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Patient and Planet

Developing a Tool to Facilitate Design of Medical Products for a Circular Economy

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Abstract

Transitioning to a circular economy requires designing products that are meant to remain within and cycle through economic systems. While circular product design principles have been applied across industries, the medical industry presents unique challenges with its complex regulatory requirements and the high-risk nature of innovating with medical products. This thesis aims to contribute to the implementation of circular design strategies in the medical industry by developing a tool to that will enable industry professionals to apply these strategies in practice. Research areas included exploring circular product design principles and strategies in literature, design considerations relevant for medical products, and current industry practices, which contributed to developing the tool. Academic literature was first synthesised and used to structure the subsequent review of industry practices, which involved synthesising and analysing a range of data sources such as interviews, company reports and webpages, industry reports and relevant regulations. A draft tool was developed based on these reviews and refined based on practitioner feedback. The final tool aims to facilitate discussions between stakeholders involved in the design process of medical products and engage them in formulating and implementing circular design strategies. Evaluation of the tool and feedback from practitioners indicates that it adds great value in challenging existing processes and influencing practitioners to consider alternative methods. Medical product safety will continue to be highly regulated, but recent events such as the COVID-19 pandemic have clearly demonstrated the interlinkages between planetary and human health. The medical industry has the potential to redesign products to safeguard natural resources without compromising patient safety. The tool developed in this thesis proposes a method to considering industry-specific characteristics in this pursuit.

Keywords: circular product design, circular economy, medical industry, healthcare, design strategy

Executive Summary

Unsustainable economic models of resource extraction and consumption have contributed significantly to widespread environmental degradation. As populations increase and begin to age, not only does this result in increased consumption but also in increased pressures on healthcare systems. These are further strained as health issues related to climate change and exposure to new pathogens from destruction of natural habitats become more commonplace. The medical industry itself is a large contributor to global problems of waste generation, generating vast amounts of waste through a shift towards often unnecessary disposables and excessive decontamination policies (Campion et al., 2015). While strategies for circular product design hold great potential in slowing, narrowing and closing the flow of resources through economic systems, these are challenging to implement in the medical industry given the risks involved in innovating medical products and services, and treating contaminated or biohazardous medical waste (Bocken, de Pauw, Bakker, & van der Grinten, 2016; Kane, Bakker, & Balkenende, 2018).

Research Questions and Methodology

Various medical industry-specific restrictions exist for circular product design such as limitations related to health and safety standards and regulations, product approvals, testing, and other requirements. In addition, even within circular design literature there is a lack of practically applicable frameworks or tools that take into consideration industry-specific characteristics and that can be effectively utilised. The aim of this research is hence to contribute to the implementation of circular design strategies in the medical industry by developing a suitable tool. This was carried out by exploring the following main and sub-research questions (RQ and SRQs):

RQ: How can circular product design strategies be applied to the medical industry in practice?

SRQ 1: How are circular product design principles and strategies described in literature?

SRQ 2: Which design considerations are particularly relevant for medical products?

SRQ 3: What are the current circular product design practices being considered and/or implemented in the medical industry?

The key research stages involved in answering the SRQs were a literature review of academic research and an industry review of relevant grey literature such as company and industry reports and practitioner interviews. Based on these, a tool was developed to answer the RQ and refined taking into consideration feedback from practitioners about its practical value and usefulness.

Main Findings and Contributions

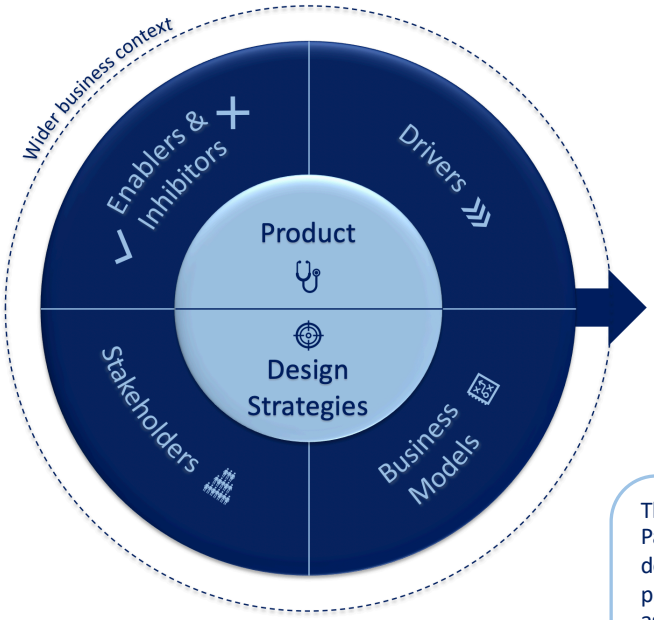
Answering the SRQs allowed the consolidation of research in a relatively unexplored area, i.e. applications of circular design principles and strategies in the medical industry. Building this foundation and knowledge base was essential in developing the tool for circular medical product design, which is the primary contribution of this thesis. In its entirety, this comprises of two refined diagrams together with introductory and explanatory text. The core elements and associated discussion points present an opportunity for stakeholders involved in the design process of medical products to consider incorporation of circular design principles. This resource is presented in the following pages in a format easily shareable and usable by practitioners.

PATIENT AND PLANET: DESIGNING MEDICAL PRODUCTS FOR A CIRCULAR ECONOMY

Roohi Ghelani, IIIEE, Lund University, 2020

Introduction

The circular economy is a vision of economic systems that manage resources optimally over time. An important step to achieving this vision is circular product design, or designing products to slow, narrow, and close the flows of resources through the system. For medical products in particular, design plays a crucial but high-risk role in the lives of patients. However, circular principles are challenging to implement in the medical industry with its complex regulatory requirements, although it is an industry in need of a circular transformation. The safeguarding of natural resources is crucial in safeguarding human health, whether from zoonotic illnesses or from health issues related to air pollution and other impacts of environmental destruction. The medical industry also generates vast amounts of waste when complete product sterility is often unnecessary.



Part 1: The Framework

Aim of the Circular Medical Product Design Tool

This tool aims to facilitate discussions between stakeholders involved in the design process of medical products, from industrial designers to upper management, on designing for circularity. It should ideally challenge existing processes and enable practitioners to consider alternative methods. This tool was developed iteratively and refined based on literature, practices of medical technology companies, and discussions with professionals including senior and industrial designers, industry experts and circular design consultants. Although intended for medical products, the tool can be generalised for medical software and services, ranges of products, or the entire design process, as appropriate.

Implementation

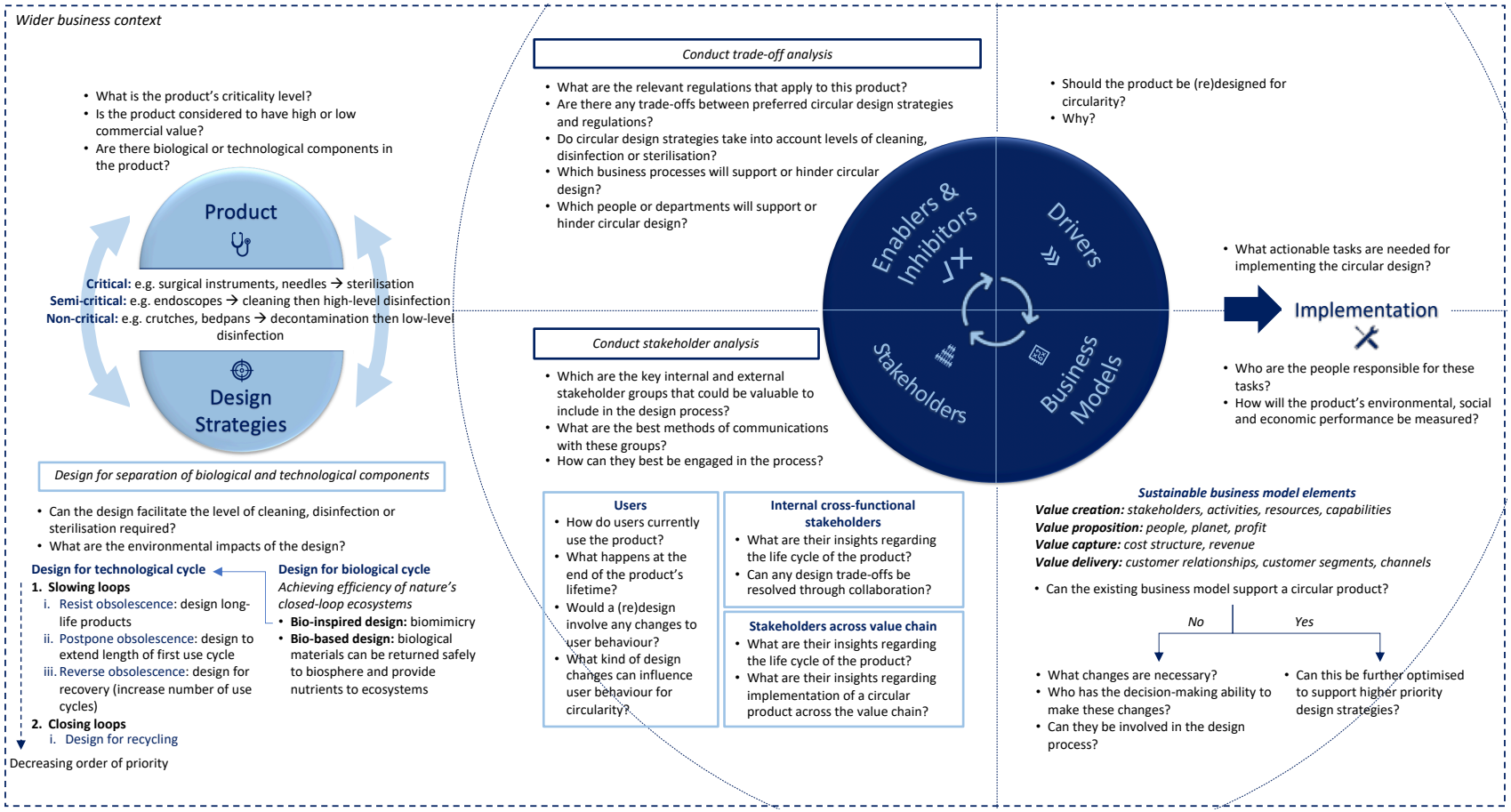
Tool Components

This tool is designed to be transformational and enable implementation of circular design strategies. **Part 1** summarises key elements necessary for consideration in circular design of medical products; all elements are interconnected and influence the design in an iterative process. **Part 2** takes the user through these in detail with associated questions.

General Guidance

The tool can be used in a workshop setting, for example, by discussing the relevance of the elements in Part 1, and any additional missing elements. With Part 2, questions can be discussed and action items determined. As a suggestion, users can begin with the core Product and Design Strategies elements then proceed outwards, or vice versa. This could be of use to medical product manufacturers and industry associations. Companies in any stage of implementing circular product design could benefit from understanding the considerations involved in doing so or reassessing internal design protocols through a new perspective. The tool can also be adapted to specific contexts by altering elements or associated questions.

DESIGNING MEDICAL PRODUCTS FOR A CIRCULAR ECONOMY
Design Considerations, Questions and Decisions



Part 2: The Decision-Making Guide

Medical products can be categorised as follows: Critical products enter sterile tissue or vascular systems and require sterilisation. Semi-critical products come into contact with non-intact skin or mucous membranes and require cleaning, then high-level chemical disinfection. Non-critical products come into contact with intact skin but not mucous membranes and require on-site decontamination with low-level disinfectants. Note that this is a simplistic summary; product-specific health, safety and regulatory requirements should be checked with appropriate medical professionals and designers.

The iterative and rigorous process of developing, refining and evaluating the tool allows it to contribute valuable insights into the study of circular design and/or medical applications of circular economy, while simultaneously providing value to practitioners in their work. These features distinguish this tool from others developed in literature and fill several gaps highlighted in this field. Practitioners have also confirmed the value of such a tool, and a rudimentary evaluation of its performance demonstrated that it meets seven out of 10 criteria suggested for developing sustainability tools (Bocken, Strupeit, Whalen, & Nußholz, 2019).

Conclusions and Recommendations

Industry practitioners, particularly professionals such as designers, do not lack knowledge about circular design strategies, they face difficulties in implementing them. The tool developed through this research does not solve the challenges of the medical industry but rather serves to engage key stakeholders in a process that will ideally result in progress towards applying these strategies in practice and contribute to the industry's transition to a circular economy. Recommendations to practitioners include pursuing circular product design actively beyond existing recycling strategies and engaging stakeholders who are able to operationalise strategies beyond the conceptualisation stage. This research has demonstrated the importance of open communication, transparency, and collaborating with stakeholders such as internal cross-functional personnel, parties across the value chain, and users of the products. Next stages for this research could involve operationalising and enhancing this tool, assessing the feasibility of implementing specific strategies for different types of medical products, and considering mechanisms for reverse flows and logistics of these strategies. Most importantly, it is necessary to conduct further practice-oriented, action-based and participatory research in order to truly contribute to changing practices and drive an industry transformation.

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Abbreviations

EHS	Environmental, Health and Safety
EC	European Commission
EU	European Union
GE	General Electric Company
HPRC	Healthcare Plastics Recycling Council
J&J	Johnson & Johnson
LCA	Life Cycle Assessment
RQ	Research Question
SRQ	Sub-research Question
USA	United States of America
USFDA	United States Food and Drug Administration
WEEE	Waste Electrical and Electronic Equipment

1 Introduction

1.1 Background and Significance

The world has reached a tipping point due to anthropogenic causes such as unsustainable and resource-intensive models of production and consumption (IPCC, 2014; Rockström et al., 2009). Environmental degradation is widespread and adverse impacts on ecosystems are starting to become irreversible. Boundaries to planetary resources, within which current economic models can safely operate, are close to being crossed (IPCC, 2014; Rockström et al., 2009). While these issues are common across industries, they are particularly complex in the medical industry, which presents unique challenges due to the risk involved in innovating medical products and services, and treating medical waste (Kane et al., 2018). Not only is the global population continuing to increase, resulting in more consumption, but it is also ageing, with the proportion of people over 60 years of age expected to double to approximately 2.1 billion by 2050 (United Nations, 2017). Healthcare systems are highly sensitive to external trends such as economic or health crises; an increasing and ageing population places further demands on these systems (Boorsma, 2016).

The current global pandemic of coronavirus disease, COVID-19, has demonstrated the vulnerability of healthcare systems around the world, including through its impact on the global demand of medical products. The pandemic has led to highly volatile markets, insecurities in medical supplies and drastic supply chain fluctuations (Lacina, 2020). As a zoonotic illness, it has also highlighted the close interlinkages between human health and the way in which humans interact with the environment (Polman, 2020; Shaikh, 2020; UN News, 2020). Human activity continues to disrupt ecosystems and destroy natural resources. As populations increasingly encroach into wild spaces, humans are gaining exposure to new pathogens (Polman, 2020). The establishment of planetary boundaries is necessary to reduce health issues across demographics, especially among vulnerable age groups (IPCC, 2014; Rockström et al., 2009). These include diseases transmitted from animals as well as health issues related to air pollution, climate change and the resultant extreme weather events (IPCC, 2014; Polman, 2020; Shaikh, 2020; UN News, 2020).

In addition to the global health issues, this pandemic has also highlighted the industry's problems with medical waste (Jain, 2020; Moduga, 2010; UN News, 2020). The medical industry has seen a shift towards disposable products largely driven by factors such as controlling infections, convenience and cost, however these are now resulting in increased expenses and waste, which are in many cases unnecessary (Campion et al., 2015). Decontamination policies in hospitals are becoming excessive; although studies have shown that complete sterility is impossible, efforts to achieve this continue and result in immense resource use, waste, emissions, and detrimental environmental impacts (Sanchez, Eckelman, & Sherman, 2020; Sherman & Hopf, 2018). Healthcare facilities in the United States of America (USA) alone generate 14,000 tonnes of waste daily, of which up to 25% may be plastic (Gibbens, 2019). Among modern healthcare facilities around the world, approximately 15% of total waste is hazardous and may be infectious, toxic, chemical or radioactive, however this proportion is much higher when waste separation is inadequate (World Health Organization, 2018). In many developed economies, medical waste management is an industry in itself resulting in significant environmental and management costs, which strain healthcare budgets (Moduga, 2010). Against this broader context of unsustainable economic models and challenges of waste generation and management, the circular economy is a vision of the economic system that focuses on managing resources optimally over time, shifting away from the traditionally linear take-make-dispose model (Blomsma & Brennan, 2017; Bocken et al., 2016).

1.1.1 Circular Economy

Circular economy has become a major buzzword across all sectors in recent years, and while businesses still largely operate in a linear economy with traditional business models, they are increasingly moving towards integrating circularity into their business models and operations. This is particularly true within the European Union (EU) where there is a political agenda for circularity (European Commission (EC), 2020a). In a circular economy, businesses attempt to shift from generating profits by selling products to generating profits from the flow of products and materials (Bocken et al., 2016). Issues of consumption, production and waste generation are addressed within a circular economy, which aims for an ideal state where materials continually loop back into the production system (den Hollander, Bakker, & Hultink, 2017).

The circular economy concept is predominantly an interdisciplinary reframing of resource and waste management strategies (Blomsma & Brennan, 2017; Pinheiro et al., 2019). While the individual strategies within the circular economy umbrella concept may not be new, reframing them within the circular economy umbrella concept enables a deeper understanding of the relationships and synergies between these strategies, which is essential for implementation (Blomsma & Brennan, 2017). It has been conceptualised by multiple seminal thinkers, think tanks, legislative bodies, businesses and in academia, with models and frameworks taking into account aspects such as technological and biological flows, stakeholders in supply chains, and various other flows of materials and products (Blomsma & Brennan, 2017). One highly regarded and often cited conceptualisation of the circular economy concept is Bocken et al. (2016)'s proposed framework of fundamental strategies for slowing, narrowing and closing resource loops and flows:

1. **Slowing loops:** strategies to slow loops aim to extend the usage of products through efforts such as designing for longevity or servicing and repair to extend lifetimes.
2. **Closing loops:** this strategy involves closing the flow between use and production, i.e. by ensuring products and materials flow from end-of-life back to being used as raw materials, either in the same forward supply chain or that of another sector.
3. **Narrowing flows:** this strategy aims to reduce resource use per product.

While the objective of both slowing and narrowing strategies is to reduce resource use, slowing involves an aspect of time by reducing the speed at which resources are used (Bocken et al., 2016). Narrowing resource flows has typically been implemented through resource efficiency initiatives by companies within the traditional linear system. However, if this is not supplemented by strategies to slow and close loops, rebound effects could lead to a more efficient linear system, causing an increase in production and consumption (Bocken et al., 2016).

1.1.2 Circular Product Design

The theoretical framework of the circular economy encompasses a wide range of concepts, principles and approaches to implementation, such as circular business models, circular supply chain management, circular product design, and various others. Industry applications of these concepts together with academic research in this field has been facilitating the transition to a circular economy. Strategies for circular product design are particularly critical because products have typically been designed to become obsolete and disposed in short periods of time, promoting shorter life cycles, greater consumption, and higher levels of material throughput and waste (Bakker, Wang, Huisman, & den Hollander, 2014). In the lifetime of a product, the design function is one that could have the largest impact across the rest of the life cycle if considerations of resource consumption and waste generation are incorporated within it. Once product specifications have been decided and supporting resources and infrastructure around the product have been allocated, only minor changes are typically possible (Bocken et al., 2016;

Pinheiro et al., 2019). Circular product design hence has the potential to create positive feedback loops across entire supply chains and markets, resulting in significant environmental benefits.

Key Terminology

Incorporating circular principles in product design enables products and materials to remain part of the system in various forms through multiple cycles. They can be recovered from various forms of obsolescence such as aesthetic, social, technological or functional, which may not necessarily be irreversible (den Hollander et al., 2017). Design for circularity enables the limits of obsolescence to be pushed and maximised, while simultaneously minimising losses of products and materials to the biosphere[1]. In addition, circular design encompasses considerations of consumption behaviour, hence several key terms in circular design literature can be defined with respect to perceived value and the product's context (den Hollander et al., 2017).

The optimal lifetime of a product is proposed to be up to the point where the environmental impacts of using the product are equal to the impacts associated with switching to a more energy efficient product, or one with lower embedded environmental impacts (Bakker et al., 2014). While products have only one lifetime until the point when they become obsolete beyond recovery at the product level, they can have multiple use cycles, wherein they become obsolete within that particular cycle, but this obsolescence can be reversed through recovery (den Hollander et al., 2017). Recovery aims to reverse obsolescence between use cycles rather than aim only for material recovery at the end of a product's lifetime (den Hollander et al., 2017).

1.2 Problem Definition

1.2.1 Challenges for Circularity in the Medical Industry

While circular product design holds great potential to transform production and consumption patterns and waste generation, there are significant challenges in implementing these principles in the medical industry as much of the waste generated is contaminated or categorised as biohazardous[2]. Product design plays a crucial but high-risk role in delivering benefits to consumers or users of medical products, wherein the slightest change in functionality of any element could have impacts on a patient's health or life (Kane et al., 2018). As such, medical products have stringent safety requirements which make it difficult to incorporate certain circular design principles and strategies, particularly around reuse and recovery, while maintaining compliance with relevant regulations (Kane et al., 2018). Various medical industry-specific restrictions exist for circular product design in addition to the inherent limitations pertaining to legislation on health and safety standards, product approvals, testing, and other requirements. A growing market for home healthcare products and the resultant shift away from centralised supply chains adds another layer of complexity for certain strategies such as implementing take-back systems. Circular product design in the medical industry has not been explored much in research, and literature is lacking in design strategies, guiding principles and comprehensive frameworks tailored to suit the industry's characteristics and considerations (Kane et al., 2018). The rationale for narrowing the focus of this research to the medical industry lies in the challenges faced in implementing circular design and the enormous potential benefits that could arise from research that contributes to circularity in this field.

[1] The biosphere is comprised of the parts of Earth where living organisms are present, including the complex of soil, water, air and organisms that forms an ecosystem (Gillard, 1969).

[2] Biohazards are "biological substances that pose a threat to (human) health" and include medical wastes (Shroder, 2015, p. xxi).

1.2.2 Gaps in Circular Product Design Theory

Within circular product design literature, there is consensus that important research gaps still remain. Researchers agree that guiding tools geared specifically towards product designers are needed, and that these should help them conceptualise an ideal vision rather than incremental improvements (Bakker et al., 2014; Bocken et al., 2016; den Hollander et al., 2017; Johansson & Woodilla, 2011; Lofthouse & Prendeville, 2018; van den Berg & Bakker, 2015). There is a lack of integrated and comprehensive frameworks with practical applicability. The industry applications, effectiveness and impacts of integrating circular product design concepts vary significantly within and between sectors, based on factors such as materials and resources for production, applicable regulations, type of industry actors, stakeholder priorities, and many others. However, studies mostly have conceptual approaches with theoretical examples but are not systematically applied across industries and in product design processes (Bovea & Pérez-Belis, 2012; Mestre & Cooper, 2017; Pinheiro et al., 2019; Prendeville, O'Connor, Bocken, & Bakker, 2017; van den Berg & Bakker, 2015). Research on how industry-specific characteristics enable or hinder implementation of circular product design is limited, particularly studies which consider biological materials[3] (Mestre & Cooper, 2017; Pinheiro et al., 2019). As potential solutions, industry-specific guiding tools specifically for designers that are clear, simple, easy to use, do not require excessive time and knowledge to use, and do not have excessive overlap from various disciplines are recommended (Bovea & Pérez-Belis, 2012; Kane et al., 2018; Prendeville et al., 2017; van den Berg & Bakker, 2015).

1.3 Aim and Research Questions

The aim of this thesis is to contribute to the implementation of circular product design strategies in the medical industry by developing a practically useful tool. This tool will be tailored for stakeholders involved in the design process of medical products and allow them to develop and implement circular design strategies. To meet the aim and achieve the objective of developing a tool, a primary research question (RQ) will be investigated and answered through exploring further sub-research questions (SRQs):

RQ: How can circular product design strategies be applied to the medical industry in practice?

SRQ 1: How are circular product design principles and strategies described in literature?

SRQ 2: Which design considerations are particularly relevant for medical products?

SRQ 3: What are the current circular product design practices being considered and/or implemented in the medical industry?

1.4 Scope and Limitations

The scope of this study was restricted to design of non-consumable medical products or devices. These range from critical[4] products such as surgical instruments to non-critical products such as crutches, including those with electronic components (Rutala & Weber, 2008). The literature review stage was limited to design-specific considerations on a general product level and examined product strategies rather than company strategies. In the review of industry practices, several medical technology companies producing medical devices were considered, with

[3] Biological materials are organic materials that "can be safely returned to the biosphere" to be utilised by other organisms "without generating waste" (Mestre & Cooper, 2017, p. S1623).

[4] Product criticality is a form of categorisation of medical products as per the Spaulding classification system, further expanded in Subchapter 3.3 (Rutala & Weber, 2008).

selection determined by criteria elaborated in Subchapter 2.2.2. In the later stages of the thesis, interviewee insights guided the expansion of the scope to include a systemic perspective or wider business strategy considerations in the development of the final tool. Other methodological decisions and their rationale are detailed in Chapter 2.

This research was conducted from a strategy perspective, be it design- or product-specific, or wider business-oriented, hence technical specifications and a detailed review of the various regulations affecting medical product were excluded. This was decided based on the lack of technical or legal expertise and the reasonable assumption that industry professionals, one of the main target groups for this study, are more well-versed in legislation and requirements affecting the design of their products. These exclusions and the lack of a case study present potential limitations. Taking into account the complexities of medical products in greater detail than their level of criticality was also a challenge. Medical products vary significantly in terms of materials, use and level of regulation. These characteristics made it challenging to review in detail the specifics of products and their different requirements, hence the decision to include all medical products within the scope of this thesis. While this presents a limitation in terms of not being able to take into account the various complexities of medical products, it also enabled a focus on higher level strategies and the ability to make industry-level observations.

1.5 Audience and Implications

This thesis aims to address the gaps in applications of circular product design concepts and strategies through a tool for the medical industry. This is anticipated to provide a starting point for professionals involved in the product design process to incorporate circular principles into their work. It will ideally facilitate discussions around design protocols, priorities, trade-offs and dilemmas, and create a space for innovation within the boundaries of medical health and safety restrictions. This research will provide useful industry-specific insights not only for medical product design professionals, thus providing a practical contribution, but also for researchers investigating circular economy, circular product design, and practical applications of these concepts, adding a theoretical contribution to the general theme of circular product design.

1.6 Outline

Chapter 1 lays the foundation of this thesis, describes the wider context and significance, and provides a background of key concepts. The problem, research aim and questions are then defined, and the scope, limitations and implications of this study are outlined.

Chapter 2 describes the methods used to conduct this research and provides a rationale for the research design. This includes an evaluation of the methods used, description of the data collection, review and analysis process, and addressing of ethical considerations.

Chapters 3 and 4 present a comprehensive review and synthesis of current circular product design strategies, principles, approaches and applications both in academic literature and in industry practices. These chapters answer the SRQs and provide a basis for answering the main RQ.

Chapter 5 presents the development and refinement of the tool for circular medical product design, developed from the literature and industry reviews in the previous chapters.

Chapter 6 discusses and evaluates the findings of this research and their applicability in practice. Implications of the developed tool are discussed and reflected upon.

Chapter 7 concludes on the thesis, provides recommendations for the intended audience and outlines potential areas for future research based on this thesis.

2 Research Methodology

This chapter presents the research design and methods used in this thesis. The chapter begins with an overview, followed by the design of the research and rationale, details on the key research areas and the development of the proposed tool, and lastly the ethical considerations of this research. Overall, this thesis involved a review of literature and industry practices, which contributed to answering the three SRQs as shown in Figure 2-1. Theories and frameworks obtained from literature and insights from industry perspectives were integrated into a medical industry-specific framework to answer the main RQ.

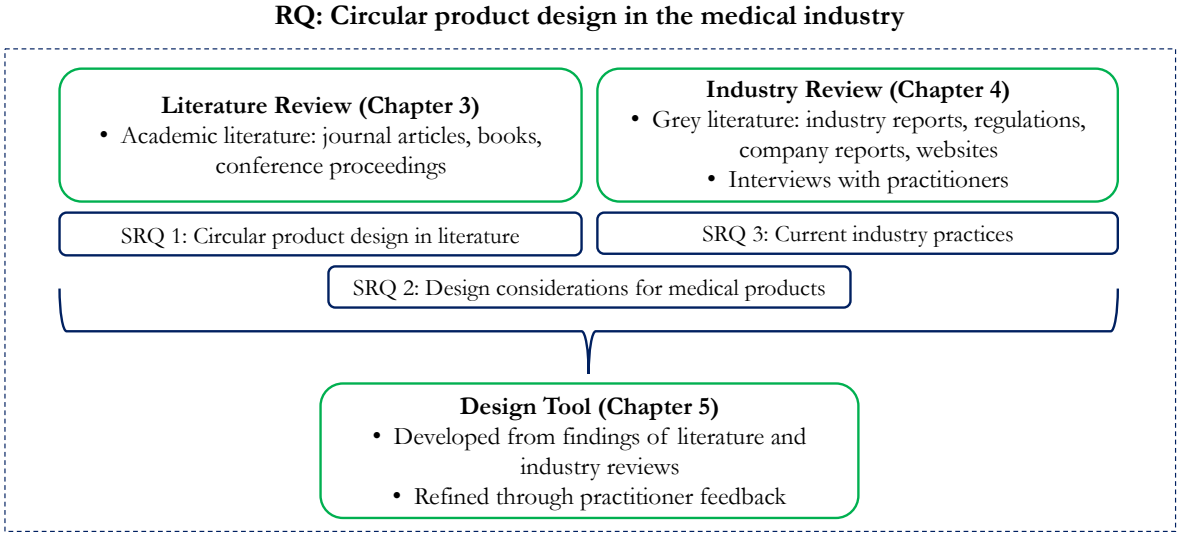

Figure 2-1. Overview of research process

Source: Author

2.1 Research Design

This research was designed to be both exploratory and applied research. An exploratory approach was found to be best suited to first develop an understanding of the knowledge gap in applications of circular design research in the medical industry (Blaikie, 2010; Kane et al., 2018). This understanding was then applied in facilitating a change in industry practices by way of developing a suitable tool (Blaikie, 2010). The research strategy for this thesis combined both deductive and inductive strategies. A deductive strategy was employed initially to determine current state of literature on circular product design theory (Chapter 3) and to understand industry practices (Chapter 4). An inductive strategy was then used in combining findings from literature and industry practices to develop a new tool for the medical industry (Chapter 5) (Blaikie, 2010).

The research paradigm of social realism was found to be most aligned with the purposes and strategies of this thesis. Social realism advocates that reality consists of structures that produce certain events but are independent of them, regardless of whether the events are observed or experienced (Blaikie, 2010). The aim of research in social realism is to discover these underlying structures and mechanisms, which corresponds with the exploratory purpose of this thesis in understanding the mechanisms of circular design in a specific industry application. The ontological assumption regarding the nature of reality follows one of cautious realism most closely, in that a cautious or critical approach must be used in observing reality and acknowledging that observation itself is subjective and interpretive (Blaikie, 2010). The epistemological assumption on how reality is known follows constructionism, which advocates

that the research conducted reflects the views, theories and background knowledge of the researcher and their interpretation (Blaikie, 2010). Both the ontological and epistemological assumptions reflect the methods used in this thesis, which presents an interpretation of academic theory and industry practices in a tool developed based on the researcher's analysis of the reality studied.

Qualitative research methods were used in the collection and analysis of data, as is detailed in the following subchapters. A range of primary, secondary and tertiary data was obtained from various sources; literature and industry practices were reviewed, analysed, and their findings presented in line with observed themes, i.e. analysed through thematic analysis. Qualitative methods were found to be most suitable for exploring circular design practices in literature and in the medical industry, and necessary in developing a tool based on an interpretation of findings. By its nature this resulted in a limitation due to data sources and interpretations being subject to researcher bias and normative judgments (Blaikie, 2010). However, biases and normative judgments are inherent in quantitative data collection and analysis as well (Fischer, 1995). A qualitative design enabled patterns, common themes, insights on wider contexts, and potential implications of observations to be drawn from the various data sources which could not discretely be measured in numerical or quantitative form (Blaikie, 2010). Another limitation of the research design was that the manual and qualitative analysis of findings potentially resulted in decreased replicability of this research (Blaikie, 2010). In addition, through these qualitative methods it was not possible to ascertain statistical significance of any trends or patterns observed either in literature or within industry practices. To compensate for these and to increase replicability as far as possible, the following subchapters describe the methods in detail.

2.2 Data Collection and Analysis

2.2.1 Reviewing of Literature

The aims of the literature review were to understand what is known about circular product design from previous research (SRQ 1[5]), and how medical applications have been studied in academic literature (SRQ 2[6]) (Blaikie, 2010). Secondary and tertiary data in the form of academic literature was reviewed, including peer-reviewed journal articles and conference proceedings. Variations of key terms and their combinations were searched in academic databases such as Science Direct and Google Scholar. Some examples include:

> Circular (product) design, product design for circularity, eco-design, eco-design dilemmas/trade-offs/contradictions, circular (product) design and medical (products/industry/sector)

Further articles were obtained by identifying relevant ones from those cited by initially reviewed articles, as well as from supervisor recommendations. The selection of articles considered the following factors but was not entirely restricted to these in cases where relevant content was covered and key terms were included:

1. Time of publication: articles published in the past five years were preferred
2. Number of citations: a higher number of citations was taken to imply wider acceptance of the proposed framework in the scientific community

[5] SRQ 1: How are circular product design principles and strategies described in literature?

[6] SRQ 2: Which design considerations are particularly relevant for medical products?

3. Newness of the elements in the proposed framework: articles which introduced or added new elements when compared to previously established frameworks were preferred to obtain a broader range of theoretical considerations

Extracts from the literature review were synthesised through manual input into an Excel spreadsheet according to the main concepts covered in the articles, key findings, and their relevance to the RQ and SRQs of this thesis. This systematic organisation of the qualitative data enabled an overview to be obtained as well as the identification of key elements and common themes discussed in literature, and their synergies and contradictions.

2.2.2 Reviewing of Industry Practices

The aim of the industry review was to explore how the medical industry approaches and implements circular design practices (SRQs 2 and 3[7]). Various sources were reviewed to obtain a holistic understanding of the industry; these can be broken down into the following components. Data collection methods for each of these are detailed below, and findings are synthesised in Chapter 4.

1. **Industry overview:** brief review of secondary grey literature in the form of key regulations and industry reports
2. **Company practices:** review of secondary grey literature in the form of annual and sustainability reports and webpages of selected medical technology companies
3. **Practitioner insights:** review of primary data in the form of interviews

Findings from the industry overview, company practices and interviews were thematically analysed and presented in an integrated manner with each component supplementing the other. This manner of presentation was to allow a coherent framing of corroborating insights obtained from the different components. A presentation structured by data sources may not have been as conducive to understanding the larger narrative.

Industry Overview

An awareness of some of the relevant requirements and general medical industry guidelines was determined to be valuable before exploring company practices in depth. These would allow insight into the aspects of circular design that could be implemented in the sector within the given limitations. A search was conducted on the key regulations pertaining to medical products in the EU and USA[8]. Another search was conducted for any guidelines or best practices for circular design of medical products by industry associations in these jurisdictions. As described in Subchapter 1.4, these documents were only reviewed briefly to inform a high-level overview of the industry.

Company Practices

To understand practices being undertaken or considered by industry actors for circular medical product design, medical technology companies were selected to be reviewed. Selection criteria were revised as the research progressed, as shown in Figure 2-2. Criteria 1 and 2 were considered to be most important, seeing as they formed the core of this thesis. The initial aim was to review ten companies to be able to draw informed conclusions. Industry leaders, or companies with large market shares, were preferred as these companies were more likely to have better-developed circular design programmes and initiatives, as well as have a greater impact through

[7] SRQ 3: What are the current circular product design practices being considered and/or implemented in the medical industry?

[8] The geographic scope is defined by the companies selected in the following subchapter.

these than smaller ones. Finally, companies based in Scandinavia were initially preferred since this region has strong policy drivers for sustainability and circularity for both public and private actors.

Figure 2-2. Progression of company selection criteria

Source: Author

Upon initiating the search for companies fitting these criteria, it was found that the largest medical technology companies were not Scandinavian (Fenske, Barbella, & Brusco, 2019). The geographic scope was hence widened to include companies from around the world, selecting from Fenske et al. (2019)'s list of 2019's top thirty medical device manufacturers, but still prioritising the inclusion of European companies. Of the ten companies selected, three did not appear to be implementing any circular design initiatives based on their publicly available information. Finally, the following seven companies were reviewed in detail:

Figure 2-3. Companies selected for review and their headquarters

Source: Compiled by author

The qualitative data reviewed in this stage was secondary data in the form of annual and sustainability reports, websites and other publicly available information of the selected companies. Companies were reviewed by observing the following aspects within their stated practices, compiling manually in an Excel spreadsheet similarly as for the literature review, and analysing themes, similarities and differences. The aspects to be reviewed were identified based on key concepts and aspects in literature which seemed to be the most relevant to the medical industry. Further granularity on the nature and extent of circular design efforts was obtained through various subcategories.

1. Product offering: description of the range of products offered by the company, in terms of product criticality[9]

[9] Product criticality is a form of categorisation of medical products as per the Spaulding classification system, further expanded in Subchapter 3.3 (Rutala & Weber, 2008).

2. Circular product design strategies: whether design strategies implied or explicitly mentioned align with slowing or closing loop strategies[10] as derived from literature
3. Design-related considerations:
    a. Life cycle perspective and stakeholder collaboration: considerations of product life cycles and engaging stakeholders across the value chain
    b. Treatment of design dilemmas: whether any contradictions, trade-offs or dilemmas in circular design are mentioned, and if so, how they are treated
4. Implementation of circular design initiatives:
    a. Explicitness of mentions: whether circular product design is implied or explicitly stated
    b. Differentiation of efforts: ranging from mentions of circular design, to efforts integrated into business-as-usual practices, to distinct programmes
    c. Implementation stage: how far along the companies are in terms of implementing strategies, initiatives or programmes
5. Other considerations: for any other circular design considerations or points raised which were not identified in literature

Practitioner Perspectives

Five semi-structured interviews were conducted with practitioners in March and April 2020 to gain deeper insights into industry practices. Primary data was gathered in the form of their answers to interview questions, insights and perspectives. Interviewees and their relevance to this thesis are summarised in Table 2-1; further details about the interviews are provided in Appendix A: Interview Details.

Table 2-1. Practitioners interviewed and relevance to thesis

Interviewee code[11] and role	Responsibilities	Relevance to thesis
Interviewee A Expert in a medical industry association	Responsible for innovation and research issues with projects including financing innovation projects and enhancing the collaborative climate between member companies and regulators.	To hear industry-wide insights gained from experience working with numerous medical technology companies.
Interviewee B Industrial designer in a large pharmaceutical company	Front end innovation for new solutions incorporating industrial design and human aspects, ranging from physical products to services and digital experience.	To understand the design process for medical products, protocols and priorities, decision-making, and considerations and restrictions for circular design.
Interviewee C Senior designer in a large health technology company	Working with colleagues dedicated to circular economy, conducting trainings and networking, driving organisational part of circular transformation through systemic design.	

[10] See further details in Subchapter 3.1.1.

[11] Names are excluded to protect confidentiality.

Interviewee code[11] and role	Responsibilities	Relevance to thesis
Interviewee D Specialist in a large pharmaceutical company	Part of the global sustainability team, specific role is regarding device and packaging sustainability, including life cycle assessments (LCAs) associated with devices or packaging introduced.	To understand design considerations and life cycle perspectives involved in product sustainability.
Interviewee E Business and design lead of a design studio and consultancy	Leads the organisation and responsible for design of circular apparel and products through design thinking, new technology, circular economy principles and biomimicry. Provides consultancy on circular product design.	To understand design priorities, the decision-making process for circular design, and considerations and challenges for organisational change in traditionally linear industries.

Source: Compiled by author

Interview guides were developed based on the analysis of academic and grey literature and tailored according to the interviewee's area of expertise. Generalised guides are attached in the appendices; however, these were tailored to suit each interviewee and new directions were pursued according to the flow of conversation during the interviews. The aim of the interviews was to supplement findings from the review of companies and gain a broader perspective on industry practices. Key themes for questions were around understanding the interviewees' perspectives on circular product design concepts used in the industry, the design process, wider industry trends and context, and the utility of a possible design tool.

2.2.3 Towards the Development of a Tool for Circular Medical Product Design

Incorporating and building on the findings of the review of literature and industry practices, a tool for circular medical product design was developed to answer the main RQ[12]. This was done in several stages:

1. **Synthesis of literature:** Frameworks and design strategies from articles studied in the literature review were compiled and synthesised, as in Subchapter 3.4. This was done by identifying elements most significant within literature and relevant to the medical industry, based on corroboration by other researchers in literature and academic judgment.
2. **Synthesis of industry practices:** A similar process was repeated for synthesising the findings of the industry review, as in Subchapter 4.4; key elements were synthesised based on major themes identified from literature as well as additional ones obtained from industry insights.
3. **Development of draft tool:** A draft was developed based on criteria for developing sustainability tools and included certain aspects determined to be valuable from the previous two steps and discussions with practitioners and thesis supervisors.
4. **Refinement of tool:** Feedback on the draft tool was requested from interviewees. Their comments and those from thesis supervisors were taken into consideration to refine the tool and ensure it would be of practical value.
5. **Evaluation of tool:** The tool was evaluated based on the checklist of criteria for sustainability tool development used to create the initial draft. Insights from

[12] RQ: How can circular product design strategies be applied to the medical industry in practice?

practitioners on elements that would be useful in their work were also considered during evaluation.

2.3 Ethical Considerations

This project aims to create significant environmental benefits by developing a circular product design tool for the medical industry, hence there is not likely to be any potential for the results of the research to be harmful in any way to the reputation, dignity or privacy of the interviewees or the companies reviewed. This research was not funded by an external organisation, there were no conflicts of interest, and there was no person in a position to influence the analysis or conclusions other than thesis supervisors. All data and records have been maintained on the author's laptop and backed up to the cloud. Ethical responsibilities to the subjects of research included consent, confidentiality and courtesy. Companies whose circular design practices were reviewed were studied based on publicly available information, hence there is not likely to be any potential that they may suffer disadvantages from the review, and confidentiality is not required to be addressed. Interviewees were provided with the aim and a description of this research, their anticipated level of involvement and confidentiality aspects. An example of a document sent out to potential interviewees is shown in Appendix E: Project Brief for Interviewees[13]. All interviewees were asked for permission to record interviews and to refer to their responses, position and organisation. All were aware that the final thesis is a document of public record. No direct quotes were used. Interviewees have not been named, no vulnerable people have been interviewed, and there is no cause to believe that any interviewee may suffer disadvantage or damage from their participation in the research. This work is unlikely to unjustifiably raise the expectations of interviewees or harm their relationships with other people. A copy of the final thesis report will be sent to all interviewees.

2.4 Impact of the COVID-19 Pandemic on Data Collection

The industry review portion of this research was originally envisioned to involve more interviews with representatives of the reviewed companies. This was in order to obtain a more nuanced understanding of the reviewed companies' practices, deeper insights, and clarification of any misunderstandings. However, due to challenges in setting up interviews and availability of contacted professionals, only one interview was conducted with a practitioner from the reviewed companies. This limitation was mostly overcome by interviewing a broader range of interviewees, each of whom contributed valuable insights and enabled a wider perspective of the industry to be obtained, as well as brief reviews of relevant regulations and industry reports. The implications of this are discussed in Subchapter 6.2.

[13] This was tailored as appropriate; in some cases, confidentiality was elaborated more in the interviews than in the brief.

3 Circular Product Design and Medical Applications in Literature

This chapter presents a synthesis of current literature on circular product design and its applications and considerations for medical products. Subchapter 3.1 presents a review of the circular product design concept and various theoretical frameworks and strategies proposed in literature, including applicable findings from eco-design literature and dilemmas in circular design. Sociological considerations for circular design are briefly presented in Subchapter 3.2. Medical products and design considerations as studied in literature are explored in Subchapter 3.3, including a classification of medical products, life cycle aspects and circularity in medical product design. This chapter concludes with a summary of key elements obtained from the various theories, concepts, frameworks, strategies and considerations reviewed and to be potentially incorporated in the tool developed in Chapter 5.

3.1 Circular Product Design

Materials and product design is understood to be one of the fundamental building blocks for a transition to a circular economy, along with new business models, global reverse networks and enabling conditions (Planing, 2015). When discussing product design for a circular economy, a key distinction is made between the concepts of eco-design and circular product design in literature.

Eco-design follows a relative approach, aiming for moving upwards in the waste hierarchy which prioritises waste prevention, then reuse, then recycling, then recovery, and lastly disposal as a last resort. While eco-design principles have been well developed and implemented in various jurisdictions, the validity of these principles are questioned when applied to facilitate a transition to a circular economy (den Hollander et al., 2017).

Circular product design follows the Inertia Principle, which states (Stahel, 2010, p. 195):

"Do not repair what is not broken, do not remanufacture something that can be repaired, do not recycle a product that can be remanufactured. … Replace or treat only the smallest possible part in order to maintain the existing economic value of the technical system"

The aim of circular product design is to maintain product integrity and keep the product in a state as close to the original as possible (den Hollander et al., 2017). Unlike eco-design, circular product design does not intend to move upwards in any hierarchy but rather designs for the utopian goal of an entirely closed-loop system without any concept of waste (den Hollander et al., 2017). While dissipative losses[14] are unavoidable, the key difference between eco-design and circular product design is in their ambitions and intentions around waste.

3.1.1 Frameworks and Strategies for Circular Product Design

Various typologies, approaches, strategies, frameworks and guidelines for circular product design have been developed in literature. Most have common elements but with slightly different approaches and focuses. Five of the main ones are summarised in the following table, then described with commentary on their elements and distinguishing features.

[14] "Dissipative losses are the flows of materials from the anthroposphere (i.e., human systems) to the biosphere (i.e., environment) in a manner that makes their future recovery extremely difficult, if not impossible" (Ciacci, Reck, Nassar, & Graedel, 2015, p. 9443).

Table 3-1. Summary of circular product design frameworks

Author(s)	Description	Key elements
Bocken et al. (2016)	Framework based on the three loops framework for the circular economy (slowing, closing and narrowing resource loops and flows).	Design strategies consider mechanisms for resource flows, built around slowing and closing loops. Biological and technological cycles are separated.
den Hollander et al. (2017)	Developed a typology based on new definitions in terms of obsolescence and perceived value rather than functionality.	Product design for recycling and integrity, ranked according to order of priority.
van den Berg and Bakker (2015)	Builds on Ellen MacArthur Foundation (2013)'s circular economy figure but for circular product design.	Includes a model, vision, detailed guidelines and a spider map emphasising a life cycle perspective for visualising progress towards achieving designs for futureproofing, disassembly, maintenance, remaking and recycling.
Mestre and Cooper (2017)	Four loop strategies covering various aspects that should be included in the design stage.	Design strategies for a life cycle perspective, separation of biological and technological cycles, and slowing and closing resource loops.
Pinheiro et al. (2019)	Looks into main circular economy practices in new product development, with drivers, barriers and stakeholders, resulting in an integrative framework.	Adapts Ellen MacArthur Foundation (2015)'s ReSOLVE framework (REgenerate, Share, Optimise, Loop, Virtualise, and Exchange).

Source: Compiled by author

Slowing and Closing Loops as per Bocken et al. (2016)

The framework proposed by Bocken et al. (2016) is considered a seminal piece and is highly regarded by researchers in this field. Bocken et al. (2016) conduct a comprehensive literature review and categorise circular design strategies according to their framework for slowing and closing resource loops. This was developed to provide a coherent framework at a product design level, addressing the problem of diverging circular economy terminology in literature and providing a guide for designers and decision-makers. These strategies for circular product design are distinguished based on how resources flow within the system, acknowledging that linear and circular economic models have fundamentally different mechanisms for resources flows (Bocken et al., 2016). Strategies for slowing loops are essentially around extending the period of utilisation through strategies for emotional and physical durability and designing for service loops. The design strategies for closing loops are around the two possible fates for waste in a circular system: recycling or reuse, or dissipative loss. Closing loop strategies hence aim to make dissipative losses compatible with biological systems, and completely recycle all other products and materials in a technological cycle (Bocken et al., 2016).

Design for Product Integrity and Recycling as per den Hollander et al. (2017)

According to den Hollander et al. (2017), strategies for circular product design achieve two main purposes: design for product integrity or design for recycling. They develop a typology of design approaches specifically for product integrity, ranked in order of priority to help designers

compare and communicate for decision-making. The order of priority goes from resisting obsolescence by designing for long use, to postponing obsolescence by designing for extended use, and finally to reversing obsolescence by designing for recovery. The differentiating elements here are that by obsolescence, they refer to the loss of perceived value, which can be reversed through recovery. This does not only refer to material recovery at the end of a product's lifetime but can also be between the product's use cycles (den Hollander et al., 2017). Den Hollander et al. (2017)'s strategies for product integrity align well with Bocken et al. (2016)'s strategies for slowing loops, and both frameworks can be combined as demonstrated in Figure 3-1.

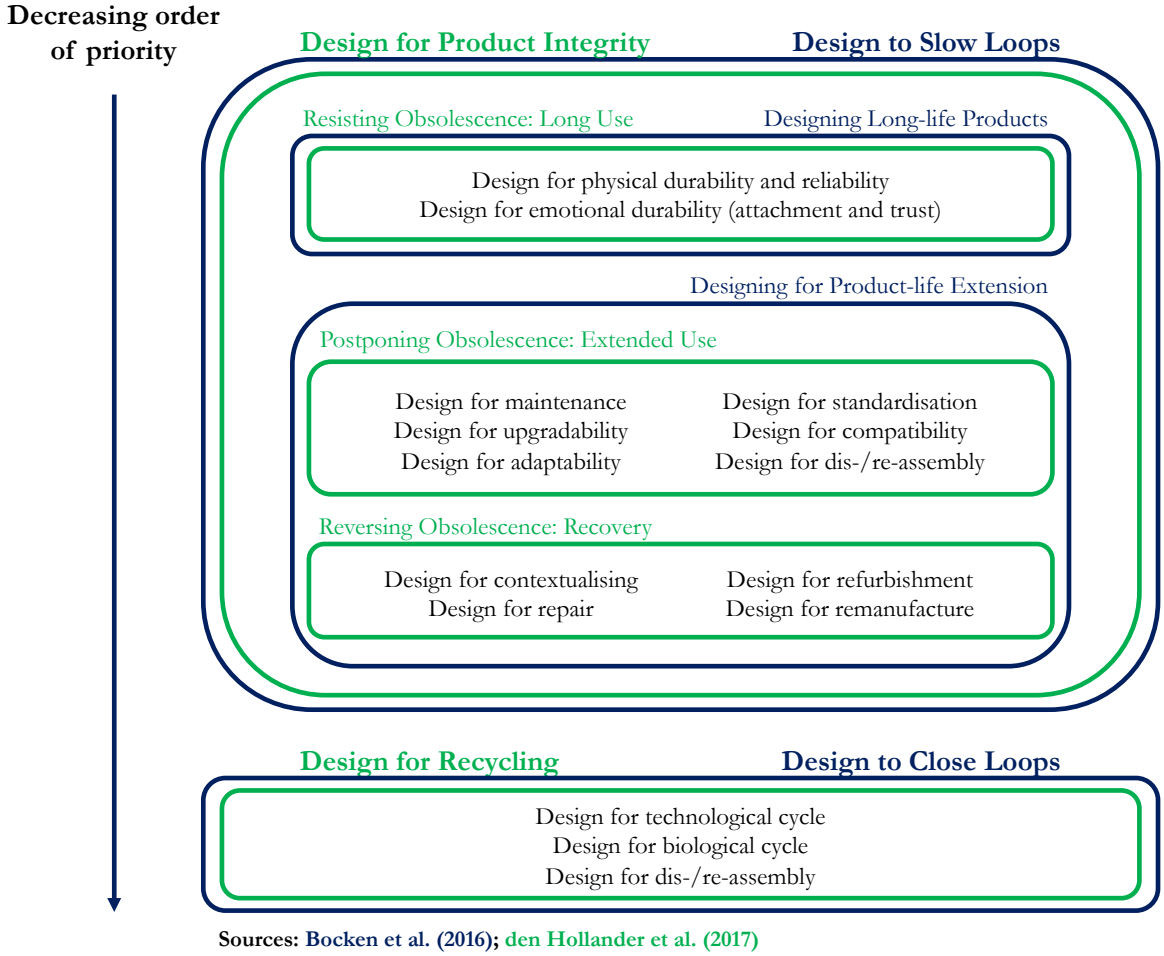

Figure 3-1. Aligning design strategies for slowing and closing loops with product integrity and recycling

Source: Built upon Bocken et al. (2016) and den Hollander et al. (2017)

Model, Vision, and Tools as per van den Berg and Bakker (2015)

Van den Berg and Bakker (2015) develop a model adapted from the Ellen MacArthur Foundation (2013)'s circular economy framework but with a product design perspective. The aim of their study is to create a new understanding of circular product design encompassing five main characteristics throughout the life cycle of a product: future-proof, disassembly, maintenance, remake and recycling. Three new tools for designers are developed: (1) a model and vision for an overview, (2) detailed guidelines for each of the five main characteristics, and (3) a spider map useful for comparing products or as a discussion tool (van den Berg & Bakker, 2015). The detailed guidelines can also be categorised according to Bocken et al. (2016)'s design strategies for slowing and closing resource loops.

Multiple Loops Life Cycle Design Strategies as per Mestre and Cooper (2017)

Mestre and Cooper (2017) contribute to literature with a clear separation and consideration of technological and biological cycles, and a life cycle perspective, both of which are not as apparent in other circular design frameworks. Their proposed multiple loops life cycle design strategic framework essentially consists of four loop strategies. The broader categories are designs for a technical, or technological, and a biological cycle. Technical cycles refer to materials and energy while biological cycles refer to natural ecosystems. Within these broader categories, design strategies are further categorised as follows:

1. **Design for a technical cycle**
    a. Strategies to slow loops
    b. Strategies to close loops
2. **Design for a biological cycle**
    a. Bio-inspired loop strategies
    b. Bio-based loop strategies

Strategies for each of these four loops are then detailed with a comprehensive list of possible activities for each life cycle stage from new concept development to end-of-life disposal. Under this framework, Mestre and Cooper (2017) assert that designs for slowing and closing loops in a technical cycle can be implemented incrementally and optimised through current business models although specific situations may call for more radical changes. Designs for bio-inspired and bio-based loops in a biological cycle typically require more radical innovation seeing as material cycling for natural ecosystems needs to be as close to perfect as possible. They are also clear in stating that designs for both technical and biological cycles should be implemented together (Mestre & Cooper, 2017).

Integrative Framework for New Product Development within a Circular Economy as per Pinheiro et al. (2019)

Pinheiro et al. (2019) analyse through a literature review the main circular economy practices and actions applied to new product development, and the drivers, barriers and key stakeholders involved in integrating these practices. A framework is then developed based on this, presenting an overview of the main aspects and considerations of new product development in a circular economy, and circular principles that could be applied. The ReSOLVE framework of the Ellen MacArthur Foundation is adapted to contextualise the findings of this study's literature review (Pinheiro et al., 2019). Key findings from this study show that adopting the following ReSOLVE concepts would be best suited for specific product types and development stages:

1. **Service-oriented products**
    a. Share: keeping product loop speeds low and maximising utilisation
    b. Virtualise: virtually delivering utility
2. **Pre-use and use stage:**
    a. Regenerate: maintaining and enhancing the earth's biocapacity
    b. Optimise: increasing product performance or efficiency
    c. Exchange: replacing old materials with upgraded technologies
3. **Post-use stage:**
    a. Loop: closing material and product loops

3.1.2 Applicable Findings from Eco-Design Literature

Although circular product design has been distinguished from eco-design, certain findings from eco-design literature are still relevant for the purposes of this thesis. In alignment with circular

design strategies to slow loops and extend product lifetimes (Bocken et al., 2016; den Hollander et al., 2017), Bakker et al. (2014) explore a range of product life extension strategies to understand how product design can proactively address life extension and recycling. They also propose a hierarchy of product design strategies based on the waste hierarchy, which forms the framework of eco-design principles, prioritising prevention over reuse over recycling. This does not add novel elements to the frameworks discussed above, however their conclusions are valuable for this research. They conclude that a tailored approach is needed for different products, and product design should take into consideration characteristics of different products such as their lifespans, technological maturity, resource intensity, and business constraints, including market dynamics and legislation (Bakker et al., 2014). They also highlight the importance of incorporating a sociological perspective, for example through social practice theory, to understand how and why shorter lifespans are being accepted (Bakker et al., 2014).

Other key eco-design literature includes a summary of main guidelines for integrating environmental considerations into product development, organised according to life cycle stages (Luttropp & Lagerstedt, 2006). Luttropp and Lagerstedt's (2006) "Ten Golden Rules" are designed as a tool to aid designers in improving and/or comparing the environmental performance of product concepts, and is an example of a guide that is most useful when customised to the needs and specific requirements of the designer, product or context (Bovea & Pérez-Belis, 2012). Bovea and Pérez-Belis (2012) write about the key factors for optimising the inclusion of environmental considerations in the design process: (1) early integration, which allows time for incorporating changes, (2) a life cycle perspective, as supported by Mestre and Cooper (2017), and (3) a multi-criteria approach that combines general product requirements with both environmental aspects and impacts. Their review of various eco-design tools provided insights on qualitative, semi-qualitative and quantitative design frameworks and tools. Qualitative and semi-qualitative frameworks are fairly quick and easy to use and can be used early in the product design and development process, however they may not be entirely reliable. On the other hand, while quantitative tools enable a detailed profile of a product's environmental aspects and impacts to be determined, significant data is required, and such tools are typically used in later stages of the design process, by which time only minor changes can typically be made (Bocken et al., 2016; Bovea & Pérez-Belis, 2012; Pinheiro et al., 2019)

3.1.3 Contradictions and Dilemmas in Circular Product Design

Incorporating environmental considerations and circular principles in product design can be challenging, not only because of conflicts and contradictions between circular principles and traditional design priorities, but also within circular product design strategies. Some examples include the following:

> *Using lightweight materials to slow and narrow loops contradicting strategies for closing loops by increasing difficulty of recycling (Bocken et al., 2016)*
>
> *Trade-offs between extending the use cycle and lifetime of a product when newer versions are more energy-efficient (den Hollander et al., 2017)*
>
> *Increasing product durability by using composite materials, which conflicts with recyclability (Mestre & Cooper, 2017)*
>
> *Using recycled content in products which might shorten the lifetime and reduce durability (Prendeville et al., 2017)*

Prendeville et al. (2017) propose a classification of types of dilemmas and a unified approach to managing these, and although they study dilemmas in the context of eco-design, their findings

can be applicable to circular design as well. Dilemmas are first defined as "scenarios that either pose upfront challenges to the decision-maker, or later lead to one or more unexpected or contradictory outcomes" (Prendeville et al., 2017, p. 1327). According to them, the term 'trade-off' has more positivist connotations emphasising an aspect of measuring product performance, while 'dilemma' represents a constructivist perspective, taking into considerations real-world experiences of designers in managing the conflicting aspects of design dilemmas (Prendeville et al., 2017). Their classification distinguishes between the following types of design dilemmas (Prendeville et al., 2017, pp. 1335-1336):

1. **Tensions** are bilateral dilemmas, such as design for disassembly conflicting with durability
2. **Hierarchies** are when dominant or reinforcing strategies preclude others, such as when disassembly favours recyclability but not durability
3. **Contradictions** such as unintended increases in environmental impacts
4. **Oversights** are when emphasis on one aspect leads to blind spots for others

The suggested method to managing such dilemmas is to have a unified and systematic approach across all decision-making levels, where actions combine operational, tactical and strategic functions and are customised according to appropriateness for the business model (Prendeville et al., 2017).

3.2 Sociology of Human-Centred Design

Bringing in social science insights, design's origins as a radical humanist paradigm mean that if this paradigm is to be followed in product design, practices should consider nuances and contextual considerations about the role of people in society, and relationships between people and products (Johansson & Woodilla, 2011; Lofthouse & Prendeville, 2018). The current discourse around product design, particularly within the circular economy agenda, is mainly in positivist terms and discussed with a technocratic framing. In other words, circular product design is mainly studied within the disciplines of management, engineering, ecology and environmental science, with production systems and technical approaches and solutions being prioritised (Lofthouse & Prendeville, 2018). Lofthouse and Prendeville (2018) argue for an expansion of the role and opportunities for designers to include insights from social science disciplines such as consumption behaviour, psychology of consumers and studies of cultural contexts. To facilitate a truly transformative move to a circular economy, systems and patterns of consumption and production should be studied by first understanding the deeply embedded societal issues of overconsumption and consumerism and framings of the ethics around them (Hobson & Lynch, 2016).

Considering sociological perspectives when implementing certain circular economy concepts enables a much broader range and deeper understanding of behaviours to be considered. For example, preferences for convenience and cost, the fallacy of purely rational, cognitive decision-making, and the influence of habits and past routines all affect purchasing decisions and consumer behaviour, which would be highly beneficial aspects to be considered right from the design stage (Botelho, Ferreira Dias, Ferreira, & Pinto, 2016; Jackson, 2004; Lofthouse & Prendeville, 2018). The circular product design discourse can be made more nuanced by including considerations of how individual identities and lifestyles are symbolically represented by consumption practices, the relationship between consumer pressure and product satisfaction, and social practice perspectives (Featherstone, 2007; Lofthouse & Prendeville, 2018).

Reviews of circular economy and product design literature have attempted to consolidate findings from diverging framings and terminologies (Bocken et al., 2016; den Hollander et al., 2017). Within these frameworks it is important to shift away from approaching people as

subjects to people as participants; this has the potential to broaden consumer involvement in the transition to a circular economy (Lofthouse & Prendeville, 2018). Incorporating a sociological perspective in product design could be in the form of updating design practices to be more human-centred and future-oriented, and to consider the temporal dimension particularly with products with multiple use cycles (den Hollander et al., 2017; Lofthouse & Prendeville, 2018).

3.3 Medical Products and Design Considerations

The medical industry and its products have been studied in literature, including design considerations for such products. This Subchapter describes a classification system for medical products and explores certain design considerations such as life cycle perspectives, collaborations and circularity in medical product design as derived from literature.

Products in the medical industry face significant scrutiny due to the inherent risks and potential impacts they have on users' health and lives. Medical products cover a vast range, from items such as crutches and bandages to injection needles and implants. The Spaulding classification system is a widely-used scale for categorising medical products and equipment according to product criticality, or the degree of risk of infection involved in using these products and the corresponding levels of disinfection or sterilisation required (McDonnell & Burke, 2011; Rutala & Weber, 2008). According to the Spaulding scale, medical products can be categorised as critical, semi-critical, or non-critical. The following examples and required levels of disinfection or sterilisation are recommended:

Table 3-2. Medical products classified by the Spaulding scale

Classification	Critical	Semi-critical	Non-critical
Description	Products that enter sterile tissue or vascular systems	Products that come into contact with non-intact skin or mucous membranes	Products that come into contact with intact skin but not mucous membranes
Examples	Surgical instruments, implants, needles	Endoscopes, equipment for anaesthesia	Patient care items: crutches, bedpans Environmental surfaces: bed rails, utensils
Level of disinfection or sterilisation	Sterilised with steam, gas plasma or liquid chemical sterilants	Cleaning, then high-level chemical disinfection	Decontaminated on site with low-level disinfectants

Source: Compiled based on Rutala and Weber (2008)

Concerns about the Spaulding scale have been voiced, largely around its oversimplification of medical products. This includes problems with complicated medical products, particularly if components fall under different levels of criticality; heat and chemical sensitivity of certain materials or products; and specific methods and optimal timings for disinfection (McDonnell & Burke, 2011; Rutala & Weber, 2008). Notwithstanding that, it remains a widely applicable and used classification system (McDonnell & Burke, 2011; Rutala & Weber, 2008). For the purposes of this thesis, further exploration of the critiques of the Spaulding scale and suggested improvements was deemed out of scope.

3.3.1 Life Cycle Considerations and Collaborations

The medical value chain is highly complex with significant risks and impacts, countless stakeholders, intricate relationships between products, human health and socio-economic aspects, and information asymmetry with upstream operations being largely removed from end-consumer use and waste (Viegas, Bond, Vaz, & Bertolo, 2019). When assessing medical products, particularly from environmental and economic perspectives, it is hence crucial to consider a life cycle perspective (Campion et al., 2015; Kaiser, Eagan, & Shaner, 2001; Sanchez et al., 2020; Willskytt & Tillman, 2019). This is particularly true when comparing whether medical products designed for extended lifetimes – reusable products, for example – have greater environmental benefits than single-use or disposable ones. Figure 3-2 shows a generalised life cycle of disposable and reusable medical products, adapted from a study assessing trade-offs between disposable and reusable blood pressure cuffs. In this figure, material flows are restricted to those outlined in the study, hence the exclusion of reverse material flows after product disposal.

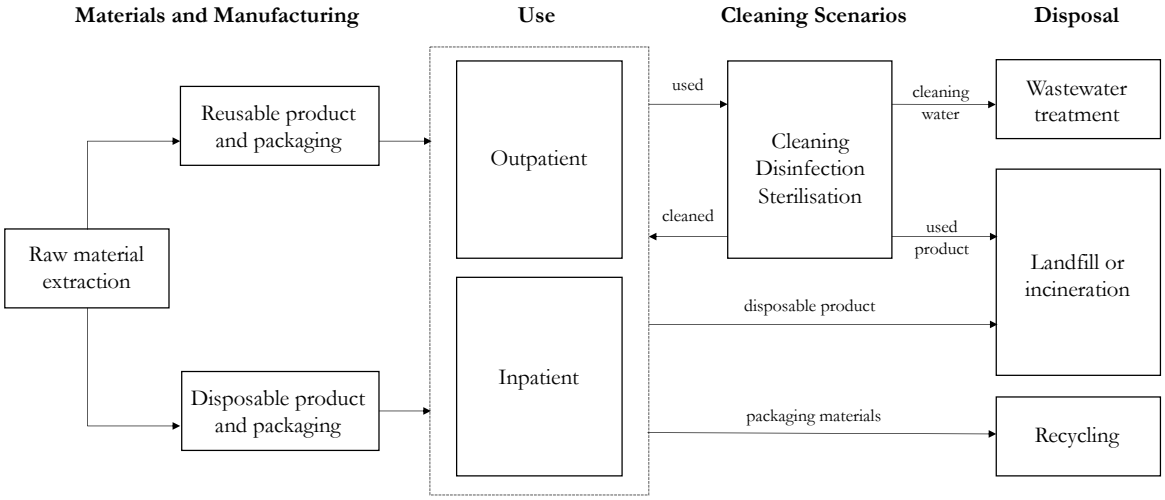

Figure 3-2. Simplified life cycle stages of disposable and reusable medical products without reverse material flows

Source: Adapted from Sanchez et al. (2020)

Whether reusable products are environmentally preferable to disposable ones highly depends on a range of variables, and a clear consensus is lacking in literature. With a life cycle perspective, the energy, water, chemical and labour demands of using reusable products can be observed, together with considerations of materials, manufacturing, transport and waste with regards to disposable products (Sanchez et al., 2020; Willskytt & Tillman, 2019). These are all important considerations for designers to factor in together with the design of the product itself (Sanchez et al., 2020).

The role of designers and manufacturers of medical products has shifted to one that requires close collaborations between various stakeholders within the company and across value chain functions (Boorsma, 2016; Campion et al., 2015; Eagan & Kaiser, 2002; Kaiser et al., 2001; Malchesky, Chamberlain, Scott-Conner, Salis, & Wallace, 1995; Subramoniam, Huisingh, & Chinnam, 2010; Viegas et al., 2019). Manufacturers have a high degree of accountability in delivering sterile products without having any control over how they are used in medical settings, which is an added incentive for developing an in-depth understanding of exactly how their products will be used (Malchesky et al., 1995). Green purchasing is one option that has been suggested for greater transparency in the medical product value chain, which is something

researchers recommend that buyers of medical products push for (Campion et al., 2015; Eagan & Kaiser, 2002; Kaiser et al., 2001).

As an example of a green purchasing tool for the medical industry, the Health Care Environmental Purchasing Tool is a supplier assessment method for medical facilities. It provides some perspective of environmental aspects that could be considered by buyers of medical products and highlights the importance of greater dialogue between designers, manufacturers and buyers. The tool was developed by researchers in collaboration with a number of actors from various healthcare organisations and State-level authorities in the USA (Eagan & Kaiser, 2002; Kaiser et al., 2001). The tool comprises of a questionnaire allowing medical product buyers to assess the environmental impacts of medical and healthcare products across their life cycles. While much of the questionnaire is technical, certain design-related considerations are also requested to be disclosed by suppliers. These can be categorised by life cycle stage according to whether they contribute to slowing or closing resource loops as follows (Eagan & Kaiser, 2002; Kaiser et al., 2001):

1. **Manufacturing**: recycled materials used in manufacturing (closing loops)
2. **Packaging and Distribution**: recycled materials used in packaging (closing loops)
3. **Use and Service**: design for disassembly, maintenance and/or repair (slowing loops, specifically product life extension)
4. **End-of-Life**: design for disassembly, refurbishment, and/or remanufacturing (closing loops)

3.3.2 Medical Product Design and Circularity

When implementing circular design principles, particularly for medical products, the nature of the product, the supporting infrastructure around it, and the relationship between design elements for functionality and circularity are some important factors to be considered (Bocken et al., 2016; Kane et al., 2018; Malchesky et al., 1995). Kane et al. (2018) conduct a literature review on how circular economy principles in the medical industry are approached and studied both in research and practice, and the associated challenges and opportunities. They find that the key factors for circular product design in the medical industry are (Kane et al., 2018):

1. **Level of criticality and corresponding sterilisation requirements:** these determine design constraints
2. **Product value:** this influences appropriateness and feasibility of recovery strategies such as whether a product is refurbished, remanufactured or recycled
3. **Organisational structure around product:** this does not directly affect design guidelines but allows for a wider consideration of potential product-service systems

Based on these findings, strategies for circular design of medical products are suggested and categorised in relation to level of product criticality and value, as shown in Figure 3-3, which are intended to enable designers to make decisions on product features or elements to optimise different forms of recovery (Kane et al., 2018). A major concern for any circular design strategy is design to facilitate cleaning, which includes considerations such as material selection, flexibility of equipment, disassembled pieces, joints and sealing (Drues, 2015; Malchesky et al., 1995). Certain trade-offs are inherent in this; for example, increased modularity may have implications for degree of cleaning possible, but decreasing modularity has implications for separation and recyclability (Malchesky et al., 1995). Manufacturers are also more likely to assign a higher Spaulding scale classification, both for safety reasons and to increase purchases of their products when users face challenges in conducting the appropriate level of cleaning, however this may result in buyers simply switching to single-use or disposable products for ease of use (Sherman & Hopf, 2018).

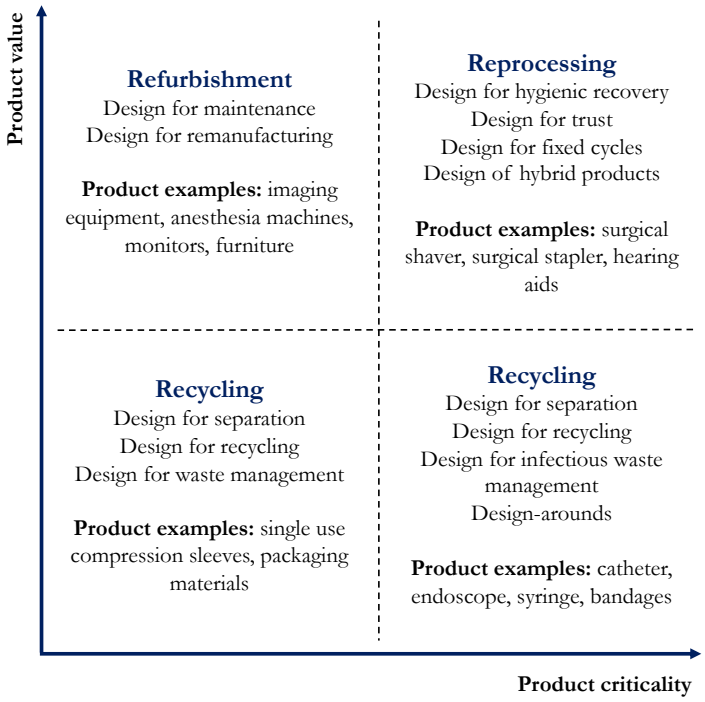

Figure 3-3. Design strategies for medical products by product value and criticality

Source: Adapted from Kane et al. (2018)

To conclude, studies agree that the primary concern for designing medical products will always continue to be user health and safety, followed by cost (Sanchez et al., 2020). That being said, complete sterilisation is not necessary when the various cleaning methods outlined for products of different criticalities are effective, particularly in the case of non-critical products (Albert et al., 2010; Sherman & Hopf, 2018). There is much potential in redesigning medical products with circular design principles in a way that meets their functional requirements while at the same time minimises their environmental impacts (Kane et al., 2018; Sanchez et al., 2020).

3.4 Summary of Literature

This review aimed to understand how circular product design principles and strategies are established in literature, and to begin exploring applicability for these in the medical industry. Insights into four key areas were obtained:

1. **Concepts and definitions** included in circular design research and their subjectivity
2. **Current state of research** on proposed circular design strategies, guiding principles, tools and frameworks
3. **Medical applications** and their corresponding considerations and strategies
4. **Challenges and research gaps** that exist in circular design research and its applications in the medical industry

Based on the literature review, Figure 3-4 was created to illustrate the synthesis of literature on circular design theory and medical industry-specific design considerations. Key elements of the concepts, strategies, frameworks and applications discussed above were incorporated into this figure. The arrows represent flows of resources, materials, information and interactions; squares represent products and include in text their design considerations; circles represent materials and include in text their design considerations.

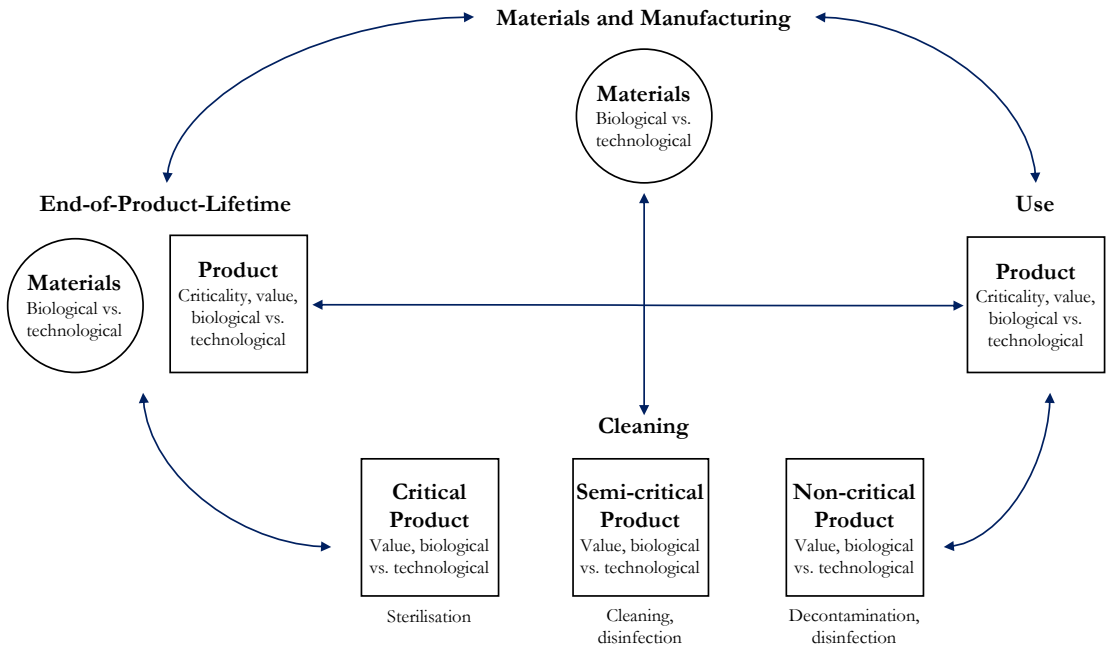

Figure 3-4. Synthesis of literature on circular product design and medical applications

Source: Author

There was general consensus that a life cycle perspective is crucial to be considered in the design stage, particularly for medical products (Boorsma, 2016; Bovea & Pérez-Belis, 2012; Campion et al., 2015; Eagan & Kaiser, 2002; Kaiser et al., 2001; Malchesky et al., 1995; Mestre & Cooper, 2017; Sanchez et al., 2020; Subramoniam et al., 2010; van den Berg & Bakker, 2015; Viegas et al., 2019). The synthesised figure follows a simplified life cycle perspective as derived above in Figure 3-2 (Sanchez et al., 2020). In addition to a life cycle perspective, collaboration and exchanges of information between various actors and stakeholders was emphasised, which is included in the flows between life cycle stages. An ideal vision of a circular economy with zero waste is depicted, following den Hollander et al. (2017)'s aim of circular product design, however it is also understood that dissipative losses are unavoidable, hence the importance of design considerations for both biological and technological cycles (Bocken et al., 2016; Mestre & Cooper, 2017). The flows of materials and resources between life cycle stages include design considerations for slowing and closing resource loops, and designing for longer and multiple product use cycles (Bocken et al., 2016; den Hollander et al., 2017).

At the product level, key design considerations, particularly for the use, cleaning and end-of-product-lifetime stages, include product criticality as per its Spaulding classification, product value, and biological and technological components (Kane et al., 2018; Rutala & Weber, 2008; Sanchez et al., 2020). Finally, the end-of-product-lifetime stage is defined as the point at which the product is beyond recovery at the product level, at which point end-of-product-lifetime options must be considered according to product criticality, value, and biological and technological components to eliminate technological losses and minimise dissipative biological losses (Bocken et al., 2016; den Hollander et al., 2017; Kane et al., 2018; Mestre & Cooper, 2017; Rutala & Weber, 2008; Sanchez et al., 2020). All the elements described here were also taken into consideration when developing the tool in Chapter 5, as detailed in Subchapter 5.3.1.

4 Circular Product Design Practices in the Medical Industry

This chapter presents a synthesis of current circular design practices in the medical industry. A brief overview of the industry is first presented, informed by a review of secondary grey literature such as key regulations. This is followed by detailed findings from company practices and practitioner perspectives, based on primary and secondary data including grey literature of the seven selected companies and interviews. This is presented thematically to provide a comprehensive review of the medical industry. The circular design strategies and considerations observed from company reports are outlined, including life cycle perspectives, stakeholder engagement and design dilemmas. The companies' implementation of circular design is then detailed. Insights gained from interviews are integrated into these themes, and practitioners' views on opportunities for implementing circular design and transforming the industry are also presented separately. The chapter concludes with a summary of medical industry practices.

4.1 Industry Overview

The medical and healthcare industry is complex, with expansive value chains and a vast network of stakeholders, as shown in Figure 4-1 (Srivatsav, Dervojeda, Lengton, & Koonstra, 2017). It is a highly regulated industry with numerous laws spanning across different jurisdictions to control for the safety and effectiveness of medical products.

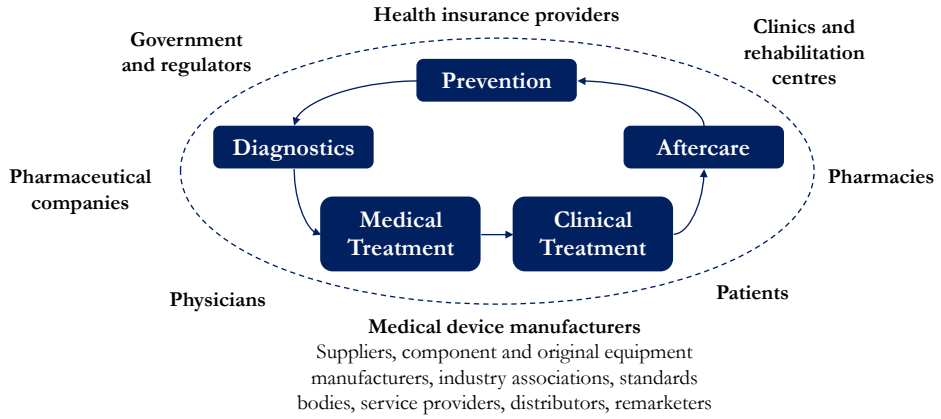

Figure 4-1. Value chain and stakeholders of the medical and healthcare industry

Source: Adapted from Srivatsav et al. (2017)

From a brief review of publications from industry associations, it was found that a wide range of guidelines and best practice recommendations have been developed for different segments of the medical industry, covering various aspects of manufacturing medical products. In a report to the EC on deploying key enabling technologies in Europe, Srivatsav et al. (2017) describe that adding to the complexity of designing medical products is the fact that medical technology is not developed in isolation. The medical industry is strongly influenced by developments in adjacent industries such as pharmaceuticals, electronics, engineering, and telecommunications (Srivatsav et al., 2017). For example, electronics companies are beginning to offer healthcare-related products such as pedometers, relying on engineering expertise for developing new technologies, with data storage by telecommunications providers (Srivatsav et al., 2017).

Overall, the interdependencies and relationships between stakeholders involved in the medical and relevant adjacent industries make the incorporation of circular design principles a challenging process, particularly when value chains extend across several regions, each with a

different set of regulations, standards and guidelines. According to interviewees A and C, circular product design in the medical industry is still maturing and discussions are largely limited to those interested in such topics. However, they agree that mindsets are changing and that there is great potential; the tipping point for industry-wide transformation is within sight.

4.1.1 Key Regulations Affecting Medical Product Design

The seven reviewed companies are headquartered in the EU and USA; hence, this subchapter provides a brief overview of the key regulations in these jurisdictions with influence on the design of medical products.

Regulation in the EU

Medical products in the EU are regulated by three Directives[15], which include rules on safety and performance of medical devices, and the CE conformity mark (EC, 2018; French-Mowat & Burnett, 2012). The Directives were repealed in 2017 with new Regulations[16] for tighter *ex ante* controls on safety and effectiveness (EC, 2017, 2018, 2020b; EU, 2018). Some of these include greater market transparency through a database and traceability system, regulation of several previously unregulated aesthetic products such as non-prescription contact lenses, and stricter controls for practices such as reprocessing single-use devices (EC, 2017, 2020b; EU, 2018). Other legislation affecting medical products and their design in the EU include Directives and Regulations covering waste electrical and electronic equipment (WEEE), the use of chemicals and hazardous substances, battery disposal, and packaging waste (TÜV SÜD, 2020).

Regulation in the USA

The U.S. Food and Drug Administration (USFDA) regulates companies which manufacture, import, repackage or relabel medical products distributed in the USA (USFDA, 2018, 2020). Medical products are classified according to level of regulatory control required; Class I products do not need to issue notifications before entering the market, Class II products require pre-market notification, and Class III products require pre-market approval (USFDA, 2018). Title 21 of the Code of Federal Regulations stipulates requirements covering various aspects of products' life cycles, from design to manufacture to post-market surveillance (Kotipalo, 2018; USFDA, 2020). Part 820, Subpart C on Design Controls covers the entire design process including planning, review, verification, validation and any design changes (FDA Design Controls, 2019; USFDA, 2020).

The strictness and number of regulations in the medical industry make designing medical products a challenging process to begin with; rethinking their design to include circular design strategies presents a significant barrier when compliance with all applicable legislation and requirements must be reassessed and revalidated. This may make designers and other key decisionmakers wary of making drastic changes to their design processes.

4.1.2 Overview of Reviewed Medical Technology Companies

To understand how medical technology companies are approaching and implementing circular product design, grey literature and publicly available information of the seven selected companies was reviewed. Table 4-1 presents a summary of findings from this review according to key themes identified from literature.

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[15] Council Directive 90/385/EEC on Active Implantable Medical Devices (AIMDD) (1990), Council Directive 93/42/EEC on Medical Devices (MDD) (1993), and Council Directive 98/79/EC on in vitro Diagnostic Medical Devices (IVDMD) (1998)

[16] Regulation (EU) 2017/745 and Regulation (EU) 2017/746

Table 4-1. Summary of findings on circular product design from medical technology company reports and websites

Company	PHILIPS	SIEMENS Healthineers	sonova HEAR THE WORLD	Medtronic	Johnson & Johnson	GE Healthcare	Baxter
Product criticality	Critical to non-critical	Critical to non-critical	Semi-critical and non-critical	Critical to non-critical	Critical to non-critical	Critical to non-critical	Critical to non-critical
Circular design strategies	Mostly slowing and closing, but presence of narrowing loop strategies as well Slowing loop strategies: resisting, postponing and reversing obsolescence	Slowing loop strategies: resisting, postponing and reversing obsolescence	Mostly narrowing, but presence of slowing and closing loop strategies as well Slowing loop strategies: postponing and reversing obsolescence	Narrowing and closing loop strategies	Slowing, narrowing and closing loop strategies Slowing loop strategies: postponing and reversing obsolescence	Slowing loop strategies: resisting, postponing and reversing obsolescence	Slowing, narrowing and closing loop strategies Slowing loop strategies: postponing and reversing obsolescence
Life cycle perspective	Life cycle assessments (LCAs) used to guide design and grow sustainable portfolio	Life cycle perspective considered in context of refurbished imaging equipment	LCAs used in product research and development to enhance circular design strategies	Life cycle impacts considered in design to reduce footprint Trialling LCA software	Product stewardship tool guides LCAs to improve life cycle areas with highest potential impact	Life cycle perspective considered in context of refurbished imaging equipment	LCAs used to drive improvements in new product development and across value chain
Stakeholder engagement	Engagement in supply chain management and responsible sourcing but not specifically for design	Not specifically mentioned by Siemens Healthineers	Strong stakeholder engagement and green procurement but not specifically for design	Internal cross-functional collaboration for new product development External collaborations not	Internal cross-functional collaboration for new product development External collaborations not	Not specifically mentioned	Internal cross-functional and external collaborations for new product development and closing loops for hospital plastics

Company	PHILIPS	SIEMENS Healthineers	sonova HEAR THE WORLD	Medtronic	Johnson & Johnson	GE Healthcare	Baxter
				specifically for design	specifically for design		
Design dilemmas	Not considered	Not considered	Not considered	Not considered	Not considered	Not considered	Dilemma between circularity and infection control addressed by two new products
Type of circular design efforts and mentions of the concept	Various explicit internal circular design efforts, distinct programmes and external partnerships	One distinct refurbishment programme with strongly implied circular design considerations	Range of internal efforts, circular design for slowing and closing loops strongly implied	Circular design implied through some efforts but not clearly	Circular design implied through some efforts but not clearly Programme with strongly implied circular design by Johnson & Johnson's (J&J) Medical Devices Business Services, Inc.	One distinct refurbishment programme with strongly implied circular design considerations	Integrated efforts with circular design strongly implied External initiative explicitly considering circular design
Implementation stage	Programmes and initiatives ongoing with goals up to 2025	Programme ongoing	LCA efforts ongoing	Internal efforts ongoing, LCA to be trialled	Programmes and initiatives ongoing with goals up to 2025	Programme ongoing	Internal and external efforts ongoing

Source: Baxter International Inc. (Baxter) (2015, 2019); General Electric Company (GE) (2018, 2020); J&J (2017, 2018); J&J Health Care Systems Inc. (2017); Koninklijke Philips N.V. (Philips) (2014, 2015, 2017a, 2017b, 2017c, 2017d, 2020a, 2020b, 2020c, 2020d, 2020e, 2020f); Medical Devices Business Services Inc. (2019a, 2019b, 2019c, 2019d); Medtronic (2019a, 2019b, 2019c, 2019d, 2020); Siemens Healthcare GmbH (Siemens) (2018, 2019); Sonova Holding AG (Sonova) (2019)

During a discussion about the state of circular design practices in the industry, interviewee A confirmed that there are several clear industry leaders among medical technology companies, and examples of companies that were pushing forward. Interviewee B added that companies are increasingly thinking about leveraging existing products, reinventing approaches and leaning into becoming more circular.

4.2 Detailed Findings

This subchapter follows the structure of Table 4-1 to describe in detail the findings of reviewing companies and conducting interviews with practitioners. In each further subchapter, the relevant section of the summary table is presented, then further elaborated upon, and interviewee insights are integrated where relevant. Throughout the review, a clear distinction was made between efforts to achieve a circular economy and efforts specifically involving circular product design. While all seven companies demonstrated various extents of circular initiatives, those not related to design, either implicitly or explicitly, were excluded. Product criticality is not detailed further as all companies offer a range of products across categories.

4.2.1 Circular Design Strategies Implemented by Companies

In the companies reviewed, with the exception of certain eco-design initiatives and recycling efforts, circular design strategies were mostly implied through practices rather than clearly mentioned as "circular design" strategies or other terms used in literature. This can be explained by interviewee E's statement that although various strategies and terminology exist for circular design principles, these terms are not necessarily explicitly used by designers.

Table 4-2. Summary of company review: circular design strategies

Company	PHILIPS	SIEMENS Healthineers	SONOVA HEAR THE WORLD	Medtronic	Johnson & Johnson	GE Healthcare	Baxter
Circular design strategies	Mostly slowing and closing, but presence of narrowing loop strategies as well Slowing loop strategies: resisting, postponing and reversing obsolescence	Slowing loop strategies: resisting, postponing and reversing obsolescence	Mostly narrowing, but presence of slowing and closing loop strategies as well Slowing loop strategies: postponing and reversing obsolescence	Narrowing and closing loop strategies	Slowing, narrowing and closing loop strategies Slowing loop strategies: postponing and reversing obsolescence	Slowing loop strategies: resisting, postponing and reversing obsolescence	Slowing, narrowing and closing loop strategies Slowing loop strategies: postponing and reversing obsolescence

That being said, analysis of company practices showed the combination of implied and few explicit mentions of circular design strategies within companies' reports and websites aligned well with slowing, closing and narrowing resource loop strategies, as shown in Table 4-2. Interviewee B corroborates this by describing that circularity in the medical industry is commonly understood as extending lifetimes and closing loops at the end of product lifetimes, against the broader context of optimising production processes. Some of the efforts, initiatives and programmes mentioned in this subchapter are described in greater detail in Subchapter 4.2.3.

Six of the seven reviewed companies demonstrated consideration of slowing loop strategies, which were most clearly observed in eco-design practices or circular economy programmes such as in Philips; repair, servicing, refurbishment or reprocessing services such as in Baxter, Sonova and J&J's Medical Devices Business Services subsidiary; and refurbishment programmes for imaging equipment such as in Philips, Siemens and GE Healthcare. Sonova, J&J and Baxter's practices aligned with strategies for postponing and reversing obsolescence by extending product use and recovery. Philips, Siemens and GE Healthcare's practices included these as well as strategies for resisting obsolescence through long-life products (den Hollander et al., 2017).

Closing loop strategies were observed in the companies' focus on design for recycling and future goals. According to interviewee A, many companies focus more on end-of-life closing loop

strategies because although medical products cover a vast range, appropriate waste management is required and essential for all. However, the design implications of these are not always clear. For example, while most of the companies mention initiatives such as trade-in or take back programmes, or compliance with the EU WEEE Directive for specific medical products with electrical or electronic components, their implications for product design were not explored or mentioned. Only J&J, Philips and Sonova explicitly mention their internal efforts to pursue design for recycling, for example by selecting materials that are already widely recycled or designing for easy end-of-life treatment (J&J, 2018; Philips, 2020e; Sonova, 2019). Baxter's leasing of certain electromechanical products that are returned, repaired and reused also implies a degree of design for closing loops in addition to slowing (Baxter, 2019).

Narrowing resource flow strategies are not particularly emphasised in circular design literature seeing as they do not involve cycling of products or materials (Bocken et al., 2016). However, five of the companies practice circular design through narrowing strategies, such as Philips, Sonova, J&J and Baxter reducing the amount and weight of materials used in their products, Medtronic and Baxter reducing manufacturing and packaging waste, and J&J using materials with recycled content (Baxter, 2019; J&J, 2018; Medtronic, 2019d; Philips, 2020c; Sonova, 2019). Baxter also has goals for innovating for greater resource efficiency by designing products to require fewer accessory products (Baxter, 2019).

4.2.2 Key Considerations in the Circular Design Process

Interviewees B and E summarised the design process succinctly during their respective interviews. According to interviewee B, while this differs among companies, the three key aspects in the typical design process tend to be: (1) the human aspect, or solving the user's need; (2) the business aspect, or whether there is a good business prospect and model for the company; and (3) the technological aspect, or whether there are technologies and processes available to meet the human and business needs. Interviewee E adds that an iterative process which empathises with the user and considers how products are actually used is highly preferred.

Table 4-3. Summary of company review: life cycle perspectives, stakeholder engagement and design dilemmas

Company	PHILIPS	SIEMENS Healthineers	sonova HEAR THE WORLD	Medtronic	Johnson & Johnson	GE Healthcare	Baxter
Life cycle perspective	Life cycle assessments (LCAs) used to guide design and grow sustainable portfolio	Life cycle perspective considered in context of refurbished imaging equipment	LCAs used in product research and development to enhance circular design strategies	Life cycle impacts considered in design to reduce footprint Trialling LCA software	Product stewardship tool guides LCAs to improve life cycle areas with highest potential impact	Life cycle perspective considered in context of refurbished imaging equipment	LCAs used to drive improvements in new product development and across value chain
Stakeholder engagement	Engagement in supply chain management and responsible sourcing but not specifically for design	Not specifically mentioned by Siemens Healthineers	Strong stakeholder engagement and green procurement but not specifically for design	Internal cross-functional collaboration for new product development External collaborations not specifically for design	Internal cross-functional collaboration for new product development External collaborations not specifically for design	Not specifically mentioned	Internal cross-functional and external collaborations for new product development and closing loops for hospital plastics
Design dilemmas	Not considered	Not considered	Not considered	Not considered	Not considered	Not considered	Dilemma between circularity and infection control addressed by two new products

This subchapter describes how and to what extent the seven companies include considerations important for circular design such as life cycle perspectives, engagement with stakeholders and treatment of design dilemmas in their processes.

Life Cycle Perspectives in Product Development

Interviewees A and B agree that the design of medical products should include analysis and perspectives of the entire life cycle to ensure robustness. A key part of product design and development in the reviewed companies was found to be the incorporation of life cycle considerations. More specifically, LCAs are used as part of this process in four of the seven

companies (Baxter, 2019; J&J, 2017; Philips, 2020e; Sonova, 2019). Interviewee D explains that LCAs for circular design could potentially be approached in two ways. An initial LCA could be conducted internally early in the design stage to compare various product and packaging scenarios. Alternatively, a more robust LCA could be conducted with a combination of internal and external data from various functions of the value chain and figures from suppliers if needed.

Philips uses LCAs to gain insights into lifetime impacts of its products and steer its eco-design efforts (Philips, 2020e). Some of Sonova's aims for conducting LCAs are to minimise resource consumption and to design for recycling and easy end-of-life treatment (Sonova, 2019). J&J has developed a product stewardship tool called EARTHWARDS, which encourages improvements to new and existing products across impact areas such as materials, packaging, energy, waste, water, social impact and innovation (J&J, 2017). This tool guides its product LCAs to help focus on hotspots of environmental impacts and identify and prioritise opportunities for improvement across the life cycle.

Baxter's product development process requires environmental, health and safety (EHS), and sustainability assessments across the value chain for all new products. These assessments include a high-level review as well as detailed LCAs, which are also used for some established products (Baxter, 2019). Similarly, Medtronic's EHS Policy requires an evaluation of EHS considerations, and for these to be incorporated into design processes. Part of its aim for product stewardship is to improve product performance across the life cycle by considering impacts of products and packaging from the materials, manufacturing, distribution and disposal functions (Medtronic, 2019a).

Stakeholder Engagement for Design and Development

In addition to considering life cycle perspectives, interviewee B states that robustness should not only be limited to the product itself but should also include key performance indicators such as the involvement of essential stakeholders and different value chain functions in the development process. While all seven companies have strong stakeholder engagement and collaboration practices in place, most do not have clear implications for the design process, with the exception of J&J, Medtronic and Baxter.

J&J holds brainstorming workshops as part of its EARTHWARDS product stewardship process with internal cross-functional teams to identify areas of improvement (J&J, 2017). Medtronic's product development process also requires collaborations across several business functions including research and development, operations, quality and marketing (Medtronic, 2019d). Baxter engages in both internal and external collaborations for product stewardship with research and development and marketing functions, as well as supply chain groups, including environmental criteria in its requests for proposals (Baxter, 2019). Most notably, Baxter leads a technical working group in the Healthcare Plastics Recycling Council (HPRC). This working group contributes to creating resources such as value chain maps for stakeholders to map material pathways in healthcare plastics recycling, and facilitates engagement of stakeholders across the value chain such as customers, peers, and recycling and disposal vendors to explore solutions for closing loops for hospital plastics (HPRC, 2016).

Circular Design Dilemmas

A major dilemma in circular design of medical products, as mentioned in literature and confirmed by interviewee A, is the trade-off between environmental footprint and infection prevention. Disposable products greatly reduce the risk of infection spread and resources required for sterilisation but generate vast amounts of waste. Two of Baxter's new product designs resolved this particular dilemma (Baxter, 2019). These two infusion systems work with Baxter's dosage safety software and are designed to increase the safety of intravenous infusions.

One of the systems enables clinicians to switch between delivering infusions through different means without needing to change equipment sets, which may reduce use of tubing by about 30% as well as decrease opportunities for touch contamination, infection and spread of pathogens. The other system has similar benefits of reduced accessory products and opportunities for touch contamination, and additionally has a modular design allowing easier and more cost-effective servicing and maintenance (Baxter, 2019).

While design dilemmas were neither mentioned explicitly nor implied by any of the other companies reviewed, interviewees contributed important insights into this topic. Interviewee B explains that certain dilemmas are inherent in designing circular medical products, and the development process is more about assessing acceptable trade-offs rather than attempting to eliminate them completely. They give an example of a possible threshold being if the redesigned product begins deviating too far from its original purpose. Interviewee A provides an example of a trade-off between regulatory and medical requirements by describing the conflict between the ban on silver in Swedish products and the need for silver to treat conditions such as chronic ulcers. Interviewee C further adds that companies with different business models have their own business-specific dilemmas. They explain that companies with refurbished product offerings need to consider the trade-offs between extending product lifetimes and keeping up with the innovation curve. Trade-offs in positioning these offerings and defining clients and markets also need to be made to ensure new products do not compete with refurbished ones. This subchapter can be summarised with an insight from interviewee B about the necessity for trade-off analysis to be an ongoing process in the design and development of medical products.

4.2.3 Implementation of Circular Design Programmes and Initiatives

Companies in general differ greatly in terms of the extent to which they pursue any sustainability efforts and initiatives. These approaches can be understood as either leading or lagging, according to interviewee D. They explain that a leading approach is essentially undertaken pre-production, such as formulating and implementing circular design strategies. On the other hand, a lagging approach involves post-production activities such as sustainability assessments for carbon or water footprints. Within the seven companies reviewed, the level of efforts for circular design varied significantly, ranging from implied mentions to distinct programmes.

Table 4-4. Summary of company review: implementation of circular design efforts

Company	PHILIPS	SIEMENS Healthineers	sonova HEAR THE WORLD	Medtronic	Johnson & Johnson	GE Healthcare	Baxter
Type of circular design efforts and mentions of the concept	Various explicit internal circular design efforts, distinct programmes and external partnerships	One distinct refurbishment programme with strongly implied circular design considerations	Range of internal efforts, circular design for slowing and closing loops strongly implied	Circular design implied through some efforts but not clearly	Circular design implied through some efforts but not clearly Programme with strongly implied circular design by Johnson & Johnson's (J&J) Medical Devices Business Services, Inc.	One distinct refurbishment programme with strongly implied circular design considerations	Integrated efforts with circular design strongly implied External initiative explicitly considering circular design
Implementation stage	Programmes and initiatives ongoing with goals up to 2025	Programme ongoing	LCA efforts ongoing	Internal efforts ongoing, LCA to be trialled	Programmes and initiatives ongoing with goals up to 2025	Programme ongoing	Internal and external efforts ongoing

This subchapter describes some of the programmes, external initiatives and internally integrated practices the reviewed companies are undertaking to pursue circular product design in their operations and concludes with a summary of the differences in their stages of implementation.

Distinct Programmes

The clearest examples of companies having programmes with strong circular design implications are the refurbishment programmes that Philips, Siemens and GE Healthcare have for their imaging systems such as magnetic resonance imaging and computer tomography equipment. Philips' Diamond Select, Siemens' ecoline portfolio, and GE Healthcare's GoldSeal

Refurbished Systems all follow similar steps in their refurbishment process (GE, 2018; Philips, 2017d; Siemens, 2019). The typical process is shown as follows:

1. **Selection**: only equipment with a traceable service history and in acceptable conditions is selected; Siemens in particular offers to take back imaging systems produced by other manufacturers
2. **De-installation**: the equipment is disassembled into its parts
3. **Refurbishment**: cleaning and disinfection of the equipment, replacement of worn parts, software updates, refurbishment, re-configuration according to purchaser specifications are all conducted in this stage
4. **Installation**: the parts are re-assembled
5. **Support and services**: purchaser's staff are trained, warranty and support services are provided

Slowing loop strategies are highly involved in such programmes. To begin with, the selection of products in an acceptable condition implies designing to resist obsolescence, or long-life products. The refurbishment process itself involves strategies to reverse obsolescence by enabling recovery between product use cycles. Warranties, servicing and repairs for both new and refurbished equipment involves strategies to postpone obsolescence, or extend use, through designs for maintenance, upgradability, adaptability, and dis- and re-assembly.

Another example of a distinct programme built around circularity is the reprocessing programme by J&J's Medical Devices Business Services, Inc. for approved single-use medical devices. Devices manufactured by one of the J&J companies as well as other manufacturers are considered as long as they meet or exceed functional requirements for at least one additional use, implying design for reversing obsolescence through recovery (Medical Devices Business Services Inc., 2019c, 2019d). According to J&J, there are five key factors essential for successful reprocessing: (1) appropriate resource assignment, (2) focus on goals, (3) progress assessment and review, (4) physician engagement, and (5) implementation plans (J&J Health Care Systems Inc., 2017). These success factors could well be extended to being necessary for implementation of circular design principles in general medical product design processes.

External Initiatives

Some of the companies reviewed are engaged in external initiatives with implications or considerations necessary for circular design. For example, Philips is a member of the Solving the E-waste Problem initiative (Philips, 2020d). Two of the initiative's aims are to extend product lifetimes and standardise recycling processes globally, for which slowing and closing loop design strategies are essential. J&J is a signatory to the New Plastics Economy Global Commitment, and part of its commitments are to design and establish partnerships for 100% reusable, recyclable or compostable plastic packaging by 2025 (J&J, 2018). As previously mentioned, Baxter is highly involved with the HPRC, through which it utilises resources and knowledge to address barriers to healthcare plastics recycling (Baxter, 2019). The HPRC focuses on closing loop strategies for hospital plastics and has published concrete design guidelines for optimal recycling. These strategies distinguish between desirable and less desirable design practices and aim to help medical product and packaging designers and engineers to rethink their design priorities and considerations (HPRC, 2016).

Companies have also had to establish programmes to meet relevant legislative requirements. For example, a range of medical products with electrical or electronic components are covered under the EU WEEE Directive, which requires compliance from producers of these products or third parties acting on their behalf (Council Directive 2012/19/EU, 2012). Baxter, Medtronic and Sonova have implemented measures for compliance such as take back systems and separate

collections for recycling or appropriate disposal, with instructions for users to return waste to designated services in the different countries these companies operate in (Baxter, 2015, 2019; Medtronic, 2019c; Sonova, 2019). Baxter also has partnerships with third party contractors in EU countries for collection, treatment, recycling and recovery, which may imply design strategies for closing loops (Baxter, 2015). Overall, while the WEEE Directive is not explicitly mentioned to be a consideration in the companies' design processes, compliance with the Directive implies that at minimum, product design needs to consider design for slowing and closing loops through recovery and recycling.

Internally Integrated Practices

Most of the companies reviewed mentioned various internally integrated practices for circular design, either explicitly or implied through their efforts. Some were clearer than others; Philips, for example, designs its products for circularity through its eco-design efforts which include strategies for both slowing and closing loop (Philips, 2020c). These include postponing and reversing obsolescence through extending product lifetimes and recovery, and strategies for recyclability, modularity and disassembly (Philips, 2020c). Furthermore, one of the five pillars in its Circular Economy programme involves embedding circular economy principles in its product design processes and business models. Another pillar involves refurbishment and take back systems for recycling, requiring design strategies for slowing and closing loops to support implementation (Philips, 2020e).

All the companies reviewed had a range of warranties, repair and refurbishment services for their products, implying that products are designed to facilitate these services, i.e. designed to postpone and reverse obsolescence. In addition, Baxter's practices include a leasing model for certain electromechanical products to be returned, repaired and reused where possible (Baxter, 2019). Many internally integrated circular design practices were found to be around integrating life cycle considerations in product development processes, as detailed earlier in Subchapter 4.2.2, including J&J's EARTHWARDS tool and Medtronic's product stewardship.

Stages of Implementation

With the exception of a couple of industry leaders with refurbishment and reprocessing programmes, the companies reviewed are more or less at similar stages of implementation. Trade in and take back systems are functional, life cycle perspectives are considered by all, and recent years have seen an increasing focus on design for circularity, albeit still mostly implicitly. Most of this focus has been on design for recycling and resource efficiency, as seen in Baxter, J&J, Medtronic, Philips and Sonova, while slowing loop strategies are being implemented more for larger and more complex equipment, such as by GE Healthcare, Philips and Siemens. Importantly, while the implementation of circular efforts can be clearly assessed, implementation of design-specific efforts is more difficult to distinguish.

Companies also vary in levels of ambition for future goals. Only Baxter, J&J, Medtronic and Philips clearly identify goals related to circularity and circular design. Medtronic aims to reduce waste and increase recycling to divert from landfill; Philips and Baxter have zero-waste ambitions; Philips, and to a certain extent J&J, have goals to increase proportions of revenue from circular products and services. Philips also has further ambitions to close loops entirely for larger equipment, in the longer term to extend circular practices across its entire portfolio of medical equipment.

4.3 Practitioner Insights on Transformation of the Industry

Through discussions during the interviews, practitioners contributed crucial insights on the opportunities and challenges for transforming the industry for a circular economy; these are

summarised in this subchapter. Two overlapping key factors emerged as being necessary for an industry-wide transformation: communication between stakeholders, and collaboration and engagement. These are also detailed in this subchapter.

Interviewee E suggests that a transition to a circular economy through circular product design requires investments in changing the entire production system and value chains on a larger scale, which poses a challenge to many companies. Interviewee A elaborates by highlighting that in countries with largely publicly funded healthcare systems such as Sweden, innovations in circular design are highly influenced by environmental and procurement policies. They further add that larger publicly listed companies' responsibilities towards shareholders make it a challenge to pursue circular design efforts if these are not credited by criteria in public procurement. Such companies may fear that radical changes to business models might lead to significant losses of customers and hence avoid such actions.

According to interviewee E, where ambition for such change is difficult to implement, major disruptions serve as an opportunity for drastic changes to be made while the entire system is in a state of uncertainty. They then outline a transition process towards a circular economy beginning with identifying hotspots of the largest negative impacts, addressing those, and building up a new product around these solutions. The three key aspects of a circular design transformation, as per interviewee E, are the product design, the value chain and the business model. They explain further that value chains need to be redefined to create a closed-loop system around a circular product, and innovations in business models are necessary to support the circular product.

4.3.1 Communication Between Stakeholders

Interviewees A, C and E agree that while customer demand is important in driving the circular agenda, communication between stakeholders is one of the key factors necessary to bring about a transformation in the circular design of medical products. According to interviewee C, the design process itself can be facilitated by the various circular design principles, strategies and business models that exist, but the challenge lies in transforming the organisation and the industry. They elaborate that for new policies to be implemented effectively, communication between stakeholders is essential. This enables a mutual understanding of leverage points to be pushed upon, which in turn enable the integration of new practices into standard processes. Interviewee C further explains that circular design practices, being mostly different from standard practices, need to be made attractive, engaging and desirable to those responsible for carrying these out, for which communication is a valuable channel.

4.3.2 Collaboration and Engagement

Interdisciplinary collaboration is the second key factor emphasised by interviewees A, B C and E for an industry transition to a circular economy. Interviewee C states that organisational and industry-wide changes should be driven by complementary top-down management ambitions as well as bottom-up employee engagement. They describe how cross-functional collaboration is key in aligning the various functions of a company, to promote the desired mindset for change, and to ensure new practices are not only relatable but also desirable. Engaging and collaborating with essential stakeholders across the company is also emphasised by interviewee A, who describes these as helping to achieve broad and interdisciplinary competence. On a wider industry level, interviewee C suggests that positioning circular economy within the Quadruple Aim[17] of the healthcare industry presents an opportunity to pursue a sustainability-driven agenda

[17] The Quadruple Aim is a widely accepted guide to improving healthcare systems and consists of patient experience, population health, reducing costs and well-being of healthcare providers (Bodenheimer & Sinsky, 2014).

within the industry. Interviewee E discusses cross-industry collaboration by explaining that the medical industry, just like any other, has great opportunities to adopt lessons from other industries. They note that observing practices and challenges faced by companies operating in other sectors and communicating with them regarding aspects such as value chain and business model innovations are highly valuable methods of promoting an industry-wide transformation. Interviewee B further adds that the knock-on impacts of an industry that demonstrates commitment to circularity, or sustainability on a broader level, may even influence end-consumers to change their own individual practices.

4.4 Summary of Industry Practices

The review of the medical industry aimed to gain a holistic understanding of several areas: the ways in which circular design concepts are being approached and implemented by medical technology companies, patterns observable among the selected companies, and practitioners' views on the industry. This review was conducted by analysing grey literature such as relevant regulations, industry reports and company reports, and obtaining primary data from interviews. The key findings and conclusions from this chapter are summarised in Figure 4-2 below.

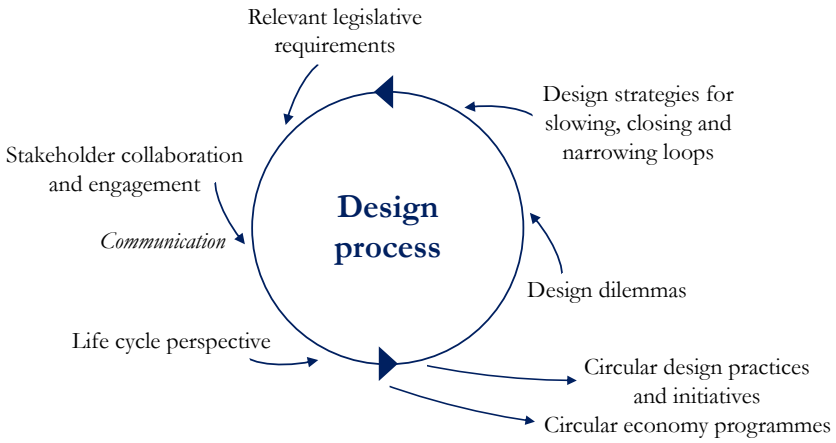

Figure 4-2. Synthesis of medical industry practices for circular product design

Source: Author

From the synthesis of literature as in Figure 3-4, additional elements to be observed among company practices included whether there was a distinction between biological and technological cycles, and differential treatment of products based on their value. These did not appear to have been explicitly considered in relation to product design in any of the companies reviewed. However, there was a tendency for high-value, low-criticality products such as imaging equipment to be designed for refurbishment, while design for recycling was more observed for low-value, low-criticality products such as packaging materials.

Overall, emphasis was placed on the circular design process being an iterative one incorporating several considerations and actors. Design strategies aligned well with those for slowing, closing and narrowing loops, albeit often not explicitly. An essential element was the inclusion of a life cycle perspective in the design process. While design dilemmas were not addressed by most of the reviewed companies, these were discussed with interviewees and trade-off analysis was recommended to be an ongoing process. Finally, stakeholder collaboration and engagement was visible through company practices and confirmed by practitioners to be essential, together with open communication channels for engaging these stakeholders.

5 Tool for Circular Medical Product Design

The aim of this thesis is to contribute to implementation of circular design strategies in the medical industry. This was envisioned to be achieved through the development of a practically useful tool. This chapter outlines the aim of the tool, criteria used for developing it and specific elements that were considered for inclusion from a review of various primary and secondary data sources as detailed in the previous chapters. Following this, a draft tool is proposed, the process of seeking and implementing practitioner feedback in refining the tool is detailed, and the final tool is presented and evaluated.

5.1 Aim of Tool

During initial stages, a tool was thought to be valuable in synthesising learnings from the literature and industry reviews. Ideas around the aim and format of the tool then evolved upon discussing potential types of tools and their purposes with interviewees. The primary aim for this tool is to facilitate discussions on designing medical products for circularity between design professionals and other stakeholders involved in the design process. Practitioners interviewed confirmed that such a tool would be valuable in their work.

The various elements of the tool will ideally provide a view of some of the considerations involved in designing or redesigning a medical product with circular design principles and foster a collaborative approach to implementing strategies. This approach was determined to be more beneficial than prescribing specific design requirements for different medical products. As per interviewee B, the main areas of added value were that such a tool might challenge existing processes and influence practitioners to consider alternative methods.

5.2 Criteria for Tool Development

Multiple options were considered and discussed with thesis supervisors for potential formats and visualisations of the tool. This could be in the form of a generic map, a diagram summarising key considerations, or a flowchart of processes and the accompanying decisions or questions. In this entire process, the refinement step was considered essential, wherein the tool would be tested and feedback sought from practitioners. Bocken et al. (2019, p. 13) created a checklist for developing circular business model tools, which could be applied to broader sustainability tools as well. This was deemed to be an appropriate starting point for developing this tool, and the criteria in the checklist were adapted to circular medical product design as follows:

1. Simple and not too time-consuming
2. Purpose-made for circular design of medical products
3. Rigorously developed from literature and industry insights
4. Iteratively developed and tested with academics and practitioners
5. Integrates relevant knowledge from different disciplines
6. Circular design objectives and impact are firmly integrated and safeguarded when tool is used by others
7. Provides a transparent procedure and guidance on use
8. Adaptable to different (business) contexts
9. Final tool has been used by practitioners, preferably multiple times, and an evaluation of this process is done to assess tool use and usefulness
10. Inspires or triggers (business) change

This checklist was used in the evaluation of the final tool, see Chapter 5.5.

5.3 Elements for Inclusion in Tool

5.3.1 Elements from Literature and Industry Reviews

Findings from the literature and industry reviews in Chapters 3 and 4 were crucial as a starting point for the tool. In particular, elements from the summaries of these chapters, i.e. Subchapters 3.4 and 4.4 were considered for including in the tool, as well as key features of the frameworks proposed in literature, as summarised in Table 3-1.

Elements obtained from literature include Bocken et al. (2016)'s framework of design for slowing and closing loops with den Hollander et al. (2017)'s typology defined based on obsolescence and ranked in order of priority. Bocken et al. (2016) and Mestre and Cooper (2017)'s separate treatment of biological and technological cycles and their respective strategies were considered important for inclusion, as well as Rutala and Weber (2008)'s consideration of medical product classification as per the Spaulding scale. Additionally, Bakker et al. (2014)'s incorporation of sociological perspectives for tailored design approaches, Lofthouse and Prendeville (2018)'s user-centred design, and Prendeville et al. (2017)'s addressing of design dilemmas across decision-making levels were considered.

Most of the industry practices reviewed followed the same categories as obtained from literature, with the addition of considering relevant legislation. The importance of engaging and collaborating with various stakeholders across all stages of the design process and considering a life cycle perspective was highly emphasised through most of the literature studied and industry insights gained. From the industry review, practitioner responses to questions related to circular design considerations for the industry were considered when developing the tool.

5.3.2 Specific Insights from Practitioners

During interviews, practitioners were also asked specifically about possible inclusions in a framework or tool. Interviewee C recommended that the tool be simple, self-explanatory and practical, with an emphasis on engaging people rather than about specific circular design requirements or business model frameworks. A broader perspective was mentioned to be desirable by interviewee B, including the types of personnel and skillsets required for implementing certain strategies, its impact on profitability and the company's approach or business model as a whole. Interviewee A added that a circular product's impact on patient care, healthcare providers' ability to carry out their work, and any changes to the status quo could also be included. Interviewee C emphasised that while tools could be useful, changing mindsets and communicating between business units and stakeholders with varying decision-making abilities was of greater importance. They provided an example of how redesigning a product for greater circularity would likely involve certain changes in business models, which designers may not have the ability to implement. This would be particularly true in cases where decisions about a single product cross multiple business units. Interviewee C recommended that linking design decisions or considerations to the people and processes required for implementing these decisions would be of value.

5.4 Tool Development and Refinement

Taking into account all of the above, a first iteration of the tool was developed. Two major components took shape: an overarching framework for the circular design process of medical products, and a flowchart to facilitate discussions on considerations and decisions. These are presented in Figure 5-1 and Figure 5-2 respectively in the following pages, and were provided to the interviewed practitioners with explanatory text in order to obtain their feedback, see Appendix F: Tool for Circular Medical Product Design (Draft for Practitioners).

5.4.1 Version 1: Draft

Part 1, the framework, provides a simple and easy overview of key elements necessary to be considered. Against the backdrop of the wider business context, all elements from the product through to stakeholders and implementation are interconnected and influence the design in an iterative process.

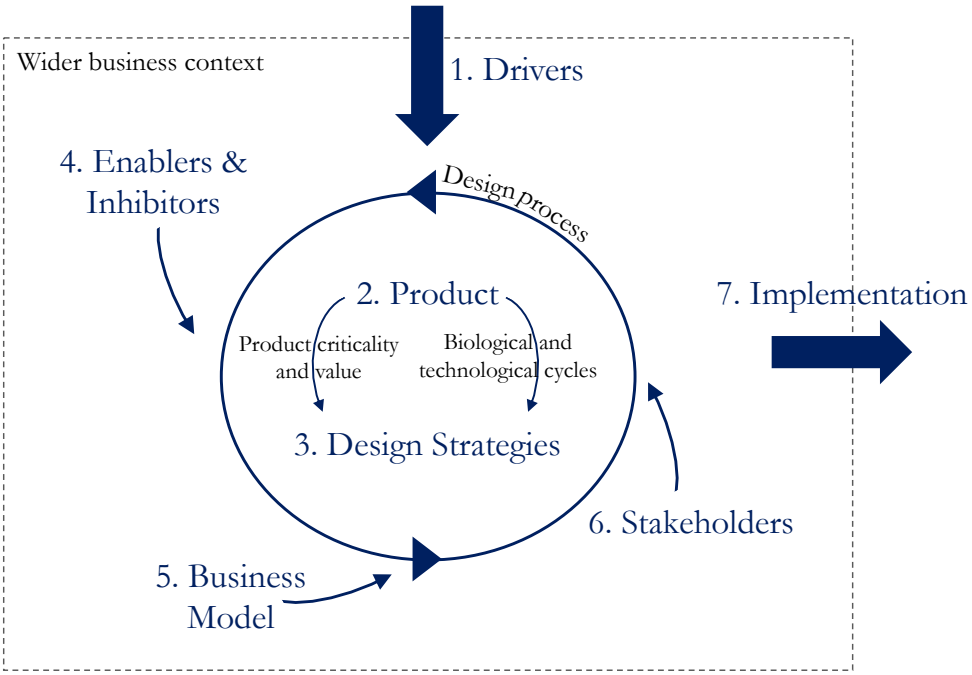

Figure 5-1. Draft circular medical product design tool part 1: framework of the design process

Source: Author

The previous chapters cover product considerations, design strategies and stakeholder engagement in detail. New elements not previously included – drivers, business models, enablers and inhibitors, and implementation were added based on practitioner insights. Through the interviews, an emphasis on the wider business context was observed, and various internal and external conditions and requirements for successful circular design were noted to be of importance. Interviewees also discussed operationalisation of new design strategies. As such, it was determined that these new elements should be included among aspects to consider when discussing circular product design. The rationale for these was drawn from interviewee insights presented in Subchapters 4.3 and 5.3.2.

Part 2, the flowchart, takes the user step by step through the various elements. It is important to note that while these are numbered in order, the process of circular design should not be a linear one. The elements in the flowchart are presented with questions that could promote greater engagement within and between relevant teams. While this reads as more complex than the framework, numbering and arrows guide the user's progress through the tool.

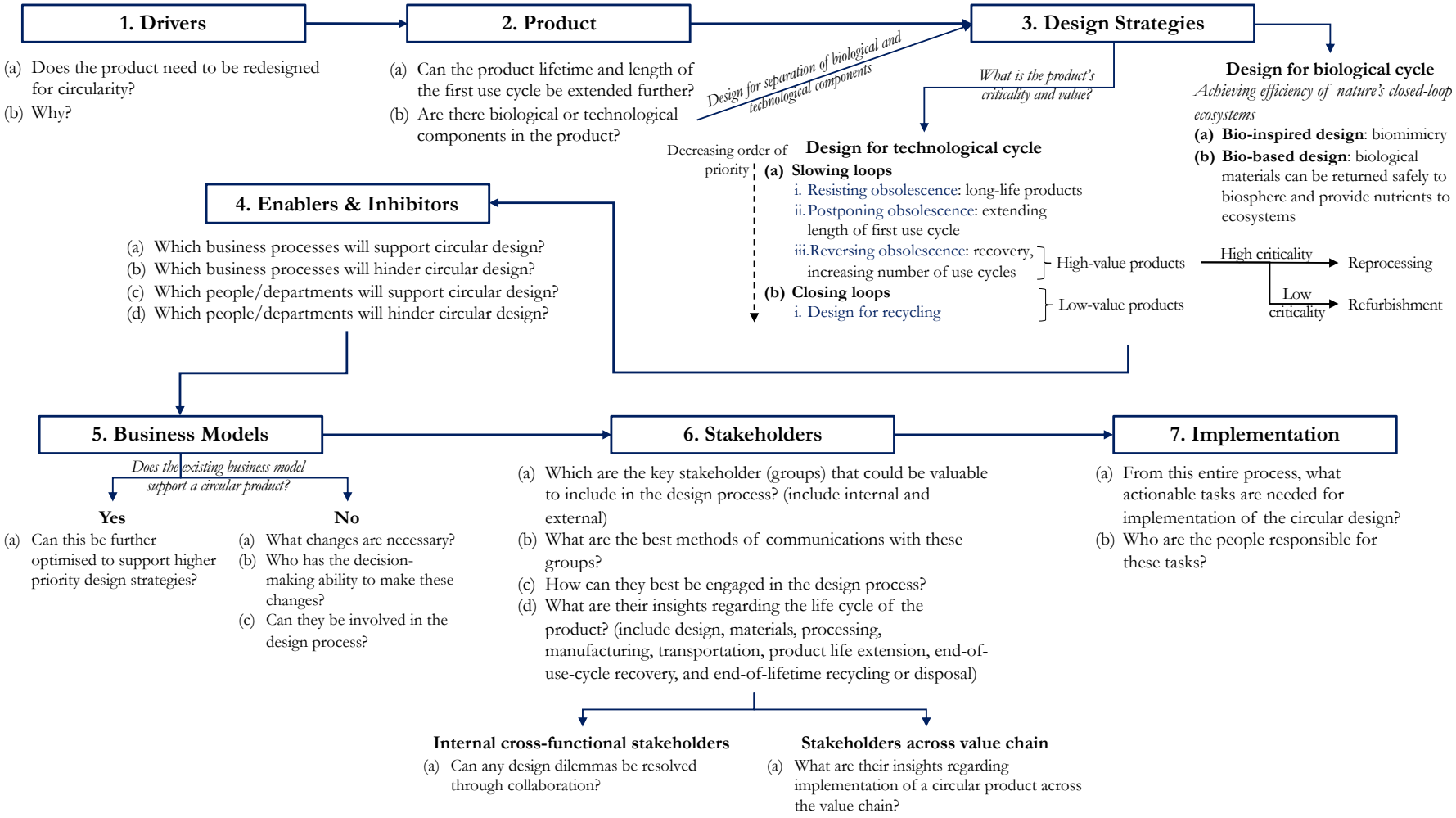

Figure 5-2. Draft circular medical product design tool part 2: flowchart of design considerations and decisions

Source: Author

5.4.2 Refinement

Feedback and comments on the draft tool were sought from practitioners and thesis supervisors. In addition to interviewees B, C, D and E, a fifth practitioner[18] who was not interviewed also provided feedback on the draft. The following questions were asked of them:

1. What are your general thoughts on the tool?
2. What are the aspects you liked? Why?
3. What are the aspects you did not like? Why not?
4. Is this tool of value to your work?
    a. If yes, how?
    b. If no, why not?
5. What would you like to see changed for the tool to be more useable?

Their consolidated comments are presented in Table 5-1 with responses, implemented changes, and rationale for unimplemented feedback grouped according to the key elements of the tool.

Table 5-1. Consolidated practitioner feedback on draft tool and response

Framework elements	Consolidated feedback	Response and changes implemented
Overall	**Positive feedback:** 1. Very good and structured overview of relevant aspects to consider 2. Placement of critical questions as suggestions for each element offers ease of practice for the user and helps to identify all relevant stakeholders to include across the company 3. Clean, straight-forward design, simple and easy to follow	The visualisation of the tool was changed from the linear flowchart process. Numbering was removed, visuals such as icons and double-headed arrows were added and the font was changed. In the new iteration, Part 1 of the tool, i.e. the framework, plays a larger role in helping the user to visualise the different elements of the tool in a simplistic manner. A circular representation was also determined to better represent the aim of the project. Due to lack of technical product-specific knowledge, a fictional scenario could not be created.
	Suggestions for improvement: 1. Is the numbering necessary? Numbering suggests a linear order even if you mention it should not be. 2. Add an example to animate your tool and make it easier to engage with it or understand how to use it, for example a (fictional) product answering the tool's questions, or a scenario around one group of questions 3. Additional elements could include, if they are not too specific: a. Impact of redesign on cost b. Regulatory requirements to consider when redesigning for circularity 4. Visuals are currently quite academic, representation with arrows could be improved to be more user friendly, perhaps with more graphics	

[18] Corporate Sustainability Manager in a multinational medical device manufacturing company; company name withheld to protect confidentiality. Permission was granted to refer to their position and the type of organisation.

Framework elements	Consolidated feedback	Response and changes implemented
Practical value	**Positive feedback:** 1. A facilitator tool rather than something more prescriptive is beneficial because each designer brings their own set of skills and knowledge on the matter, it is important to not make them feel "limited" but rather well guided and able to include their own insights 2. Provides a good overview of the topic and a generally good guideline for a more responsible process 3. It is refreshing to see my own guidelines from a different perspective and compare similarities and differences; its usability is quite high as it is 4. It is nice to have a circular strategy detailed and documented in this manner, similar to processes for manufacturing. It adds a robustness process to designing circular products.	NA
Purpose of tool	**Suggestions for improvement:** 1. It is crucial to position the tool and describe the outcome more clearly: a. Who is the target group? Could you mention a few examples of companies and ideal stakeholders? b. Is this a strategic tool, a transformation tool or a programme, and how can you adapt it accordingly? c. How and when should it be used? In a workshop or by two people? Is this meant for a company at the start of a transformation with limited awareness on circularity or when its awareness is either intermediate or advanced?	This was added to the final version, see Subchapter 5.4.3 and Executive Summary.
Tool part 2 individual component: Drivers	**Suggestions for improvement:** 1. We frequently have challenges with the following, which are also missing: a. Can sterilisation of critical and semi-critical items be demonstrated? What are the environmental impacts? Can colleagues and regulators then be convinced? b. Showing that trade-offs are common would be a useful addition to the drivers.	Questions of sterilisation, product criticality and trade-offs were added to the Enablers and Inhibitors element. Environmental impact was added to both Design Strategies and Implementation elements. It was noted that the term "trade-offs" is more commonly used than "dilemmas".
Tool part 2 individual component: Product	**Suggestions for improvement:** 1. Consider another word; product sounds hardware focused whereas software and services could be included too 2. Design implications for over the counter vs. prescribed products could be considered	The scope of this thesis is limited to medical products, i.e. hardware, however the generalisability of this tool to medical software and services is addressed in the

Framework elements	Consolidated feedback	Response and changes implemented
		final version. Design implications for different types of products were partially covered by a new question added to the Enablers and Inhibitors element.
Tool part 2 individual component: Design Strategies	**Positive feedback:** 1. It is well thought through, and I like the framework around design strategies and the sequence of resisting, postponing and then reversing obsolesce. It shows that only once these areas are exhausted should you look for closing loops. 2. Design for technological cycle: the two main definitions of slowing and closing loops are nice.	Linking arrows were added between bio-inspired design and design for technological cycles. More detailed requirements could not be added within the frame while still maintaining simplicity and ease of use. The decreasing order of priority was maintained as it was considered crucial. The strategies for products based on values and criticality were based on observations of the medical industry by Kane et al. (2018). They were not intended to be prescriptive and were removed to avoid confusion since low-value products need slowing loop strategies and high-value ones need closing loop strategies as well. Questions regarding product criticality and sterilisation were added to this element as well as to the Enablers and Inhibitors element but adding greater detail on context was not possible.
	Suggestions for improvement: 1. There is a possibility to intertwine the two strategies as a product might consist of organic and synthetic materials which are separated afterwards 2. Design for biological cycle: biomimicry does not necessarily apply only to biological cycles. Form, processes and ecosystems can be mimicked by using durable materials for certain parts, which can then be separated from the organic materials and recycled through industrial symbiosis. 3. Design for technological cycle: a. There are number of requirements missing on a more detailed level such as repairability and cleanability b. The decreasing order of priority needs clarification in the sense that loops for high-value products must be closed as well, while your schematic communicates that it might be only for low-value products 4. Product classification system (Spaulding scale): this should be specified with some context to explain what you are trying to show here. This seems like a limited example. It is unclear if you are trying to show an example of a detailed level of requirements.	
Tool part 2 individual component: Enablers & Inhibitors	**Suggestions for improvement:** 1. Trade-offs often happen with stakeholders providing suggestions, for example materials experts suggesting alternatives that may be more biodegradable or plant-based. However, changing materials means that the structural integrity and previous analyses have to be revalidated with rigorous testing to meet safety and health standards.	Questions of trade-offs and relevant regulations were added to this element.

Framework elements	Consolidated feedback	Response and changes implemented
	2. Regulations and requirements could also be included here; these are very important and complex for medical products.	
Tool part 2 individual component: Business Models	**Suggestions for improvement:** 1. This is quite high level, will the users of the tool have the knowledge to answer these questions or can you provide examples to help them, such as mentioning performance and access models for example?	Providing examples without adding greater detail or an explanation of the examples was challenging, hence the key elements of the sustainable business model canvas developed by Bocken (2015) were added to aid potential users.
Tool part 2 individual component: Stakeholders	**Positive feedback:** 1. I like that you talk about stakeholders **Suggestions for improvement:** 1. Many elements are from a business-perspective, but the user/beneficiary perspective should be made more explicit: a. Customers often demand that producers take responsibility for lowering the environmental impact of the product or initiating take back systems b. Understanding the user perspective influences what changes businesses can make. Businesses ultimately depend on them for any design strategy, including circular design. c. This could include how users are taking care of their products, extending product lifetimes, having emotional attachments to their products, whether and how they recycle 2. Understanding the drivers of national healthcare providers could motivate development of a circular mindset	Users were added as a separate stakeholder group with specific questions since this was highlighted by several practitioners. National healthcare providers were considered to be covered under other value chain stakeholders due to lack of space.

Source: Compiled by author

Both parts of the tool were redesigned, refined and updated as described above and are shown in the following pages. Practitioners' comments and suggestions were incorporated where possible, while bearing in mind that the aspects that were commented positively upon should remain close to original. The original tool's simplicity and ease of use were commented on by several reviewers. Hence, one key concern was that changing the visualisation of the tool in its entirety and removing the linear flow and numbering might make the tool appear complex and less easy to follow. To account for this, the visualisation of part 1 of the tool, or the framework, was improved and simplified for it to play a larger role in enhancing potential users' understanding of what the key elements were.

It was also determined that the final tool should not consist only of the two refined diagrams but should take the form of a two-page information sheet, similar to the document with the draft tool that was provided to practitioners. A resource such as this was deemed to be more

valuable to practitioners, the target audience of the tool, providing them with the significance and intended aim of the tool, presenting the two parts, and including brief guiding comments. The utility of this resource is as much in its presentation as it is in its content, hence it was designed in a format that could be easily shared between those involved in the design process. Selected content of the sheet is presented in the following subchapter, expanded for the purposes of the thesis. The condensed and appropriately formatted version in shown in the Executive Summary above. It is envisioned that this will be published and distributed to interviewees and reviewers involved in this project upon completion of the thesis.

5.4.3 Version 2: Final

General Guidance

This tool is designed to be transformational and enable involved practitioners to pursue implementation of strategies. The target audience of this tool is any practitioner involved in the design process of medical products in medical technology or pharmaceutical companies. Examples of potential users include industrial designers and sustainability managers. Company personnel with higher decision-making authority should ideally be involved to operationalise decisions made while using the tool, and involving cross-functional stakeholders such as marketing professionals would be highly valuable. Industry associations may also find this of use in understanding at a glance some of the elements manufacturers of medical products often need to consider.

It can be used in a workshop setting by discussing the different elements and their associated questions. Beginning with Part 1, the framework in Figure 5-3, users can discuss the relevance of the included elements to their company and their specific roles, and any additional elements they consider to be important but missing in the framework. This can be applicable to any particular product, a range of products, or the entire design process, as deemed appropriate. Users can then move on to Part 2, the decision-making guide in Figure 5-4, and discuss the questions for each relevant element. Unlike the draft version, this guide is not numbered and does not present a linear flow since this discussion process should be an iterative one and all elements are interlinked. Possible difficulty in determining a starting point or logical flow can be overcome by beginning with the core elements of Product and Design Strategies, then working outwards, or vice versa, or in any other order the discussing team deems appropriate.

This tool is meant for companies with an intermediate understanding of certain circular economy concepts such as slowing or closing loops and the types of specific design strategies that align with these concepts. However, design professionals in companies in early stages of considering circularity are reasonably likely to be able to grasp these concepts with minimal research. This tool is also considered to be beneficial to companies in advanced stages of implementing circular design strategies, even if it serves as a means to reassess internal design protocols through a new perspective. The tool can be adapted to specific company contexts by altering the elements included, or altering questions associated with the elements.

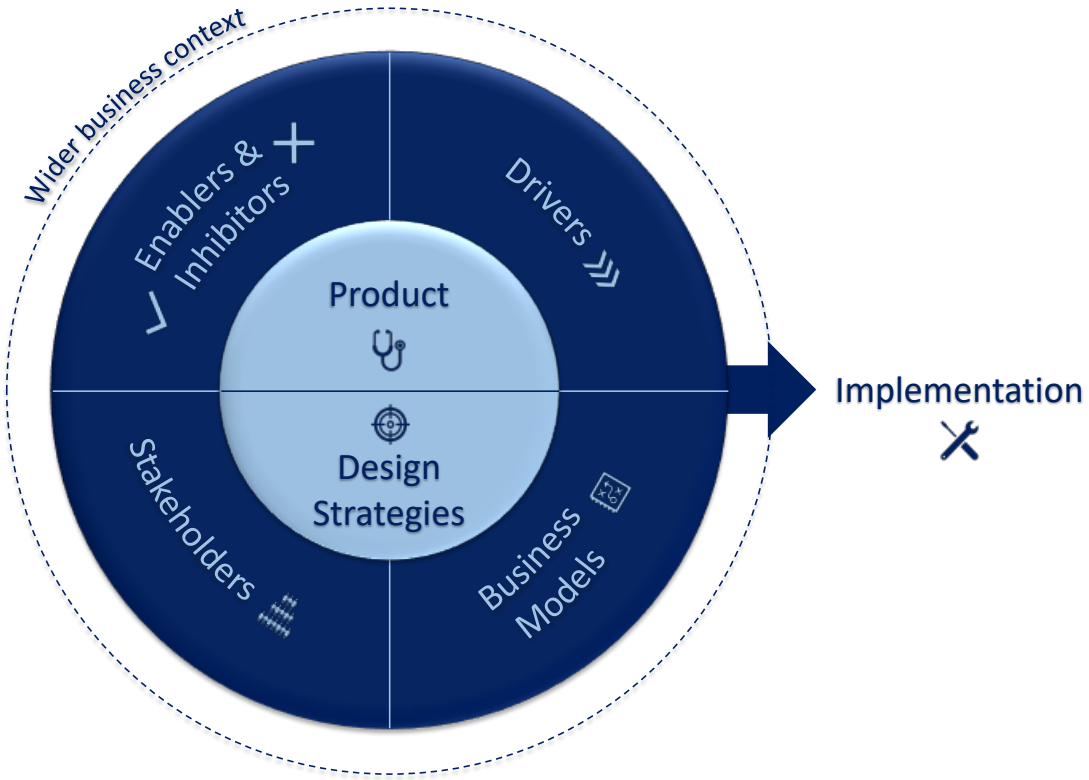

Figure 5-3. Circular medical product design tool part 1: framework of the design process

Source: Author

The various aspects of the tool represent some of the considerations involved in circular design of medical products. Part 1, the framework, summarises key elements necessary for consideration; all elements are interconnected and influence the design in an iterative process. Part 2, the decision-making guide, takes the user through these elements in detail with questions relevant to circular design of the product to promote greater engagement within and between teams.

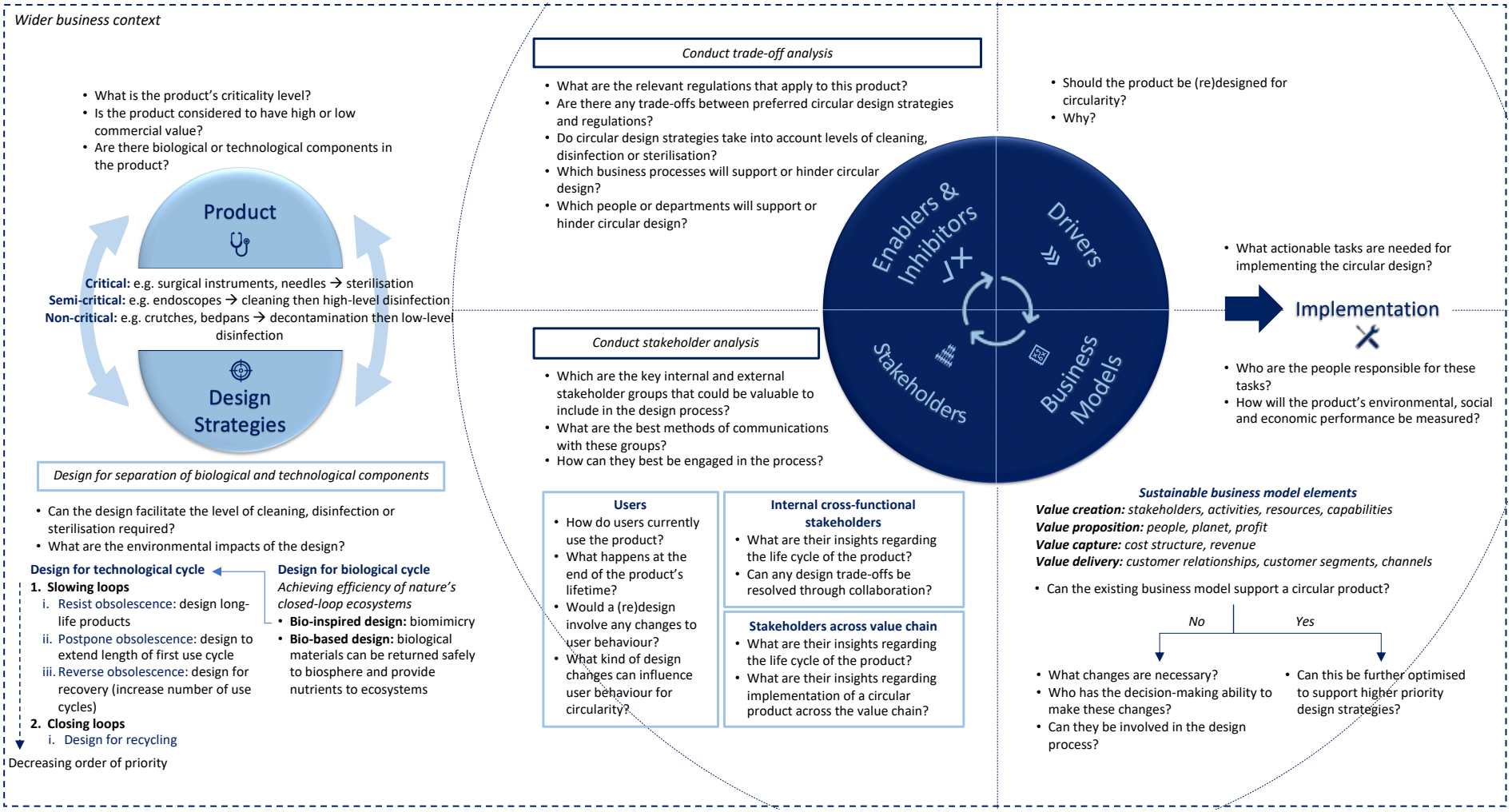

Figure 5-4. Circular medical product design tool part 2: design considerations and decisions

Source: Author

5.5 Evaluation of the Tool

The refined tool was evaluated on its performance against the checklist of criteria for developing sustainability tools in Chapter 5.2 above. This was conducted as shown in Table 5-2 below.

Table 5-2. Evaluation of circular medical product design tool

Criteria	Evidence and rationale	Conclusion
1. Simple and not too time-consuming	Part 1 provides a simplistic overview and Part 2 consists of facilitatory questions which are fairly simple. General guidance is provided with a suggested approach. Time taken to discuss the questions depends on the setting it is used in.	**Criteria met**
2. Purpose-made for circular design of medical products	This was developed from literature and industry reviews specific to the circular design of medical products.	**Criteria met**
3. Rigorously developed from literature and industry insights	As above, developed from reviewing relevant literature, key regulations, industry guides, medical technology company practices, and interviews with practitioners in the industry.	**Criteria met**
4. Iteratively developed and tested with academics and practitioners	Significant changes were made to the tool based on feedback from thesis supervisors and practitioners, all while keeping in mind that this should be a practically valuable tool.	**Criteria met**
5. Integrates relevant knowledge from different disciplines	Literature on this topic spans across social sciences, environmental sciences, management and design. Integrating industry-specific knowledge added further robustness.	**Criteria met**
6. Circular design objectives and impact are firmly integrated and safeguarded when tool is used by others	Circular design strategies are integrated into the Design Strategies element. The tool serves more to facilitate discussions on the wider context around the product and design strategies.	**To be tested**
7. Provides a transparent procedure and guidance on use	The procedure is outlined clearly in the general guidance.	**Criteria met**
8. Adaptable to different (business) contexts	The tool can be used for any particular medical product, a range of products, or the entire design process. Elements and associated questions can be altered depending on the setting and user. Companies at any stage of implementing circular strategies can use this.	**Criteria met**
9. Final tool has been used by practitioners, preferably multiple times, and an evaluation of this process is done to assess tool use and usefulness	At the time of writing, this tool has not been published. Ideally, it will be used upon publication, distributed to the involved practitioners and shared on appropriate platforms for greater use and evaluation.	**Criteria not met**

Criteria	Evidence and rationale	Conclusion
10. Inspires or triggers (business) change	It is believed that the tool has the potential to inspire or trigger change, or at the very least to inspire practitioners to reassess their own processes. However, this cannot be confirmed at present.	**To be tested**

Source: Compiled by author with criteria adapted from Bocken et al. (2019, p. 13)

Testing and conclusions were based on the author's evaluation of the tool and feedback gathered from thesis supervisors and practitioners, and hence may lack robustness. The implications of the evaluation and the usability of the tool are discussed in the next chapter.

6 Discussion

The aim of this thesis was to contribute to the implementation of circular product design strategies in the medical industry. The previous chapters have explored medical applications of circular design both in literature and in practice, and developed a practically useful tool to meet the aim of the thesis. This chapter begins by discussing the reviews and tool development in the context of the RQ and SRQs posed in the beginning, and comments on how this relates to existing knowledge. A critical reflection on the tool, which was the main outcome of the thesis, and its implications is then presented.

6.1 Results and Contribution to Existing Knowledge

The RQ and SRQs are reiterated as follows:

RQ: How can circular product design strategies be applied to the medical industry in practice?

> SRQ 1: How are circular product design principles and strategies described in literature?
>
> SRQ 2: Which design considerations are particularly relevant for medical products?
>
> SRQ 3: What are the current circular product design practices being considered and/or implemented in the medical industry?

The SRQs in themselves were designed to achieve a descriptive research purpose and allow a deeper understanding of key areas such as circular product design theory and medical industry applications to be obtained (Blaikie, 2010). Separately, they do not contribute significantly to existing theories and knowledge; however, these questions and the descriptions generated through answering them were a crucial part of this research, and their importance should not be underestimated (Blaikie, 2010). Answering the SRQs allowed the consolidation of research in a relatively unexplored area, i.e. applications of circular design in the medical industry. Building this foundation and knowledge base was also essential in developing the tool, and in doing so, answering the primary RQ, which was designed to achieve the research purpose of bringing about change and resulting in practical outcomes (Blaikie, 2010).

Key discussion points relating to the individual SRQs are presented below, however the main topic of discussion is the RQ, which makes substantial contributions to theory and practice. The topic representing the bulk of this chapter is therefore the tool for circular medical product design, its contributions, implications, limitations and directions for possible enhancement.

6.1.1 Answering the SRQs and Building a Knowledge Base

SRQ 1: How are circular product design principles and strategies described in literature?

The first SRQ was answered by conducting a review of literature, during which a wide range of theoretical circular product design frameworks were found. Of these, only the key ones were presented and detailed in Chapter 3. Some had similar elements and aligned well together, while others provided different perspectives and contributed new elements to be considered.

It was found that most individual strategies or guidelines found in other tools or frameworks could be aligned well with Bocken et al. (2016)'s product design strategies for slowing and closing loops. Seeing as their aim was to create a coherent terminology, this was to be expected. The integration of these with den Hollander et al. (2017)'s typology for product design

approaches was highly preferred as it added elements of reversible obsolescence and ordering of design strategies. Several studies also highlighted the importance of incorporating a sociological perspective and user-oriented dimension in product design to understand consumption behaviour (Bakker et al., 2014; Lofthouse & Prendeville, 2018). While this was initially left out from the draft tool, it was later emphasised to be crucial enough by reviewers that a separate user group was added, as discussed in Subchapter 6.1.2 below.

This review did not contribute to existing literature but rather enabled a deeper understanding of circular design theory, which was crucial in identifying gaps in literature as presented in Subchapter 1.2.2, refining the aim, RQ and SRQs of this thesis and identifying further relevant literature. In addition, findings from literature informed the structure of reviewing industry practices, which enabled new insights gained from companies and interviews to be contextualised in literature. Most importantly, answering this SRQ shaped the direction and process of developing the tool.

SRQ 2: Which design considerations are particularly relevant for medical products?

This SRQ was answered in part by reviewing literature on medical applications of circular design, as well as by reviewing considerations taken into account by medical technology companies and interviewing practitioners. Companies reviewed mostly did not explicitly mention product-specific design considerations. Rather, inferences were made and trends were observed from stated or implied design strategies. In instances where this was lacking, practitioner interviews and their reviews of the draft tool provided valuable insights into industry perspectives.

From literature and practitioners, the primary distinguishing characteristic of medical products was found to be the product's criticality and corresponding level of sterilisation required. Around this, several key design considerations were found to be relevant to medical products. Literature recommended a design approach tailored for the specific product, taking into consideration not only product characteristics but also aspects such as business constraints, market dynamics and legislation (Bakker et al., 2014). This was reinforced by practitioners, who discussed the importance of considering the wider business and regulatory context in the design of medical products both during interviews and in later stages when providing feedback on the draft tool. Design trade-offs, contradictions and dilemmas were found in literature to be challenging but important to consider in circular design, which was similarly supported by practitioners, who emphasised its importance particularly for medical products.

While product-specific design strategies were not detailed by companies, certain tendencies were observed, as summarised in Subchapter 4.4 above. Companies offering high-value, low-criticality products such as imaging equipment tended to focus their strategies on design for slowing loops through refurbishment, while strategies described for low-value, low-criticality products such as packaging materials revolved around design for closing loops through recycling. This aligned well with Kane et al. (2018)'s categorisation of circular design strategies for medical products.

SRQ 3: What are the current circular product design practices being considered and/or implemented in the medical industry?

The review of industry practices encompassed a range of sources, main ones being publicly available information of medical technology companies and practitioner interviews. This was intended to understand how companies and practitioners were approaching and implementing circular design in the industry. The review was framed in the context of existing knowledge by structuring according to key categories derived from literature.

While reviewing company reports and websites, it became apparent that most of their approaches to circular product design were not clearly stated either; many of these had to be inferred from their stated practices or treatment of certain considerations such as slowing and closing loops. This reinforced the value of framing the findings of the company review in the context of literature as it enabled comparisons to be made and conclusions to be drawn. In addition, it highlighted the limitation in attempting to understand company practices only through their publicly available information. The implications of this on the development of the tool are discussed in Subchapter 6.2 below. Although the review of medical technology company practices does not comprehensively reflect the entirety of the companies' actions and priorities for circular design, consolidating and comparing their stated or implied approaches will ideally trigger a discussion on the potential of this industry to integrate circularity in a way that does not compromise product safety. Additionally, this may result in some reflection on clearer and more detailed public disclosures about design processes.

The industry's understanding of and approaches to circular product design was somewhat clarified by the alignment of certain stated practices with literature. While Bocken et al. (2016)'s circular economy framework comprised of slowing, closing and narrowing loops, their primary focus was on product design strategies for slowing and closing. This sentiment was echoed by practitioners who demonstrated familiarity with and a preference for "slowing" and "closing" loops in interviews and in feedback provided on the draft tool. However, while company practices included these too, there was also a substantial focus on narrowing strategies, which literature described as resource efficiency efforts that companies have typically been implementing within linear systems as well (Bocken et al., 2016). As was expected, companies were observed through their programmes and goals to be at different stages of considering and implementing circular design. Their initiatives for transitioning to a circular economy were apparent, but design implications often needed to be inferred. Overall, circularity in product design did not appear to be a major concern for the companies reviewed, which is to be expected given that the primary focus of medical product design is patient or user health and safety.

The inclusion of empirical data from practitioner interviews provided significantly deeper insights into the mechanisms of company actions and commentary on necessary conditions for an industry transformation. Interviewees expanded on several new concepts and topics that were not initially included in the scope of this research, such as business models, drivers and barriers. All interviewees emphasised the importance of systems thinking and considering the wider business context, including internal and external momentum for change. This is strongly supported by literature, with multiple authors stating that business models and the wider context is crucial to enable and support the implementation of circular design (Bocken et al., 2016; den Hollander et al., 2017). Pinheiro et al. (2019) discussed the need to be aware of both top-down and bottom-up drivers, and a need for commitment from top management, which was also echoed during the interviews. These contributed significantly not only to developing the tool but also in helping to identify some of the factors that need to be considered when furthering the study and implementation of circular design in the medical industry.

6.1.2 Answering the RQ and Developing a Tool

RQ: How can circular product design strategies be applied to the medical industry in practice?

The tool for circular medical product design answers the RQ and was developed by consolidating responses to the SRQs. It provides a method to starting a discussion and enabling the application of circular product design strategies to the medical industry in practice. The tool makes a strong theoretical and practical contribution to the broader field of circular product design as well as to industry-specific applications by addressing several major gaps highlighted

in Subchapter 1.2. Some of these were that industry-specific tools guiding professionals in the visualisation process were lacking, as well as frameworks with practical applicability since many existing ones were largely conceptual or theoretical. This was found to be particularly true for the medical industry, in which the implementation of circular design was largely unexplored and lacking in tailored guides.

The development and refinement of the tool addresses these through several layers of robustness. Firstly, it was designed to be more than a conceptual or theoretical tool by incorporating industry insights to supplement findings from literature. Secondly, these industry insights included several new elements brought up and emphasised by multiple interviewees as being crucial to circular design in the medical industry, which were not specifically considered in the scope of the literature or industry reviews. These added to the tool's relevance and value. Thirdly, questions about types of tools and their elements were specifically asked of practitioners to enable a tool to be designed that would be of practical use to them. Finally, a tool designed from literature and industry insights was then further refined by incorporating practitioner feedback to ensure it was designed to be as usable and valuable as possible within the scope of a thesis project. In addition, this feedback provided significant insight into some of the industry-specific aspects, issues or concerns practitioners considered most challenging or important to include in discussions. One major change was adding users of medical products as a distinct stakeholder group based on practitioner feedback. Although they would have been included under value chain stakeholders, multiple reviewers emphasised the importance of considering the user's perspective specifically with tailored questions, which reinforced the value of user-centred design as highlighted in literature as well.

This iterative and rigorous development and testing process allows the tool to contribute valuable insights into the study of circular product design and/or medical applications of circular economy, while simultaneously providing value to practitioners in their work. These features distinguish this tool from others developed in literature and fill several gaps highlighted in this field. Practitioners have also confirmed its value through their feedback on the facilitatory nature of the tool, its structured overview and placement of critical questions, its contribution to internal robustness processes, and specifics such as inclusion of key stakeholders and prioritisation of design strategies to slow and close loops. In addition, a rudimentary evaluation of its performance demonstrated that it meets seven out of 10 criteria suggested for developing sustainability tools, with the remaining three unable to be tested prior to publication.

6.2 Reflection and Implications

The main RQ was about applying circular design strategies to the medical industry in practice; the tool addresses this completely by ensuring that its core consideration was about usability and value to practitioners, and by including important conversations that are necessary in order to implement circular design strategies. Nevertheless, there were challenges in the development process.

While the tool is built upon literature and industry reviews, there were limitations in obtaining a comprehensive understanding of company practices through only publicly available information. The actions, decisions and processes of companies extend far beyond what is publicly disclosed. This was particularly apparent when exploring design processes. By the nature of their products, companies producing medical products need to have robust design protocols, regulatory checks and documented processes in place, but the information published on these is extremely limited. It was hence initially envisioned that more interviews would be conducted with representatives of the reviewed companies. The COVID-19 pandemic and the resulting changes to work schedules and priorities is likely to have significantly impacted

availability of practitioners. This includes those reached out to for initial interviews as well as for providing feedback on the draft tool.

Interviewing more representatives of reviewed companies would have contributed greatly to a deeper understanding of specific company practices, perspectives of relevant personnel, as well as insight into companies' disclosure preferences. The addition of more interviews may or may not have changed the final tool since those that were conducted and feedback that was received were already invaluable and sufficient in developing a robust and practically useful tool. However, it would have enhanced the tool's credibility and allowed more areas of improvement to be identified. Interestingly, although interviews were conducted in the midst of a global pandemic, practitioners did not mention or hint to prioritising medical product safety at the expense of environmental impacts. In fact, all agreed that the subject of this thesis was a crucial one for the industry to take action on.

Designing and developing a tool for circular design applications was also challenging given the lack of technical or industry expertise, although this also enabled the incorporation of a higher-level perspective. Beginning the development involved drawing inspiration from a range of different frameworks in literature, which also presented difficulties due to the lack of design expertise. These factors contributed to the decision to make this tool a facilitatory one comprising of key questions and considerations, as a suggestive guide to the user. This was later appreciated by practitioners who reviewed the draft tool. In the refinement stage, using a methodological framework for obtaining and incorporating practitioner feedback could have added further structure. However, conducting additional research on this was deemed to be secondary compared to addressing reviewers' comments and implementing changes. While a methodology rooted in theory could not be employed, a transparent method was nonetheless followed by sending the draft tool to practitioners in the same format, asking specific questions of them, structuring their feedback according to the core elements of the tool, and providing a rationale behind any changes made or suggestions not implemented.

While this tool meets several research gaps, one that remained incomplete was that tools should help designers conceptualise an ideal vision rather than aim for incremental improvements. This was challenging to achieve within the scope of the thesis while attempting to maintain a balance among the various trade-offs, such as simplicity and ease-of-use compared to comprehensiveness and addressing the various reviewers' comments and feedback while retaining the key value of the tool. For example, one suggestion included providing greater guidance around the Business Models element. A fairly simplistic overview of sustainable business model elements was added, which may not have accurately portrayed the complexity of circular business models but was necessary for the sake of tool usability. Overall, while the medical industry-specific elements and questions in the tool are not extensive, this also presents a benefit. In its current form, it is highly usable by practitioners in the medical industry, yet it can also be easily adapted to suit other industries with their own specific requirements.

7 Conclusions

This thesis set out to explore possibilities for meeting some of the challenges the medical industry faces with respect to resource use and waste generation by examining potential for circular product design. A large portion of the environmental impacts generated across the lifecycle of any product are determined in the design stage, making it crucial to incorporate circular economy principles in this stage. However, one of the most significant barriers to doing so in the medical industry is that any circular strategy that could potentially compromise product safety is not likely to be implemented until even the slightest increase in risk to patients and users has been addressed.

This research does not solve the challenges of the industry or propose a way to implement circular design across the entire range of medical products, but rather proposes a method for embarking on this process. Industry practitioners, particularly professionals such as designers, do not lack knowledge about circular design strategies; they face difficulties in implementing them. The tool developed through this research most notably serves to engage key stakeholders in a process that will ideally result in progress towards applying these strategies in practice and contribute to the industry's transition to a circular economy.

The nature of the industry means that it will continue to be highly regulated, particularly with respect to product safety. It will also continue to be highly influenced by external events such as global environmental and health crises; the COVID-19 pandemic has demonstrated clearly the interlinkages between planetary and human health. While there are challenges to implementing circular design in the medical industry, an industry-wide transition is necessary. Successful and long-standing practices such as refurbishing imaging equipment have proven that there is potential for the wider industry to pursue strategies appropriate to the type of product.

7.1 Practical Applications and Further Research

Through every step of the thesis process, the practical applicability of this research and its contribution was kept in consideration, while also taking note of the scope and extent of technical knowledge and expertise available. This subchapter outlines possible directions for developing the tool, applying the findings of this research, and advancing further research in this field.

7.1.1 Note to Practitioners

Circular product design should be actively pursued beyond existing recycling strategies, regardless of nuances in terminology such as eco-design and circular design, or dilemmas and trade-offs. The wider context and business environment can be more important than the process of designing, or redesigning, a product. In order to implement strategies, it is necessary to engage the right people and decision-makers who would then be able to operationalise strategies beyond the conceptualisation stage. This research has also demonstrated the importance of collaborating with stakeholders such as internal cross-functional personnel, parties across the value chain, and users of the products. There is a need for a broader, more accessible, and more nuanced discussion about the role of circular product design in the medical industry. In this process, open communication and transparency is key. Not only will this encourage trust in the company, but it also has the potential to inspire other industry players to follow suit, implement learnings, and eventually contribute to an industry-wide transition to a circular economy.

7.1.2 Operationalising and Enhancing the Tool

It is proposed that the next stages for this research should be operationalising and enhancing this tool. To begin with, this thesis and the tool will be distributed among practitioners who were interviewed and provided feedback, as well as shared via appropriate platforms. Some of these practitioners have expressed interest in sharing these findings further with their respective industry associations, which will be highly beneficial in gauging the tool's effectiveness and value. The intended end result would be achieved if utilising this tool leads to implementation of circular design strategies. A logical next step for testing whether the tool would in fact be useful in practice could be, as one reviewer suggested, to run through it and answer its questions for an example product or scenario. While this could not be done in the scope and timeframe of the thesis, it would undoubtedly solidify the applicability and value of the tool. Operationalising the tool is likely to occur in practice rather than academia, however both academic and practical assessments will be beneficial in tweaking and enhancing the tool's usability and effect.

7.1.3 Further Research

Building on the recommendation to run through the tool with example products, an avenue for further research could be to conduct feasibility assessments of implementing specific strategies. These could be conducted in collaboration with designers and/or product managers, ideally with different scenarios for products across different levels of criticality to provide greater context around the Spaulding classification system. Mechanisms for reverse flows and logistics of operationalising certain strategies could also be taken into account, and findings from LCAs included to ensure that circular design innovations in products eventually do result in lower environmental impact.

This study reviewed practices of larger medical technology companies, but future research could study circular product design innovations of smaller and more niche companies as well to compare with. This should include more than just publicly available information and would provide a more comprehensive view on circular design practices in the industry as a whole. Most importantly, it is necessary to conduct further practice-oriented, action-based and participatory research in order to truly contribute to changing practices and drive an industry transformation. For example, interdisciplinary teams could research specifics around medical legislation and the space available for product design innovations. This would necessitate having academics and practitioners involved who are well-versed in industry-specific legislative requirements and have the appropriate design and technical expertise.

This thesis has contributed to an evolving field and attempted to further the progress towards reaching a circular economy. Ambitious action to safeguard planetary resources is needed now more than ever. Every industry must do its part to shift away from resource-depleting models and rethink entire systems. In this effort, it is crucial for academics and practitioners to join forces to ensure that climate action is guided by science and research, and that research is geared towards being practically useful and affecting change.

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Appendix A: Interview Details

Permission was requested before beginning all recordings.

Interviewee code	Position and organisation	Type of organisation	Date and duration (min:sec)	Medium	Recorded
Interviewee A	Expert, Swedish Medtech	Industry association of medical technology companies in Sweden	16 March 2020 17:35	Zoom	Yes
Interviewee B	Industrial Design Lead, Novo Nordisk	Danish multinational pharmaceutical company	11 March 2020 26:10	Phone call	Yes
Interviewee C	Senior Service Designer, Circular Design, Philips	Dutch multinational health technology company	24 March 2020 36:07	Microsoft Teams	Yes
Interviewee D	Safety, Health and Environment Specialist, AstraZeneca	Swedish-British multinational pharmaceutical company	6 April 2020 22:44	Skype	Yes
Interviewee E	Founder and Designer, Solve	Innovation studio in design and sustainability Began as a circular fashion studio but now addresses product design in general	13 March 2020 35:25	In person	Yes

Appendix B: Interview Guide, Designer or Specialist

Part 1: Introduction and confidentiality

1. May I record this interview to transcribe?
2. Could you tell me about your role and the work you do at *[organisation]*?

Part 2: Concepts

3. How are circular economy and circular product design typically understood in the context of your industry?

Part 3: Design process

4. What is the typical process for designing a medical device?
5. What type of interactions do you have with stakeholders from other parts of the products' life cycles?
6. What are your main considerations and priorities for designing the device?
7. Do you have to make any trade-offs in the design process?
    a. What are these trade-offs and how do you deal with these?

Part 4: Industry status

8. Where is *[organisation]* currently at in terms of incorporating these concepts in designing products?
9. In my research I found that there are a couple of industry leaders that have clear circular design initiatives and programmes, whereas in other companies this is not mentioned much. Is this consistent with what you see?
    a. If yes, why do you think there is such a disparity?
10. How do you feel you are performing compared to your competitors and other industry leaders?

Part 5: Opportunities and challenges

11. What are the key challenges you see in circular design of medical products?
12. What are the key opportunities?

Part 6: Framework

13. Would a conceptual framework to aid circular design specifically tailored for medical products be useful in your work?
14. What do you think are the most important elements to include in such a framework?
15. Would you be interested in having a look at the draft framework and providing brief feedback?

Part 7: Closing

16. The final thesis is a public document, can I use your responses and refer to your position and organisation?

Appendix C: Interview Guide, Industry Expert

Part 1: Introduction and confidentiality

1. May I record this interview to transcribe?
2. Could you tell me about your role and the work you do at *[organisation]*?

Part 2: Concepts

3. How are circular economy and circular product design typically understood in the context of your industry?

Part 3: Industry status & wider implications

4. Where do you think medical device manufacturers are at in terms of implementing circular product design?
5. In my research I found that there are a couple of industry leaders that have clear circular design initiatives and programmes, whereas in other companies this is not mentioned much. Is this consistent with what you see?
    a. If yes, why do you think there is such a disparity?
6. Based on your experience, what do you think could trigger or facilitate the industry to move further along towards integrating circular principles in their practices?

Part 5: Opportunities and framework

7. If you could change the way medical devices are designed at the moment from an environmental perspective, what might you like to change?
8. In a conceptual framework to aid circular design specifically tailored for the medical industry, what do you think the most important elements to include would be?

Part 7: Closing

9. The final thesis is a public document, can I use your responses and refer to your position and organisation?

Appendix D: Interview Guide, Business and Design Lead

Part 1: Introduction and confidentiality

1. May I record this interview to transcribe?
2. Could you tell me about your role and the work you do at *[organisation]*?

Part 2: Concepts

3. How are circular economy and circular product design typically understood in the context of your industry?

Part 3: Design process

4. Can you briefly describe your design process?
5. How actively do you consider the circularity of the product during the design stage?
6. Do you have to make any trade-offs in the design process?
    a. What are these trade-offs and how do you deal with these?

Part 4: Wider context and implications

7. For a product that is typically linear, how does one begin to think about integrating circular principles?
8. I understand your entire business model is built around circularity. What effect does trying to implement circular design to such a product have on the wider business?
    a. Are any changes necessary to the business as a whole, and if so, what are these?
9. What do you think could trigger or facilitate an industry-wide transformation?

Part 5: Framework

10. Do you think a conceptual framework to aid circular design of a typically linear product would be useful for designers?
11. What do you think are the most important elements to include in such a framework?

Part 7: Closing

12. The final thesis is a public document, can I use your responses and refer to your position and organisation?

Appendix E: Project Brief for Interviewees

Circular Product Design in the Medical Industry

Project Brief

This project is investigating circular design principles and their application to the medical product industry. While circular economy and design have been explored thoroughly in literature, industry-specific research is lacking. The medical industry is a particularly unique case given the immense amounts of waste generated and the various health and safety considerations which make certain circular practices such as reuse and recovery challenging.

Project Aim

My aim is to develop a conceptual framework that is practically applicable to designers of medical products, integrating elements from theory and practitioner perspectives. This will ideally facilitate discussions around design protocols, priorities, trade-offs and dilemmas, and create a space for innovation within the boundaries of medical restrictions.

Your Involvement

I would love to hear your perspectives from your experience and expertise in this field through an interview. This would be invaluable for my understanding of current practices and in developing a comprehensive and practically applicable framework.

- **Duration:** no longer than 1 hour
- **Date:** between 9 March to 27 March, subject to your availability
- **Medium:** phone call, Skype, Zoom, as per your preference

The findings from this research will provide useful industry-specific insights for practitioners as well as an academic perspective to a specific application of circular product design, both of which may be of value to your work. The final thesis report can be sent to you in June if you are interested.

Confidentiality

All interviewee names will be anonymised. During the interview, I will ask for permission to record, to include your responses in my analysis, and to refer to your position and company. If I use any direct quotations, I will run them past you first to obtain permission.

Appendix F: Tool for Circular Medical Product Design (Draft for Practitioners)

Purpose of Tool

The overall aim for this tool is for it to be practically useful for designers and others involved in the design process of medical products. The main areas of added value are that such a tool might challenge existing processes and influence practitioners to consider alternative methods. This tool will ideally facilitate a collaborative approach to circular medical product design, rather than prescribing specific design requirements for different medical products.

Tool Development and Components

This tool comprises of two major components: an overarching framework for circular medical product design, and a flowchart to facilitate discussions on design considerations, priorities, and various decisions that need to be made. These components were developed from a synthesis of key findings from literature, company practices, and interviewee and supervisor insights. The refinement step, or testing this tool and gathering feedback from practitioners, is essential in the development of the tool.

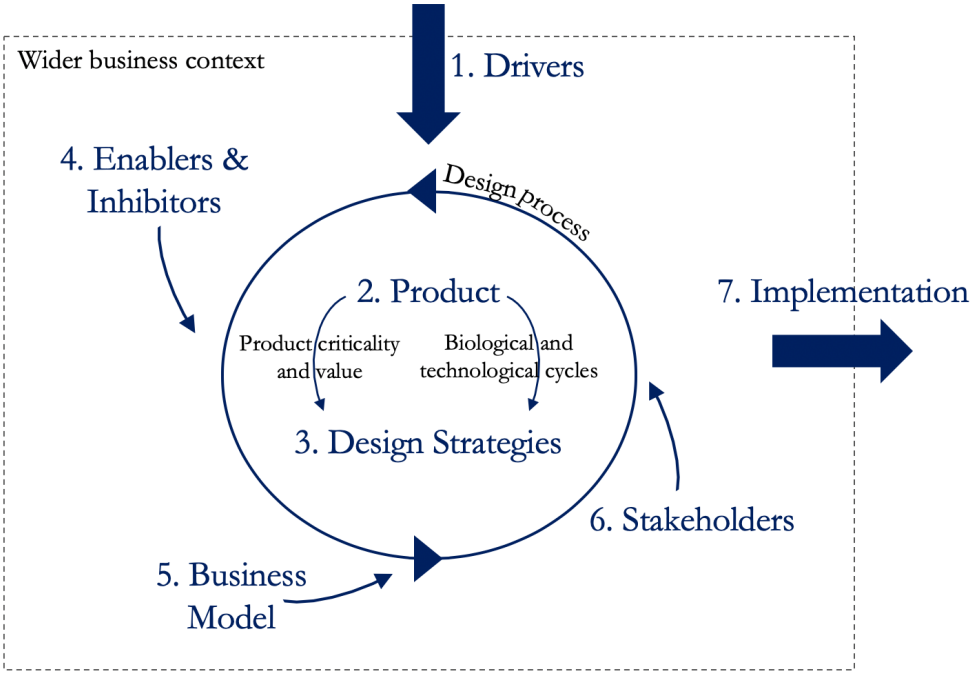

Figure 1. Circular medical product design tool part 1: framework of the design process
**Classification system of critical, semi-critical and non-critical medical products shown after Figure 2*

Part 1, the framework, provides a simple and easy overview of key elements necessary to be considered, with questions that could promote greater engagement within and between relevant teams. Against the backdrop of the wider business context, all elements from the product through to stakeholders and implementation are interconnected and influence the design in an iterative process. Part 2, the flowchart, takes the user step by step through the various elements. It is important to note that while these are numbered in order, the process of circular design should not be a linear one.

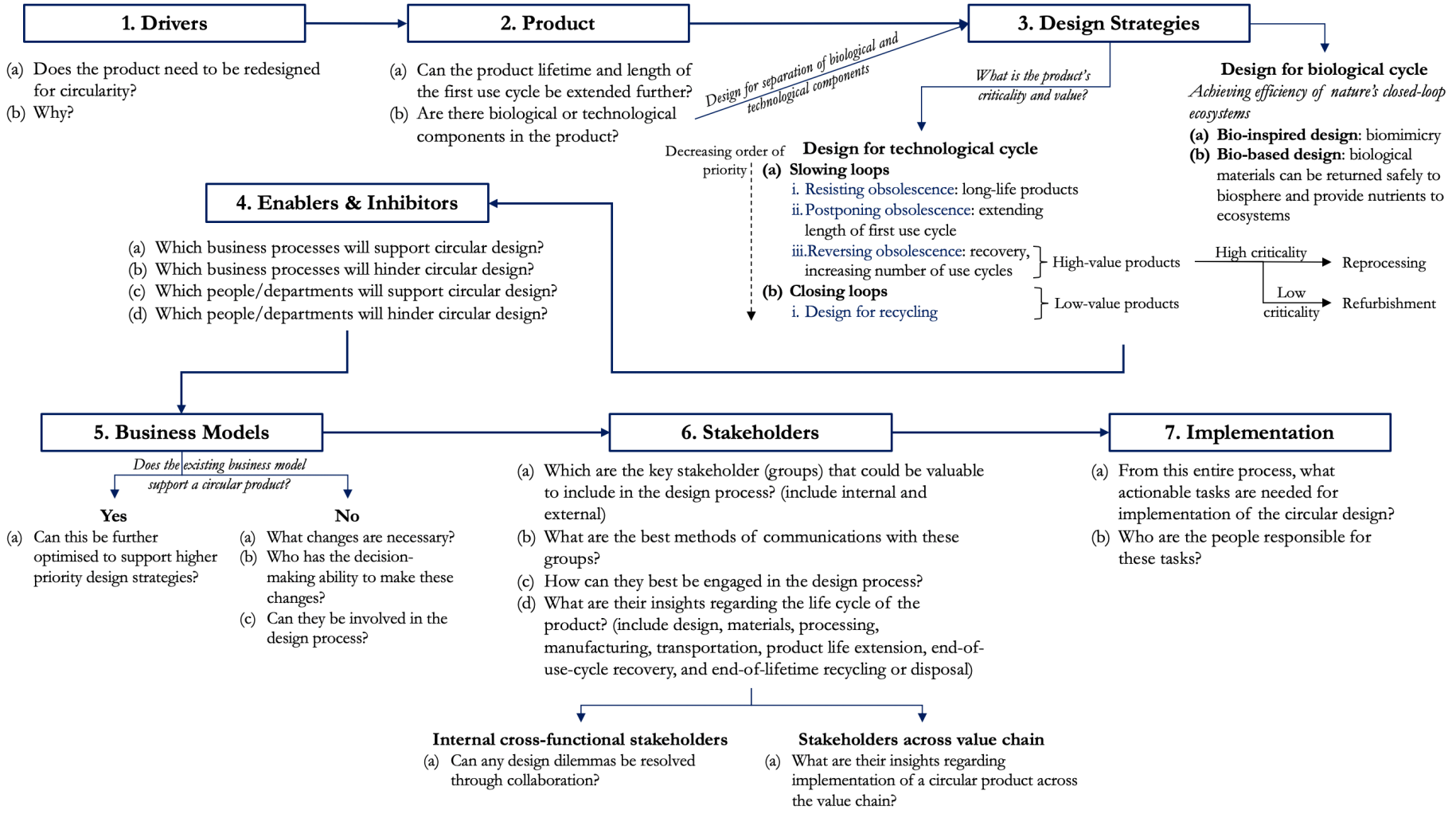

Figure 2. Circular medical product design tool part 2: flowchart of design considerations and decisions

Table 1. Medical products classified by the Spaulding scale

Classification	Critical	Semi-critical	Non-critical
Description	Products that enter sterile tissue or vascular systems	Products that come into contact with non-intact skin or mucous membranes	Products that come into contact with intact skin but not mucous membranes
Examples	Surgical instruments, implants, needles	Endoscopes, equipment for anaesthesia	Patient care items: crutches, bedpans Environmental surfaces: bed rails, utensils
Level of disinfection or sterilisation	Sterilised with steam, gas plasma or liquid chemical sterilants	Cleaning, then high-level chemical disinfection	Decontaminated on site with low-level disinfectants

Source: Compiled based on Rutala and Weber (2008)