapter 7.1.1, radical product innovations are necessary for the implementation of DfCE and the transition from a linear to a circular economy. However, within the traditional economic model, new circular innovations must compete with existing products that benefit from large, established markets and lower costs afforded by mass production and the economies of scale principle (Chapter 7.3.3). As explained in Chapter 8.1, enabling flexible production of individualised products, digital fabrication and robotic assembly may help improve the economic feasibility and profitability of bringing new circular innovations to market in small batches with minimal risk. This is further aided by the elimination of tooling costs and the need to set up rigid production lines. With on-demand production, there is also no need to produce vast quantities of stock at a time, which would normally incur storage costs and represent an additional investment risk. As a result, new circular product innovations may no longer entail a competitive disadvantage against existing, traditional products, helping to reduce economic and market barriers to transitioning from a linear to a CE.

Another industrial principle with the potential to be reversed by Industry 4.0 is the centralisation of production. As highlighted in Chapter 6, this has been a common trend throughout previous industrial revolutions, with manufacturing moving into cities, factories and then, with the advent of ICT, to distant manufacturing hubs in low-wage countries, seeking economies of scale and reduced labour costs. With the elimination of the economies of scale principle and the capacity for digital fabrication and robotic assembly equipment to fabricate individualised products in any location, Industry 4.0 is expected to reverse the centralisation principle, facilitating decentralised production. With smart manufacturing processes also becoming increasingly automated and self-modulated, there also exists the potential to significantly reduce associated labour costs (Chapter 8.1). This may in turn enable the re-shoring of production close to the point of consumption with the benefit of reducing lead times and logistics costs (Chapter 8.4). As a result, there may be increased opportunities to create products from locally available materials and to create local resource loops to recover used products, components and materials without the need to ship these back to distant manufacturing hubs. Opportunities such as these may therefore help to further improve the economic case for DfCE.

Beyond the manufacture of products, Industry 4.0 may also deem other processes, which have the potential to support CE business models, more economically viable. Smart products, for example, may not only help improve the operations of product rental models and product service systems, but also reduce costs by automating tasks that would traditionally require physical store fronts and staff to carry them out (Chapter 8.4). Another example is the automation of product disassembly and the possibility of using existing, smart manufacturing equipment to carry it out. By eliminating the need for manual product disassembly and the setting up of dedicated facilities, automation may help to improve the cost effectiveness of disassembly processes. As these examples demonstrate, Industry 4.0 has the potential to change not only what’s possible, but also what’s profitable in terms of processes as well as products. Automation may provide designers with new solutions and a means of avoiding potential trade-offs between economic and DfCE criteria when designing products, supporting business models and services for a CE.

In addition to presenting opportunities for improving the economic viability and profitability of CE solutions, changes to economic conditions as a result of Industry 4.0 may also lower that of traditional, linear solutions. By enabling the automated, small batch production of individualised products on demand and without prohibitive upfront costs, such as tooling, smart manufacturing has the potential to democratise the production of products (Chapter 8.4). Where product designs become little more than digital files, there exists the potential for products to be easily shared and replicated on a decentralised basis by individuals for personal use, undercutting businesses that sell them. This has been observed in other industries where products have become digitised, including music retail. In such cases, where it has become difficult for companies to profit from the sale of physical products, innovative access and utility-based business models, such as streaming services, have emerged (Chapter 8.4). Whilst the pirating of digital music files remains possible, these new services provide consumers with added benefits, such as convenience and a wider selection of music than would otherwise be achievable. As such, there exists potential for traditional, linear business models that currently profit from the sale of physical products to be undermined by the digitalisation of products associated with Industry 4.0. This may act as a disincentive, helping to reinforce the case for access and utility-based business models that are better aligned with a CE and which incentivise the extension of resource loops.

It should be noted, however, that the economic conditions that arise as a result of Industry 4.0 may also present new challenges for implementing DfCE. One example is the potential for the increasing ease, immediacy and affordability of manufacturing to change how the value of physical products is perceived. As highlighted in Chapter 6, the development of injection moulding and new plastic materials enabled products to be produced much more rapidly and cheaply than before, which in turn promoted the democratisation of rapid consumerism and the emergence of disposable products. This trend could be reinforced by the introduction of more intuitive and accessible digital design processes, such as generative design (Chapter 8.3) and increasingly automated, affordable and accessible means of production, such as digital fabrication (Chapter 8.1), which may further democratise product design and manufacture. The ability to cost-effectively produce anything at any time may see a proliferation of low-quality products and prototypes and a change in consumer perceptions about the material value of a product when it can be easily replicated. This has already been identified in the case of 3D printing within makerspaces[27], serving as an early example of the implementation of a digital fabrication technology (Smith & Light, 2017). What this demonstrates is that changes to

[27] 'Makerspaces' may be defined as accessible shared spaces which provide access to social technologies for hands-on making experiences (Hui & Gerber, 2017).

economic conditions associated with Industry 4.0 may also present new challenges for the transition to a CE and the implementation of DfCE.

These results suggest that there exists potential for Industry 4.0 to radically transform the prevailing industrial paradigm to realise new economic conditions, which in turn may have several significant implications for economic and market barriers to DfCE implementation. Many of these are positively aligned with DfCE, including improvements to the economic competitiveness of new, CE innovations, reductions in the profitability of traditional, linear products and business models, and the creation of market conditions that are more conducive to CE strategies and that increase the economic viability of processes that support the achievement of a CE. However, there also exists potential for new challenges to arise, such as a reduction in the perceived value of products afforded by reduced costs and the increased accessibility of production. As such, the potential opportunities and challenges presented as a result of changes to economic conditions in Industry 4.0 should be carefully navigated.

### 9.1.3 Law and Policy

As highlighted in Chapter 7.4.2, a lack of supporting law and policy, necessary for incentivising the transition to a circular economy and disincentivising and regulating contradictory activities, constitutes a key barrier to DfCE implementation. Addressing this issue is further complicated by the fact that law and policy for a CE can conflict with other interests of businesses and decision makers. Further to this, the application and of law and policy for a CE can also face challenges with regards to effective implementation and enforcement.

Industry 4.0 may have several implications for these barriers. Firstly, the development of new product and process innovations, as discussed in Chapter 9.1.1, as well as new economic conditions, highlighted in Chapter 9.1.2, may provide solutions that enable conflicts between law and policy for a CE and other important interests to be avoided or resolved. In terms of implementation and enforcement, Industry 4.0 could complicate this further as the decentralisation of production may make this more difficult, especially in the case of pro-sumption (Chapter 8.4). However, the ability to automatically track and trace production processes, products and services as a result of digital connectivity could provide new opportunities for law and policy enforcement. This may be complemented by blockchain to provide authentication digitally, without the need for a third party (Chapter 8.4). A further implication presented by Industry 4.0 is the potential for the re-shoring of production from manufacturing hubs to locations closer to the point of consumption to expose operations to stricter laws and regulations. As such, Industry 4.0 may present indirect opportunities for overcoming some of the challenges associated with a lack of law and policy for a CE, in the form of new solutions and new means of enforcement, as well as new potential challenges.

### 9.1.4 Consumer Behaviour

As explored in Chapter 7.4.3, consumer behaviour may represent a further barrier to DfCE implementation. Whilst the results of the designer interviews suggested growing consumer interest in sustainable and circular products, barriers can include limited awareness and a lack of information to support purchasing decisions, the preferencing of other criteria above circularity resulting in an attitude-behaviour gap and a reluctance to accept new, unfamiliar modes of consumption.

Industry 4.0 affords several developments that may help to address DfCE barriers associated with consumer behaviour. Firstly, improvements in the transparency and traceability of value chains afforded by digitalised manufacturing processes and smart, connected products, coupled with authentication technologies, such as blockchain, may help to provide consumers with more comprehensive and reliable information, helping to inform purchasing decisions (Chapter 8.1). With regards to the prioritisation of other criteria above circularity, Industry 4.0 may present new product and business model possibilities for a CE, providing solutions that no longer necessitate other criteria, such as cost and quality, to be compromised (Chapter 8.2 and 8.4). This may be further facilitated by changes to economic conditions, as highlighted in Chapter 9.1.2, which have the potential to favour circular solutions over traditional, linear ones, helping to improve their consumer appeal. Finally, consumer apprehension surrounding unconventional modes of consumption in line with a CE, such as product service systems, may be reduced through the integration of Industry 4.0 technologies. One of the consumer concerns highlighted in Chapter 7.4.3 was a loss of freedom and control by switching from product ownership to sharing models. As such, the advent of smart, connected products that enable physical assets to be tracked, controlled and organised remotely (Chapter 8.4), may help to allay some of these concerns by providing a more reliable, efficient and convenient consumer experience that allows consumers to avoid the hassle of having to maintain and store their own products. As such, there exists potential for Industry 4.0 to aid in overcoming existing DfCE barriers associated with consumer behaviour.

A further opportunity may be realised through consumer-led customisation and co-design of products afforded by smart manufacturing (Chapter 8.3). It has been suggested that consumers develop a stronger emotional attachment to products when they are more involved in the design process or where products are personalised to their specific needs and tastes (Haug, 2018). As a result, customisation and co-design may provide an opportunity to realise DfCE by encouraging consumers to keep and use products for longer, extending resource loops. However, it is also important to consider that customisation may present new challenges for product sharing and redistribution, should consumers come to expect personalised products. As highlighted in Chapter 8.4, smart products may present a solution by enabling digital updates and the customisation of interfaces, allowing for customisation to be achieved on an ongoing basis. The impacts of Industry 4.0 on consumer behaviour is therefore an evolving area, whereby new DfCE opportunities and challenges are likely to arise.

### 9.1.5 Information Availability and Accessibility

Industry 4.0 may also address the unavailability and inaccessibility of information necessary to support the DfCE process and the identification and development of circular solutions. As Industry 4.0 is built on the capture and exchange of data in real-time through the implementation of cyber physical systems, there exist several new sources of information that may be of use to designers in implementing DfCE. As explained in Chapter 8.3, smart, connected consumer products have the potential to provide designers with insights past the point of sale and throughout the later stages of their lifecycle. This may serve as useful information about product use and consumer behaviour that could support the development of new, circular product and business model designs. As highlighted in Chapter 8.3, collaboration between stakeholders in the design process, as supported by digital connectivity, simulation and virtual reality, may also help to break down information silos and support the exchange of information. Industry 4.0 developments such as these may therefore help to supply designers with the information necessary to inform DfCE processes.

Additionally, as already highlighted in Chapter 9.1.1, the collection and retention of data about a product's composition and condition by embedded chips may also help to promote DfCE by facilitating services that extend product life, such as the on-demand production of spare parts and guided maintenance and repair. The provision of this information may therefore provide designers with more viable circular solutions.

However, it should be noted that with economic viability and profitability a primary concern for businesses and therefore designers, collaboration and the provision and sharing of data can be seen as a possible risk, raising issues associated with intellectual property, ownership rights and liability (Chapter 7.3.3). Therefore, whilst the added data capture and connectivity afforded by Industry 4.0 has the potential to help overcome DfCE barriers in relation to the unavailability and inaccessibility of information, this does not necessarily mean that such opportunities will be realised.

## 9.2 Organisational Barriers

### 9.2.1 Organisation-wide Awareness and Leadership

As identified in Chapter 7.3.1, a lack of organisation-wide awareness of CE principles and leadership from senior decision makers can act as a barrier to DfCE implementation. As highlighted in Chapter 9.1.5, Industry 4.0 may help to improve the availability and accessibility of information as a result of data capture and digital connectivity, which may help to raise awareness of the implications of design decisions and support the implementation of DfCE. However, the need for such CE awareness and leadership was found to be in part due to the fact that a number of design decisions are made, not by designers, but by other stakeholders in the value chain (Chapter 7.2.3). Therefore, changes to organisational structure (Chapter 9.2.2) and designer autonomy (Chapter 9.3.3), as a result of Industry 4.0, may also have implications for DfCE barriers associated with organisation-wide awareness and leadership.

### 9.2.2 Organisational Structure

As evidenced in Chapter 7.3.2, DfCE barriers pertaining to organisational structure differ depending on the size of an organisation. For large operations, issues can arise when circular solutions require changes to complex, centralised supply chains and well-established stakeholder relationships. This is further complicated by the division of labour, which makes coordinated change even more challenging. As such, the potential for Industry 4.0 to create agile, flexible and networked value chains, comprising smart manufacturing processes and supporting services, could help large organisations to overcome the challenges of transitioning from a linear to a circular economy (Chapter 8.1)

In the case of smaller companies, the lack of available resources to invest in innovative, circular products and business models was identified as a barrier to DfCE implementation (Chapter 7.3.2). As such, industry 4.0 could help overcome these challenges by lowering the costs and risks involved in innovating for a CE (Chapter 9.1.2). Therefore, DfCE barriers associated with organisational structure may be somewhat addressed by Industry 4.0 developments in the case of both small and large organisations.

### 9.2.3 Business viability and profitability

As the business viability and profitability of products is key to the success of organisations, the potential for DfCE to compromise this represents a key barrier to its implementation. The possibility for Industry 4.0 to introduce new economic conditions, as discussed in Chapter 9.1.2, may therefore present a solution. This is particularly the case where the economics of circular solutions are supported by connectivity and automation, which may help to provide an alternative to traditional, linear business models undermined by developments, such as pro-sumption and the decentralised replication of digital product files. Additionally, smart products may open new business opportunities, such as digital services, that generate additional value from existing physical assets, as evidenced by the example presented in Chapter 8.2 depicting an application created between Phillips Hue lighting and Netflix video streaming services. These results therefore suggest that Industry 4.0 has the potential to improve the business viability and profitability of circular solutions and present additional opportunities for revenue generation through new digital services, which may help to address DfCE barriers related to business viability and profitability.

## 9.3 Designer Barriers

### 9.3.1 Awareness and Values

Chapter 7.2.1 identified that if designers are to be instigators of DfCE, then it is necessary for them to hold CE values, which firstly requires awareness. As explained in Chapter 9.1.5, Industry 4.0 has the potential to facilitate the capture and exchange of data, particularly with respect to product performance and lifecycles past the point of sale. This may provide designers with a greater level of insight into the consequences of design decisions and help to raise awareness of the need for CE and instil CE values within designers (Chapter 9.1.5).

Further to this, it was identified that designers face challenges in implementing DfCE where circular values conflict with the variety of other values that they consider to be of importance, whether personally or on the behalf of other stakeholders, such as organisations or consumers. Such conflicts may be resolved should Industry 4.0 bring about technological and infrastructure developments that facilitate new product and process innovations, including those optimised for a CE (Chapter 9.1.1). Whilst it is not guaranteed, these could provide designers with new avenues to explore that may help to avoid trade-off scenarios between CE values and other values that influence design decision making.

Industry 4.0 therefore has the potential to aid in overcoming DfCE barriers associated with a lack of designer awareness and CE values by providing access to information as well as new opportunities for avoiding trade-offs between values.

**9.3.2 Knowledge and Training**

As highlighted in Chapter 7.2.2, implementing DfCE requires designers to possess knowledge and understanding of CE principles. However, as designers are well equipped with research skills and the ability to fill information gaps, formal education and training specific to DfCE may not necessarily be a prerequisite before approaching the task. The potential for Industry 4.0 to provide improved data availability and access to support the design process (Chapter 8.3), may therefore better support the design process by making the sourcing of information and the filling of gaps easier. Automated CAD software has the potential to aid in the delivery of information and inform designers of the consequences of their design decisions as they are made, which could make the process of DfCE more intuitive and efficient. Another development that could provide designers with the knowledge required to implement DfCE is the potential for stakeholders in the value chain to become increasingly networked and digitally connected in Industry 4.0. As noted in Chapter 8.3, this could support added collaboration, helping to break down knowledge silos, although consideration should be given to possible conflicts of interest in sharing information between organisations and stakeholders (Chapter 9.1.5).

In addition to acquiring CE specific knowledge and information, Chapter 7.2.2 also identified a need for designers to possess the ability to convince stakeholders and decision makers of the business case for CE solutions if they are to realise DfCE. Failure to do so may limit the potential for circular solutions to be realised and implemented, particularly where designer autonomy is limited and other decision makers are involved in the design process, such as in organisations (Chapter 7.2.3). Whilst Industry 4.0 may not address this need directly, the ability to prototype and manufacture economically feasible small batches of products with minimal set-up costs (Chapter 8.1), could enable designers to demonstrate circular design solutions and their success within the market, helping to win over decision makers.

These results demonstrate the potential for Industry 4.0 to support designers in acquiring the knowledge necessary to carry out DfCE and to develop circular solutions, as well as proving their market viability of such solutions, helping to overcome barriers associated with convincing decision makers.

### 9.3.3 Designer Autonomy

Even in cases where designers possess the necessary CE awareness, values and knowledge, a lack of designer autonomy can constitute a key limiting barrier in the implementation of DfCE. As evidenced in Chapter 7.2.3, designers may be limited in terms of their freedom to direct the design process, with key design decisions that determine product outcomes being made by other stakeholders in the value chain. This may be due to several limitations placed on designers as a result of their employment by or within organisations, including being confined to only certain parts of the design process as a result of the division of labour or being constrained by briefs determined by senior management or marketing teams. The centralisation of production and the formation of large organisations has occurred following economic conditions, such as the economies of scale principle (Chapter 6). As explained in Chapter 8.4, Industry 4.0 is expected to change many of these economic conditions, resulting in mass customisation, on-demand small-batch production and decentralisation. As a result, there may be a reduction in large, centralised organisations and entry of many more, smaller companies and even individual designers into the market. Industry 4.0 may therefore present a situation where designers have greater autonomy.

However, another barrier associated with designer autonomy was the existing tendency for designers to collaborate and work in teams, whereby personal design convictions may be diluted or overridden (Chapter 7.2.3). Whilst this may be somewhat reduced as a result of decentralisation, Industry 4.0 may promote new forms of design collaboration that could have a similar effect. As explained in Chapter 8.3, the advent of mass customisation may see consumers become increasingly involved in design decision making, reducing designers' control over the design process. Additionally, the use of generative design software may inadvertently influence or restrict possible design outcomes, according to the algorithms and codes employed. Whilst designers or consumers may input their required design parameters and select from the resulting outputs, some design decisions will have been made by the program developers (Chapter 8.3). As such, Industry 4.0 may remove some limitations on designer autonomy associated with collaboration, whilst simultaneously introducing new ones.

With the design process becoming increasingly intuitive and manufacturing becoming more accessible, there may also emerge opportunities for consumers to take over the design process entirely, designing and producing products from start to finish for personal consumption (Chapter 8.3). As such, this represents a considerable change to who is taking on the role of the 'designer' and making design decisions (Chapter 8.3). Such a development would also change the purpose of design, from generating revenue to personal fulfilment. As a result, individuals would become entirely autonomous and in control of design decisions, which could empower those with CE values to implement them. This was evidenced in the designer interviews with those who had or were planning their own entrepreneurial businesses who said they would be freer to act according to their own values and principles if in complete control of the design process.

As such, Industry 4.0 is expected to present opportunities for designers to reclaim autonomy previously unavailable as a result of organisational aspects but may also see designers relinquish some autonomy to other stakeholders, such as consumers and software programmers. In the case of pro-sumption, individuals may also become autonomous designers in their own right, free to make individualised design decisions according to personal values.

## 9.4 Task Barriers

### 9.4.1 Innovation, Investment and Risk Taking

As explored in Chapter 7.1.1 the transition from a linear to a circular economy requires considerable change and innovation, not only in terms of new circular products, but also business models and supporting services and infrastructure. Achieving such innovation demands a great amount of resources and time, as well as the risk that a return on investment is not guaranteed. As such, designers can struggle to implement DfCE within the constraints of their roles where resources and time are often limited. Investing in innovative, circular solutions can also constitute a difficult business decision to take, with the potential to compromise the viability and profitability of an organisation (Chapter 7.3.3). As such, the need for innovation, investment and risk taking can be a key barrier to DfCE implementation.

As Industry 4.0 is expected to promote innovation in several ways, it holds significant potential in helping to overcome this barrier. Firstly, as explored in Chapter 8.2, digital fabrication may enable innovative new product possibilities. Additionally, the integration of Industry 4.0 technologies into products themselves is expected to give rise to a new generation of smart products. Combined with widespread internet connectivity and new digital processes, these may also make possible new business models and services (Chapter 8.4). Whilst these innovations may not necessarily align with CE principles, they provide new avenues for designers to explore as part of the DfCE process.

In addition to new product and process opportunities, Industry 4.0 may also improve the economic conditions for innovation. The economies of scale principle has been an influential factor in the traditional, linear economy (Chapter 6). This has resulted in the conformity and standardisation of products in order to reap significant gains from producing many of the same product. As such, product innovation has had to work against these prevailing economic conditions. However, in Industry 4.0, digital fabrication has the potential to reduce the costs of rapid prototyping and small batch production, enabling new innovations to be tested in the market and continually adjusted and refined with minimal expenses (Chapter 8.1). Products may also be manufactured on-demand, eliminating the need for minimum order quantities and reducing the risks associated with mass producing radical new CE products in order to achieve economies of scale only to be left with unsaleable stock. Therefore, in a future where single products can be produced, on demand, this changes the paradigm so that new innovations can be offered almost risk free. This may therefore reduce DfCE barriers associated with innovation, investment and risk taking.

### 9.4.2 The Extension and Expansion of the Scope of Design

As identified in Chapter 7.1.2, DfCE requires an extension and expansion in the scope of the design task, through the adoption of a life-cycle perspective and by taking into consideration multiple product lifecycles, as well as the business case for all stakeholders involved, including as service providers. Whilst Industry 4.0 may not change this fact, associated technologies have the potential to help designers navigate these additional considerations. As described in Chapter 8.3, Industry 4.0 is expected to see a proliferation of data capture and exchange as a result of the integration of cyber physical systems and the Internet of Things (IoT). As a result, designers may have improved access to a wider array of information, which may help them to navigate new CE considerations as part of the design process. Additionally, advancements in digital design, simulation and augmented and virtual reality may foster greater collaboration between stakeholders (Chapter 8.3). This could help facilitate the coordination and the joint development of successful CE solutions, which consider and serve the interests of all parties involved. These results suggest that navigating and addressing additional areas, as required by the DfCE process, may become easier and more efficient with the roll-out of Industry 4.0 technologies and developments.

### 9.4.3 The Increased Complexity of Design

With the introduction of circular design criteria, which must then be balanced against all other design requirements, DfCE increases the complexity of the design task. As a result, the process may take more time and resources to arrive at comprehensive solutions that address all criteria simultaneously (Chapter 7.1.3). Industry 4.0 may help to ameliorate these challenges by supporting the design process with new design technologies, such as algorithms, Big Data and simulation. As explored in Chapter 8.3, these technologies may help to take over some of the more repetitive, technical aspects of the design task, expediting the development of solutions optimised for multiple criteria. This may then allow designers to concentrate on more creative and innovative aspects of the design process. Further to this, the development of generative design programs, as discussed in Chapter 8.3, may provide a means of rapidly developing potential design solutions that simultaneously meet all necessary criteria. Combined with simulation to virtually test and evaluate the success of potential solutions, designers may be able to better navigate complex DfCE challenges whilst shortening lead times and conserving resources. Therefore, whilst the DfCE task will remain complex in nature, Industry 4.0 may provide new mechanisms for helping to overcome associated challenges.

### 9.4.4 Design Trade-offs

As explained in Chapter 7.1.4, designers can face trade-offs between DfCE criteria and other, conflicting design requirements. Product cost and performance were found to be of particular importance in terms of both their potential to conflict with DfCE criteria and designers' inability or reluctance to compromise on them for the sake of DfCE. Such trade-offs may be avoided when there is an elimination or de-prioritisation of the conflicting design requirements.

Several Industry 4.0 developments have the potential to bring such changes about. Firstly, the transformation of economic and market conditions, as explored in Chapter 9.1.2, could reduce conflicts between product costs and DfCE criteria where new paradigms favour circular solutions, such as product service systems. Secondly, changes to who is making design decisions, as discussed in Chapter 9.3.3, could see products designed for different purposes, such as pro-sumption rather than profit, resulting in a change in the prioritisation of design requirements. Beyond these contextual changes, there also exists potential for Industry 4.0 to introduce new product possibilities and innovative design solutions. As such, trade-offs may also be avoided where alternatives, that were not previously possible, become available as a result of technological advancement. Whilst contextual changes and new product possibilities may not necessarily be aligned with a CE, they present the potential for realising new DfCE solutions.

### 9.4.5 The Limitations of Available DfCE Tools and Methods

As evidenced by Chapter 7.1.5, the method of implementing DfCE is complex, requiring both innovation, to develop radically new solutions for a CE, as well as technical analysis to ensure that such solutions are effective and do not lead to further sustainability issues. As such, high-level, strategic frameworks lack the necessary specificity and practicality, whilst technical and analytical tools can stifle the creativity required for innovation. New DfCE tools that combine both approaches have begun to emerge, however, the time and resources required to implement them can prove challenging. However, this is less a reflection of the tools and methods, and more to do with the complex nature of the DfCE task, as outlined in Chapters 7.1.1 to 7.1.4. Therefore, the implementation of DfCE comprehensive approaches are likely to benefit from the potential Industry 4.0 developments already discussed in Chapters 9.4.1 to 9.4.4, including lowered costs and risks associated with innovation, improved access and availability of information, the automation of solution generation and new product, process and business model possibilities.

In summary, this chapter has brought together the findings from Chapters 6, 7 and 8 to provide a discussion of the potential interaction between Industry 4.0 and DfCE. From this it is evident that, whilst Industry 4.0 is not inherently aligned with a CE, it has the potential to bring about several changes with which new opportunities for implementing DfCE arise. Firstly, the technological advancement brought about by Industry 4.0 brings with it new possibilities, in terms of new methods of automated manufacturing, new types of products and new business models. Whilst these may not be inherently circular in nature, they present new avenues to explore for potential CE solutions. Secondly, as Industry 4.0 is expected to transform many economic principles that have shaped industry and design to date, it will also change what is affordable and profitable to produce. This is likely to help overcome barriers related to the costs and risks of innovating for a CE, as well as leading to subsequent changes to the ways in which value is captured, destabilising long-established norms and making room for new circular models, such as product service systems. This may also present secondary changes for organisational structures and lead to the democratisation and decentralisation of manufacture and design. As a result, existing DfCE barriers related to organisational size and complexity, lack of resources and power relationships, such as a lack of designer autonomy, may be ameliorated. Finally, the digitalisation of manufacture, products and processes expected as part of Industry 4.0 has the potential to better support the DfCE task, whilst automated design programs utilising such information may also help to expedite the process, helping to overcome time and resource related barriers and freeing designers for more innovative and creative tasks. In addition to these opportunities for realising DfCE, a number of new potential challenges were also identified, such as a reduction in the perceived value of goods due to the increased affordability, accessibility and immediacy of production or added product complexity as a result of the integration of electronics. Therefore, what the results of this chapter demonstrate is that, whilst Industry 4.0 has the potential to present new opportunities for implementing DfCE and in overcoming existing barriers, this is not a given and new challenges will also need to be addressed. Additionally, as Industry 4.0 remains in the early stages of deployment, the findings presented cannot be considered an extensive list of implications, but rather an early exploration of the potential interactions between Industry 4.0 and DfCE. The value of doing so is in the ability to map the research area, provide an advanced awareness of the relevance of Industry 4.0 to design and the CE, and to highlight important areas for future research. As such, this research has the potential to support the timely exploitation of DfCE opportunities and the avoidance or counteraction of possible complications.

# 10. Conclusion

The research presented in this thesis set out to understand the potential implications of Industry 4.0 for the implementation of Design for a Circular Economy (DfCE). Upon reviewing the existing literature (Chapters 3 and 4), two knowledge gaps were identified. The first was a lack of understanding regarding the barriers impeding the successful application of DfCE to date. Whilst interest in DfCE had been increasing, its implementation was found to be limited, with production and consumption remaining tied to a traditional, linear take-make-waste model. The second was an absence of DfCE within the Industry 4.0 agenda. Although sustainability was often promoted as a benefit of Industry 4.0, there existed minimal research specifically focused on its implications for a CE. Whilst papers addressing Industry 4.0 and CE have since begun to emerge, this research remains original in its adoption of a design perspective at the time of publication. Filling these knowledge gaps was therefore essential in order to meet the central aim of the research. In research concerned with two emerging phenomena, Industry 4.0 and DfCE, it was also important to avoid mere speculation by triangulating evidence which also helped to provide structure to the research process. The research was therefore approached from three separate angles (Chapters 6, 7 and 8), the findings of which were then combined in a final, thematic analysis (Chapter 9).

## 10.1 Research Synopsis

Chapter 6 built an understanding of the relationship between industry and design, establishing the ways in which industrial change had impacted on the design of products in the past. An explorative historical review was conducted, drawing on literature concerned with key technological and socio-economic developments that have shaped industry and, in turn, design. As the scope of the research limited this to a purposeful review of specific and relevant events, it may not be considered a comprehensive historical record. Nevertheless, the results demonstrated how design has evolved in line with industrial development to maximise the generation and capture of financial value by reducing costs and maximising sales. This provided an explanation as to why it may have proven so difficult for designers to adopt DfCE whilst still operating within a linear economy. Additionally, it suggested that further industrial transformation, such as that afforded by the emergence of Industry 4.0, may have the potential to transform design, with implications for DfCE. In addition to supporting the central focus of the thesis, these results may also be of value to other researchers interested in instigating change within design more broadly.

Chapter 7 identified existing barriers limiting the successful implementation of DfCE, providing understanding as to why it had not yet gained widespread adoption. To this end, an explorative literature review was employed, supported by in-depth, qualitative interviews with designers and representatives from entrepreneurial CE companies. The results provided a detailed account of the design process, highlighting key influential and limiting factors with the potential to derail DfCE implementation. These included those associated with the DfCE task, designers, organisations and external factors. The results also corroborated the findings from Chapter 6, demonstrating that design is heavily influenced and constrained by its industrial context, which is in turn a reflection of wider economic, social and cultural conditions. A limitation of this research was the fact that the in-depth nature of the qualitative interviews and the challenges faced in recruiting interview participants resulted in a relatively small sample size. The results therefore fell short of determining the extent or prevalence of the DfCE barriers identified, which is instead recommended for future research. Nevertheless, the contextualised and detailed exploration of key DfCE barriers was sufficient to provide a framework against which potential implications of Industry 4.0 could be assessed. Beyond the aims of this thesis, the results may also be of value for other purposes. Whilst mention of DfCE barriers exist within the wider literature, this chapter brings these together to provide a single point of reference, highlighting potential interactions between them. This may prove useful for designers, businesses and policy makers attempting to implement DfCE and wishing to avoid common pitfalls. The findings also represent a new direction for DfCE research, which has previously tended to consider the designer as an instigator for change, promoting designer awareness and training, when designers may not actually be free to act on this knowledge.

Chapter 8 explored the implications of Industry 4.0 for the design of consumer products. This involved a literature review combined with case studies depicting the early adoption of Industry 4.0 technologies and associated design outcomes. The results again reinforced the findings of Chapter 6, highlighting the fact that industry and design are inextricably linked. They also demonstrated that, whilst Industry 4.0 is first and foremost concentrated on the advancement of manufacturing, the impacts are far reaching with many implications for design. In addition to new manufacturing processes, implications identified included new product possibilities, changes to the design process and new business models. Further, it was found that such outcomes were not solely afforded by the direct application of Industry 4.0 technologies but were also the result of the changes they presented for economic, social and cultural conditions. The results of this research therefore suggest that there exists a significant relationship between

Industry 4.0 and design, promoting design as an important focus for the discussion surrounding Industry 4.0. A limitation of this research was that, as Industry 4.0 remains at an early stage of development, findings are based on an early or preliminary account of the emergent phenomenon. Additional implications for design may therefore arise as Industry 4.0 develops further. Nevertheless, the results were sufficient for providing an advanced awareness of the potential changes to design brought about by Industry 4.0, facilitating a comparative analysis with the results of Chapter 7. In addition to the purposes of this thesis, the results may also prove valuable for a variety of other stakeholders, including designers, educators and businesses attempting to prepare for the potential disruption and opportunity brought about by industry 4.0 technologies.

Chapter 9 brought together the results of Chapters 6, 7 and 8 in a thematic analysis in order to meet the overarching aim of this thesis. With the knowledge of how previous industrial transformation has impacted on design, as established in Chapter 6, the DfCE barriers identified in Chapter 7 were used as a framework against which the design implications of Industry 4.0, as determined in Chapter 8, were evaluated. From this it was possible to deduce the potential for Industry 4.0 to resolve or exacerbate existing DfCE barriers as well as to consider the possibility of new challenges and opportunities for DfCE implementation. The results of this chapter therefore present a clear DfCE agenda for Industry 4.0. By mapping this new research area created by the intersection between design, CE and Industry 4.0, it also outlines areas for future research, particularly those focused on individual aspects.

### 10.2 Key Findings and Conclusions

Key findings of the research presented in this thesis include the fact that, whilst DfCE is not currently a core focus of Industry 4.0, the phenomenon has the potential to present several key implications for its implementation. The first is the increased accessibility and affordability of digital design and production. This is likely to promote innovation, including that for a CE, by reducing risk and cost barriers. However, it may also simultaneously reduce the perceived value of physical products, resulting in an increase in the rate of production and waste generation. Industry 4.0 technologies are also expected to give rise to new product, process and business model possibilities, such as smart, connected products and new product service systems (PSS), which may be exploited for the purpose of achieving a CE. However, it must be taken into consideration that, whilst these opportunities may emerge, there is no guarantee that they will be exploited. Further to this, developments, such as the integration of electronics into products to facilitate the Internet of Things (IoT), may present new challenges for DfCE, for example, adding complexity to product disassembly and material recovery processes. The changing roles of designers and consumers, as well as the restructuring of organisations and value chains brought about by Industry 4.0 may also help to overcome existing DfCE barriers, such as a lack of designer autonomy. Although, it is important to recognise that such changes may also present new challenges, such as the inability to regulate design and production once these activities become decentralised. Finally, Industry 4.0 is also expected to alter and challenge prevailing economic, social and cultural conditions. Whilst previous industrial revolutions have reinforced key norms, including centralisation, standardisation, mass manufacture and the economies of scale principle, Industry 4.0 introduces decentralisation, mass customisation and economically feasible on-demand manufacture in batches of one. If realised, such developments will inevitably change what is profitable and the ways in which value is able to be generated and captured. With some foresight, this, coupled with a backdrop of disruption and change, may present opportunities for embedding DfCE within the next industrial paradigm. However, with the potential for such significant change, there also exists scope for further challenges and barriers to arise. Whilst these key findings do not provide definitive answers as to whether Industry 4.0 will or will not facilitate the future implementation of DfCE, they do provide an early mapping of key considerations, providing valuable awareness and foresight, and directing future research.

### 10.3 Research Evaluation

The central aim of the research was to explore the intersection between two emergent phenomena; Industry 4.0 and DfCE. The objective of this was to provide early insights regarding the potential opportunities and challenges afforded by Industry 4.0 for the future implementation of DfCE. The research therefore addressed an evolving, real-world sustainability problem, requiring a transdisciplinary, sustainability science approach.

Without an existing body of research upon which to build, an original research methodology had to be devised. Following the principles of sustainability science, it was important that this was problem-focused and solution-oriented, incorporated an element of stakeholder engagement and transcended disciplinary boundaries. The latter brought with it several challenges and limitations. In order to reconcile the theoretical issues associated with transcending disciplines with differing and opposing ontological and epistemological stances, it was necessary to adopt a critical realist positioning. This in turn entailed certain limitations with regards to the results of the research and the knowledge claims that could be made.

As critical realism is based on the belief that reality cannot be directly observed, the approach is focused on developing and revising robust, explanatory theories from available evidence in the form of experienced events. Research findings therefore remain fallible and revisable in light of further evidence. As the research presented within this thesis mapped a new area, the results may be considered an early conceptualisation of the relationship between Industry 4.0 and DfCE. It is expected that this will be further developed and refined as both phenomena continue to emerge and as additional research presents new evidence for consideration.

In order to improve the robustness of the research, triangulation was employed, both in terms of the research questions posed and the methods used to gather evidence. The research questions addressed the problem from three separate angles, including the relationship between design and industry to date (Chapter 6), existing barriers limiting DfCE implementation (Chapter 7) and the impact of Industry 4.0 on the design of consumer products (Chapter 8). The findings were then brought together in a thematic analysis (Chapter 9). The research methods employed were also triangulated, with Chapter 7 combining a review of the literature with primary research in the form of designer interviews, and Chapter 8 complimenting a review of the literature with case studies exploring the early adoption of Industry 4.0 technologies within a consumer product context. This triangulation helped to provide a variety of evidence, providing a richer understanding and helping to reduce the potential for bias.

A further limitation associated with addressing a complex, real-world problem and adopting a critical realist approach, was that the problem at hand could not be isolated or reduced to a simple question of cause and effect, with many interconnected variables at play. Instead, it was necessary to observe the problem in-situ, whilst narrowing the scope by defining the central focus of the research (i.e. Industry 4.0, CE and design). As such, it is important to acknowledge that the research is limited by its scope. For example, whilst the relevance of design to CE is well established in Chapter 3, it must be understood that other influential factors also exist. Further, in the case of CE, it is recognised that other models for sustainability exist, whilst the case for focusing on CE is made in Chapter 3. Additionally, Industry 4.0 is inextricably linked to various social, economic, political and technological systems, all of which may impact on its materialisation. Whilst Industry 4.0 is evidently relevant to the design of consumer products and, in turn, DfCE, it is not the only determining factor. In order to make the research feasible, the scope was further narrowed to focus on consumer products and the case for European Union countries. This was due to the fact that mass consumption of consumer products, as in the EU, has a significant environmental impact which may be addressed through the successful implementation of DfCE. Despite this narrowing, key findings may still be used to understand, explain and theorise with respect to other contexts and variables.

Finally, the research conducted was also limited by the time and resource constraints associated with a PhD project. However, in line with a critical realist approach, all evidence is considered valid, whether intensive or extensive, with theories and explanations becoming increasingly robust and refined as further evidence is gathered. Due to the limited sample sizes, both the designer interviews and Industry 4.0 case studies may not be considered statistically significant, nor representative of the wider population or situation. However, the results shed important, initial, in-depth insights that may guide further, more focused research aimed at determining the extent of observed trends. As such, the research presented within this thesis serves as a valuable initial scoping of a new and emergent research area.

Upon evaluation, the research presented in this thesis has begun to develop an understanding of the potential implications of Industry 4.0 for the implementation of DfCE. Whilst the results may not be considered definitive nor all-encompassing, they do provide valuable, advanced insights The qualitative nature of the research also means that the results do not shed light on the prevalence of the DfCE barriers and Industry 4.0 developments observed, however, this may be achieved through future research, underpinned by the findings of this thesis.

Additionally, as the thesis adopts a critical realist theoretical approach, it is acknowledged that reality, whilst objective, cannot be directly observed, but rather constructed from evidence in the form of experienced and observed events. As such, the results are in part influenced by the researcher's interpretations based on the evidence available at the time the research was conducted. The explanations and theories are therefore expected to change and evolve as new evidence comes to light and as Industry 4.0 matures. However, rather than rendering the findings of the thesis obsolete, as would be the case had the research adopted a reductive approach, the explanatory nature of the research means that the findings lay the groundwork for further development, whereby additional evidence helps to create ever more robust theories and explanations.

The research provides value in a number of ways. Firstly, it establishes a new area of research, cementing the relevance of Industry 4.0 within the DfCE discussion as a potential facilitator of change and opportunity. As an initial mapping of the subject, the research results create a DfCE agenda for Industry 4.0, presenting a variety of avenues for future research. The findings of the research also provide an advanced awareness of the potential implications of Industry 4.0 for

DfCE. As Industry 4.0 is still in an emergent stage, there exists the potential for early interventions to help exploit potential DfCE opportunities and safeguard against possible future challenges, embedding DfCE within the next industrial paradigm. As described in Chapter 10.1, the findings from each chapter may also be of value individually, helping to inform designers, educators, businesses and policy makers in the topics covered, i.e. the relationship between design and industry, existing barriers to DfCE implementation or the design implications of Industry 4.0.

Finally, from a more general perspective, the success of the research project, as a whole, may provide guidance to other researchers aiming to address complex, transdisciplinary sustainability science problems. This includes allowing the problem to frame the focus of the research, rather than existing disciplinary norms and practices, and structuring the research to produce findings that help to build solutions to the problem at hand. A critical realist theoretical positioning also presents a promising option for researchers needing to reconcile otherwise incompatible ontological and epistemological differences between disciplines that must be merged to effectively tackle real-world problems through transdisciplinary research.

This thesis therefore serves as a significant, original contribution to knowledge on a number of levels, from the identification and mapping of a new research area with significant potential for future research and the provision of advanced insights on emergent phenomena with practical applications to the outlining of an effective research approach in a fledgling discipline. Whilst the research is upfront about its limitations and what can and cannot be claimed with regards to the results, it has produced valuable insights and knew knowledge within an important and current field.

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