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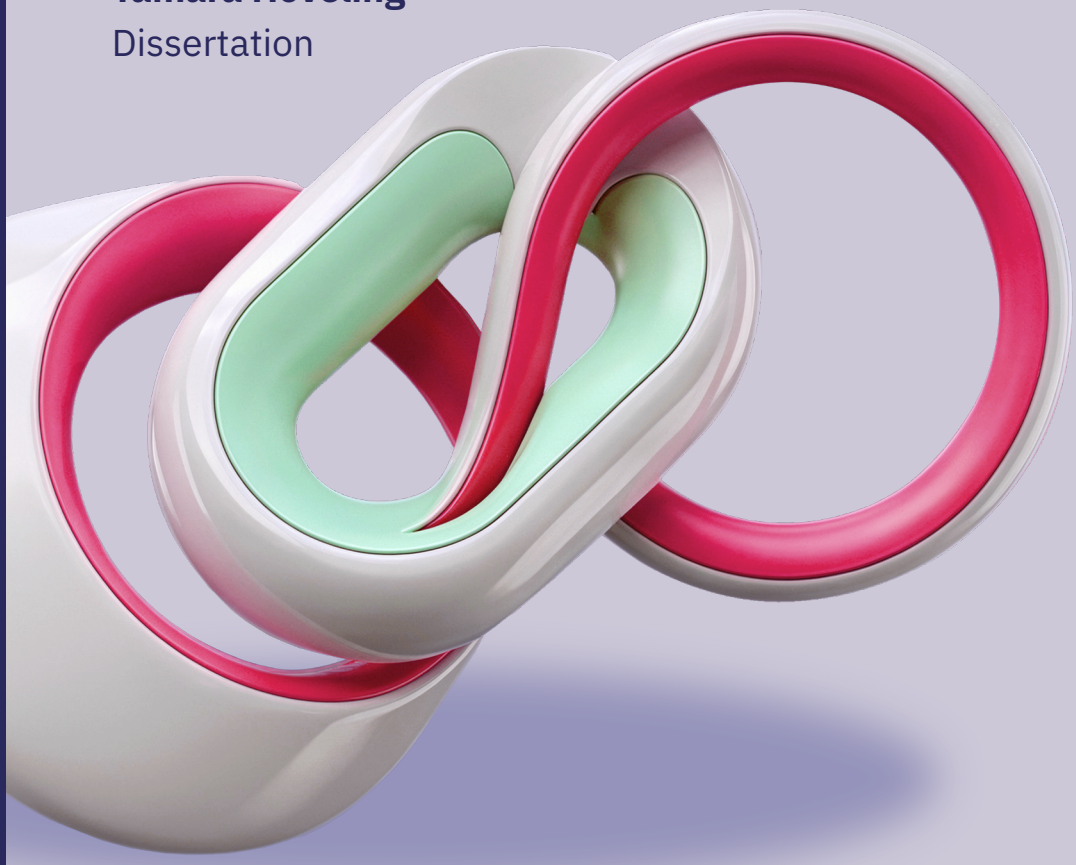
TU Delft

Healing **Without Harm**

Designing Medical Devices for a Circular Economy

Tamara Hoveling

Dissertation



Healing Without Harm

Designing Medical Devices for a Circular Economy

Tamara Hoveling

Healing Without Harm

Designing Medical Devices for a Circular Economy

Dissertation

for the purpose of obtaining the degree of doctor

at Delft University of Technology

by the authority of the Rector Magnificus,

Prof. dr. ir. H. Bijl,

chair of the Board for Doctorates

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To those who believe true care embraces both people and the planet, may this work stand as a testament to knowledge that heals, sustains, and inspires.

And to my partner, family, and friends, thank you for your love, patience, and for surviving my obsession with this research.

“Anyone who believes in infinite growth on a finite planet is either mad, or an economist.” — Kenneth Boulding

Samenvatting

(Dutch Summary)

Klimaatverandering wordt algemeen erkend als de grootste bedreiging voor de volksgezondheid, maar de zorgsector zelf draagt ook in belangrijke mate bij aan milieuschade. Milieudruk die verder gaat dan klimaatverandering, zoals de aantasting van natuurgebieden die het risico op pandemieën vergroot en de toenemende vraag naar schaarse grondstoffen die worden gebruikt in moderne technologieën, draagt eveneens bij aan deze gezondheidsrisico's. Ondanks deze uitdagingen blijven veel hightech oplossingen afhankelijk van schaarse materialen, terwijl ze slechts kort worden gebruikt, en wordt een toenemend aantal producten ontworpen als wegwerpartikel. Eenmalige producten, zoals verpakkingen, medische disposables of complexe elektronische apparaten, worden vaak na minimaal patiëntcontact weggegooid, omdat dit als het meest veilig wordt beschouwd.

Een specifieke uitdaging binnen deze context wordt gevormd door medische hulpmiddelen met elektronische componenten. Deze apparaten zijn afhankelijk van kritieke grondstoffen en energie-intensieve productieprocessen en bestaan uit complexe, multi-materiaal assemblages. Aan het einde van hun levenscyclus leidt hun afdanking tot milieuproblemen, aangezien inzamel- en recyclingsystemen slechts een beperkt deel van de materialen terugwinnen, terwijl onjuiste verwerking van elektronisch afval kan leiden tot het vrijkomen van schadelijke stoffen in het milieu. In combinatie met snelle technologische ontwikkeling en strikte regelgeving bemoeilijken deze factoren de toepassing van circulaire benaderingen in het ontwerp. Dit proefschrift onderzoekt niet alleen waarom dit het geval is, maar ook hoe dit kan worden verbeterd.

De centrale onderzoeksvraag van dit proefschrift luidt daarom:
Hoe kunnen medische apparaten met elektronische componenten worden herontworpen om een circulaire economie te ondersteunen, terwijl aan klinische en regelgevende eisen wordt voldaan?

Om deze vraag te beantwoorden is het proefschrift opgebouwd uit vijf delen. Deel I introduceert het probleem en verkent de milieueffecten van de zorgsector, ontwerpuitdagingen van medische hulpmiddelen en de onderbouwing van circulaire economieprincipes. Deel II onderzoekt de huidige stand van zaken in het ontwerp van medische hulpmiddelen via literatuuronderzoek en kwalitatieve methoden, waarbij barrières en kansen voor circulariteit worden geïdentificeerd en wordt verduidelijkt hoe stakeholders effectief kunnen samenwerken. Daarnaast wordt de Circular Healthcare Flows visuele taxonomie gepresenteerd, die laat zien hoe R-strategieën kunnen worden toegepast en die in kaart brengt hoe materialen, componenten en apparaten kunnen circuleren binnen klinische, regelgevende en operationele contexten, en zo een gedeelde taal en conceptuele helderheid biedt voor ontwerpers, clinici en beleidsmakers. Deel III presenteert twee ontwerpcasussen die de praktische toepassing van circulaire economieprincipes demonstreren en daarbij trade-offs, integratie-uitdagingen en strategieën om deze te overwinnen belichten. Deel IV vertaalt deze inzichten naar praktische benaderingen en vormt daarmee de basis voor een Circular Design Guide. Tot slot bespreekt Deel V de geleerde lessen, reflecties en richtingen voor toekomstig onderzoek.

Het onderzoek laat zien dat circulaire strategieën in de gezondheidszorg mogelijk zijn, maar sterk contextafhankelijk. Analyse van meer dan 1.400 medische hulpmiddelen liet zien dat,

hoewel sommige apparaten hergebruik implementeren, de meeste nog steeds single-use zijn. Barrières zijn niet alleen technologisch: ze ontstaan ook door regelgeving, institutionele praktijken en risicopercepties, terwijl inconsistent gebruik van terminologie en concepten de coördinatie tussen stakeholders bemoeilijkt. De visuele taxonomie helpt deze conceptuele ambiguïteit te verminderen, waardoor stakeholders terminologie kunnen afstemmen, circulatiestromen beter kunnen begrijpen en contextspecifieke beslissingen kunnen nemen. Designexperimenten illustreren hoe deze inzichten in de praktijk kunnen worden toegepast. Middelste R-strategieën zoals hergebruik, reparatie en refurbishment leveren concrete milieuwinst op zonder klinische workflows te verstoren. Breder toepasbare strategieën, zoals refuse, rethink en reduce, kunnen grotere impact hebben, maar vereisen een heroverweging van het gebruik van apparaten en de organisatie van zorg. Afwegingen tussen circulariteit, veiligheid, bruikbaarheid en naleving kunnen worden beheerd—en soms zelfs worden omgezet in synergieën—door zorgvuldig ontwerp, betrokkenheid van stakeholders en iteratief testen. Deze bevindingen vormden de basis voor aanbevelingen in een Circular Design Guide, die praktische stappen biedt om circulariteit te integreren in het dagelijkse ontwikkelproces van medische hulpmiddelen. Het onderzoek laat zien dat circulair ontwerpen in de gezondheidszorg haalbaar is wanneer milieudoelstellingen worden afgestemd op klinische, regelgevende en operationele realiteiten.

Naast individuele apparaten benadrukt het werk ook bredere implicaties. Samenwerking tussen disciplines en organisaties, digitale tools om apparaten gedurende hun levenscyclus te volgen en te optimaliseren, en educatie om circulair denken in de praktijk te verankeren zijn essentieel om impact op grotere schaal te realiseren. In zijn geheel laat dit proefschrift zien dat duurzaamheid en circulariteit in de gezondheidszorg geen abstracte idealen zijn, maar toepasbare benaderingen die worden ondersteund door instrumenten zoals de visuele taxonomie en de Circular Design Guide, die richting kunnen geven aan beleid, industriële praktijk en toekomstig onderzoek.

Summary

(English Summary)

Climate change is widely recognized as the greatest threat to human health, yet healthcare itself contributes significantly to environmental harm. Environmental pressures beyond climate change, such as the encroachment on wild lands that increases pandemic risks and the growing demand for scarce resources used in modern technologies, also contribute to these health risks. Despite these challenges, many high-tech solutions continue to rely on scarce materials but are used only briefly, and an increasing number of products are designed to be disposable. Single-use items, whether packaging, medical disposables, or complex electronic devices, are often discarded after minimal patient contact, as this is perceived to maximize safety.

A particular challenge within this context is posed by medical devices containing electronic components. These devices depend on critical raw materials and energy-intensive production processes and are composed of complex multi-material assemblies. At end of life, their disposal raises environmental concerns, as collection and recycling systems achieve only partial material recovery, while improper treatment of electronic waste can release hazardous substances into the environment. Together with rapid technological development and strict regulatory requirements, these factors complicate the application of circular approaches in design. This dissertation examines not only why this is the case, but also how it can be improved.

The central research question of this dissertation is therefore:
How can medical devices containing electronic components be redesigned to support a circular economy while ensuring clinical and regulatory compliance?

To answer this question, the dissertation is structured in five parts. Part I introduces the problem, exploring healthcare's environmental impact, medical device design challenges, and the rationale for circular economy principles. Part II investigates the current state of medical device design through literature review and qualitative methods, identifying barriers and opportunities for circularity and clarifying how stakeholders can collaborate effectively. It also presents the Circular Healthcare Flows visual taxonomy, which shows how R-strategies can be implemented and maps how materials, components, and devices can circulate within clinical, regulatory, and operational contexts, providing a shared language and conceptual clarity for designers, clinicians, and policymakers. Part III presents two design case studies, demonstrating practical application of circular economy principles and highlighting trade-offs, integration challenges, and strategies to overcome them. Part IV translates these insights into practical approaches, forming the foundation for a Circular Design Guide. Finally, Part V discusses lessons learned, reflections, and directions for future research.

The research shows that circular strategies in healthcare are possible but context dependent. Analysis of over 1,400 medical devices revealed that while some devices incorporate reuse, most remain single use. Barriers are not only technological—they stem from regulations, institutional practices, and risk perceptions, while inconsistent terminology and concepts complicate coordination across stakeholders. The visual taxonomy helps address this conceptual ambiguity, enabling stakeholders to align on terminology, understand circular flows, and make context-sensitive decisions.

Design experiments illustrated how insights can be applied. Mid-level R-strategies such as reuse, repair, and refurbishment provide tangible environmental benefits without disrupting clinical workflows. Broader strategies, such as refuse, rethink, and reduce, offer greater impact but require reconsidering device use and care delivery. Trade-offs between circularity, safety, usability, and compliance can be navigated—and sometimes leveraged—through careful design, stakeholder engagement, and iterative testing.

These findings informed recommendations for a Circular Design Guide, offering practical steps to embed circularity into everyday medical device development. The research demonstrates that circular design in healthcare is achievable when environmental ambitions are balanced with clinical, regulatory, and operational realities.

Beyond individual devices, the work emphasizes broader implications. Collaboration across disciplines and organizations, digital tools to track and optimize device lifecycles, and education to embed circular thinking into practice are essential to scaling impact. Overall, this dissertation shows that sustainability and circularity in healthcare are not abstract ideals, but actionable approaches supported by tools such as the visual taxonomy and Circular Design Guide for medical devices, which can guide policy, industry practice, and future research.

Prologue

All throughout my life, I have been obsessed with writing and anything creative. I would spend my days reading, drawing, and exploring the world around me. So, when I started my education in industrial design, life felt like a true playing field. It didn't take long for me to realize that design, to me, is where science and art break-even—and that good design can make a huge contribution to the world. And that's what I wanted to do: to make an impact in a field that needed it.

For me, the healthcare sector felt like just the place. The place that hadn't been touched by many designers yet still had so many design challenges left to tackle. After growing my interest in the human body and in how modern medicine can make life easier, I'm proud to have already contributed to the development of some innovative medical devices with real potential to save lives. Yet, frustrations began to linger. Every life-changing device came with a heavy burden: high energy use, extreme safety precautions, and, as a result, an endless number of single-use products. Not because disposability was truly needed, but because "this is how we always do it," "this is what's expected of us," or simply, "let's dispose of it, just in case." I couldn't help but wonder: do we really need to heal patients at the expense of the planet? Personally, I felt we could do better.

I started this PhD not because I was particularly interested in the circular economy itself, but because, as a medical device designer, I felt obliged to explore it and make it my own—so that I wouldn't harm the planet while trying to save lives. And, as a bonus, there's simply no better way to combine your passion for writing, researching, and designing than through an industrial design PhD.

Little did I know that this PhD—and circularity for that matter—would become my new obsession. It would become my hyperfocus, something I would dream about, talk about, and dive into at any moment of the day. While not every step of this journey has been easy—for me or my loved ones—I can truly say that, unexpectedly, I fell in love with academia. And even if I step back into industry, entrepreneurship, or something completely different, I will forever be, and remain, a researcher.

"I am so clever that sometimes I don't understand a single word of what I am saying."

— Oscar Wilde

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List of Abbreviations

CE	Circular Economy
CE-mark	Conformité Européenne Mark
CH	Chapter
CHFs	Circular Healthcare Flows
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide Equivalent
DiCE	Digital Health in a Circular Economy
EoL	End of Life
EF	Environmental Footprint
EMF	Ellen MacArthur Foundation
EU	European Union
EU-MDR	European Union Medical Device Regulation
FDA	Food and Drug Administration
ISO	International Organization for Standardization
LCIA	Life Cycle Impact Assessment
LCA	Life Cycle Assessment
LED	Light-Emitting Diode
MedTech	Medical Technology
NFC	Near Field Communication
OEC	Original Equipment Company
OEM	Original Equipment Manufacturer
OR	Operating Room
PhD	Doctor of Philosophy
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QR-code	Quick Response Code
R&D	Research and Development
RIVM	Rijksinstituut voor Volksgezondheid en Milieu
RQ	Research Question
RtD	Research through Design
TU Delft	Delft University of Technology
USB	Universal Serial Bus
US	United States
VPC	Value Proposition Creation
WFD	Waste Framework Directive
PET	Polyethylene Terephthalate

Glossary

Active (medical) device	Any device, the operation of which depends on a source of energy other than that generated by the human body for that purpose, or by gravity, and which acts by changing or converting that energy. Devices intended to transmit energy, substances, or other elements between an active device and the patient, without any significant change, are not considered active. Software is also considered an active device. (Synonym: Digital Medical Device for DiCE project purposes.)
Active implantable medical device	Any active medical device intended to be totally or partially introduced, surgically or medically, into the human body or a natural orifice, and intended to remain after the procedure.
Best circular practices	Selected examples of circular digital health devices on the current market based on practicality, acceptability, and affordability.
Cleaning	Removal of contaminants to the extent necessary for further processing or intended use.
Collection	Gathering of waste, including preliminary sorting and storage for transport to a waste treatment facility.
Clinical benefit	Positive impact of a device on health, expressed in meaningful, measurable, patient-relevant outcomes, including diagnosis, patient management, or public health.
Circular Health Flows strategies (CHFs)	Strategies outlining steps for efficient collection, processing, and safe reintegration of materials and medical products within healthcare to minimize waste and maximize resource value. Includes refuse, replace, rethink, reduce, maintain, repair, reuse, refurbish, remanufacture, repurpose, recycle, renew, recover energy, adapted for safety and healthcare requirements.
Circular Recovery Hierarchy	Structured sequence of prioritized CHF strategies guiding decision-making while minimizing environmental impacts.
Coating	Surface treatment applied to a product to provide protective or functional properties.
Depollution	Selective treatment removing potentially harmful substances or components from products or materials.
Decontamination	Process of removing or neutralizing contaminants (e.g., microorganisms) from surfaces or devices to prevent infection. Includes cleaning, disinfection, and sterilization based on device use.
Digital health device	Physical device for health applications containing electronics and operating on an external energy source. Devices classified as medical devices under EU-MDR are also active devices.
Disassembly	Process of taking a product apart in a way that allows reassembly and operational use.

Disinfection	Process to inactivate viable microorganisms to a defined level appropriate for the intended purpose.
Disposal	Any operation that is not recovery, even if it results in incidental reclamation of substances or energy.
Ecodesign	Integration of environmental aspects into product design to improve environmental performance throughout the product lifecycle.
Electrical and electronic equipment (EEE)	Equipment dependent on electric currents or electromagnetic fields to work properly, including generation, transfer, and measurement of such currents and fields, designed for use ≤1,000 V AC or ≤1,500 V DC.
Environmental sustainability	Practices, processes, or approaches that preserve natural resources, reduce pollution, and maintain ecosystem integrity for the benefit of current and future generations.
Fancy plastics	Plastic materials difficult to separate or recycle due to unique composition, combinations of plastic types, additives, or coatings.
Hazardous waste	Waste displaying hazardous properties (e.g., infectious) capable of causing disease in humans or other organisms.
Health device	Product or technology used in healthcare for health applications, regulated to varying degrees.
Infectious waste	Waste capable of causing or spreading disease in humans or other living organisms, containing viable microorganisms or their toxins.
Invasive device	Device that penetrates the body, via orifice or surface.
Manufacturer	Person or entity that manufactures, fully refurbishes, or has a device designed/manufactured/refurbished, and markets it under their name or trademark.
Medical device	Instrument, apparatus, appliance, software, implant, reagent, or material intended for human medical purposes (diagnosis, prevention, monitoring, treatment, investigation, replacement, or information), excluding principal action by pharmacological, immunological, or metabolic means.
Medical incineration	Burning healthcare-generated wastes for disposal, including from hospitals, clinics, and research facilities.
Medical waste	Waste generated by healthcare activities, ranging from needles, syringes, dressings, body parts, samples, chemicals, devices, to radioactive materials.
Medication adherence	Extent to which a person's behaviour matches agreed recommendations for medication, diet, or lifestyle changes.
MDR criticality classification	Risk-based classification system for medical devices, considering use, physical characteristics, body part affected, duration, invasiveness, toxicity, and energy dependency. Classes: I, IIa, IIb, III (highest risk).

Preparing for re-use	Checking, cleaning, or repairing products or components that have become waste so they can be re-used without further processing.
Refurbish	Restoring a product to good working condition via decontamination, repairs, upgrades, cosmetic changes, reinstallation, or parts replacement.
Reprocessing	Preparation of devices to enable safe reuse (e.g., cleaning, sterilization).
Refuse	Intentional rejection of production, consumption, or use of a medical product, material, or procedure that is unnecessary, unsustainable, or harmful.
Replace	Substituting a product or procedure with an alternative that reduces environmental impact while serving the same purpose.
Rethink	Systemically enhancing procedures surrounding product use to drive environmentally sustainable practices, e.g., telemedicine, shared products, multifunctionality.
Reduce	Increasing efficiency in healthcare delivery and product manufacturing by minimizing energy, resource use, and waste, avoiding unnecessary production/consumption, limiting hazardous substances, and reducing procedures as appropriate.
Repair	Restoring a faulty product or component to usable state, ensuring safety and performance standards.
Remanufacture	Restoring products or components (often using parts from discarded products) to as-new condition through disassembly, decontamination, quality control, certification, repackaging, and redistribution.
Repurpose	Using discarded products or parts for purposes different from original intent, e.g., in other procedures, contexts, or locations.
Reuse	Repeated use of a medical device on multiple patients for the same purpose, after decontamination, without significant modification.
Reverse logistics	Activities to recapture the value of products, parts, and materials after end-of-use or end-of-life.
Social Life Cycle Assessment (S-LCA)	Methodology for assessing social and socio-economic impacts of a product across its lifecycle, including effects on workers, communities, and stakeholders.
Single-use medical device	Device intended to be used on one individual during a single procedure.
Separate collection	Collection of waste streams separately by type and nature to facilitate specific treatment.
Sharps	Objects or instruments that can cut, prick, cause injury, or infection in healthcare activities.
Sterilisation	Validated process rendering products free from viable microorganisms. Survival is probabilistic; absolute sterility cannot be guaranteed.

Waste	Resource no longer considered an asset at the time, but value may be assigned if needed by another party. Includes energy content if not recovered.
Waste hierarchy	Priority order in waste prevention and management: (a) prevention; (b) preparing for re-use; (c) recycling; (d) other recovery, e.g., energy; (e) disposal.
2K injection moulding	Manufacturing process where two polymers or colours are injected sequentially or simultaneously to create a single part with multiple materials or properties.
Life Cycle Assessment (LCA)	Methodology for assessing environmental impacts of a product or system across its entire lifecycle.

PART I

laying the groundwork

Chapter 1

Introduction: Saving Lives, One Landfill at a Time

Single-use electronic medical devices greatly benefit patients today—but may harm them tomorrow. Hospitals and clinics worldwide are incredible polluters; they generate vast quantities of plastics, electronic waste, and chemical residues, which leach into soil, waterways, and air. In fact, the global healthcare sector is even responsible for approximately 4.6% of global greenhouse gas emissions. To put this into perspective, if healthcare were a country, it would rank as the fifth-largest emitter worldwide. [1] This pollution does not just harm ecosystems. It cycles back to humans, contributing to respiratory problems, hormone disruption, and other serious health risks [2]. In trying to save lives, we are inadvertently creating new threats to human health. The irony is clear: healthcare systems, while striving to improve human health, are themselves major contributors to environmental degradation. The resulting pollutants re-enter the human body through air, water, and food, increasing the burden of disease that healthcare systems are meant to alleviate. Thus, environmental degradation becomes both a cause and consequence of ill health.

Yet within this challenge lies a unique opportunity that this dissertation explores: rethinking how medical devices are designed, used, and circulated can help healthcare protect both patients and the planet.

The remainder of this chapter introduces the concept of circular design (Section 1.1), discusses why healthcare has struggled to adopt it (Section 1.2), defines the research problem and objectives (Section 1.3), explains the research approach (Section 1.4), and outlines the structure of the dissertation (Section 1.5).

1.1 Circular Design as a Major Opportunity

In an ideal world, there would be no waste. A regenerative system would keep products and materials in use for as long as possible, capturing “waste” as a resource to create new materials and products. This kind of system is called a circular economy. The terms “circular economy” and “environmental sustainability” are often used interchangeably, but they are not the same. Environmental sustainability is the broader goal of living within the planet’s limits, while a circular economy is a concrete approach that helps achieve it by minimizing waste and keeping resources in continuous use. Failing to implement circular design also represents significant lost economic value from materials and products that could otherwise be recirculated.

To come as close as possible to the unobtainable vision of full circularity, we need to rethink our design practices. Many products today are not designed to be durable, repairable, or easily recyclable. This is especially true for electronics, which often contain complex components that make repair, refurbishment, and material recovery extremely difficult. Laptops and phones can, by and large, not be repaired. Toasters suddenly break down. While metals and other materials are technically recyclable and often contain some recycled content, much of this waste is still burned or landfilled and replaced with new materials. This is why we need so-called circular design.

This challenge is particularly visible in electronic products. These systems often contain complex components and tightly integrated hardware, making repair, refurbishment, and material recovery extremely difficult. Researchers around the world are tackling these challenges—not only the design itself, but also the financial incentives, supply chain constraints, and behavioural changes needed to make circular solutions viable [3], [4]. Examples from other sectors include modular smartphones and laptops [5], [6], clothing designed for repair or recycling [7], and reusable packaging systems [8]—all aimed at keeping materials in use and reducing reliance on virgin resources.

The healthcare sector has not yet succeeded in taking similar steps forward.

1.2 Why is Healthcare Lagging Behind?

Research in circular design has already produced a range of guidance and frameworks. Strategies for product life-cycle extension, design-for-disassembly, and material recovery are now well documented [9]. These approaches, however, are typically not tailored to the unique challenges of the healthcare sector.

Circular design principles are difficult to apply in any field, but healthcare adds an extra layer of complexity. High-criticality medical devices—those whose failure could cause serious injury or death—raise profound ethical questions. Would we, for instance, accept even the slightest risk of harming a patient by reusing a device multiple times? Many healthcare professionals might instinctively resist, and it's easy to see why: time is short, budgets are tight, and patient safety is always the priority. These constraints leave little incentive to experiment with circular solutions. In fact, as medical devices increasingly incorporate electronic components and are designed for shorter lifecycles, they contribute ever more to the growing stream of (electronic) waste.

Manufacturers face their own obstacles. Their business model depends on producing large numbers of new, disposable devices. It works well, is profitable, and above all guarantees safety. Moving away from it, however, would mean taking on significant regulatory, financial, and ethical risks. If a circular device fails, responsibility falls squarely on their shoulders.

Luckily, there's also good news. As this dissertation further elaborates, circular design does not automatically jeopardize safety, compromise clinical outcomes, or require extensive financial investment. In fact, it can enhance all three.

While other industries have developed practical approaches to circular design, healthcare has yet to adapt these methods to its unique requirements of safety, hygiene, and regulation. This research therefore investigates how established circular strategies can be translated and applied to medical devices, which increasingly rely on electronic components as part of their clinical functionality.

1.3 Finding the Path Forward

The gap in circular design for healthcare devices raises a clear question:
How can medical devices containing electronic components be redesigned to support a circular economy, while ensuring clinical and regulatory compliance?

This question forms the foundation of the research. Finding the path forward means moving beyond critique to creation—exploring how the ideals of circularity can be turned into concrete, workable solutions within healthcare's demanding context. To guide this exploration, the research pursued three key objectives:

1. **Identify** current barriers and opportunities for circularity in electronic medical devices.
2. **Develop** strategies and frameworks that make circularity feasible without compromising safety, usability, or compliance.
3. **Translate** these insights into practical guidance and tools that designers, manufacturers, and policymakers can apply in real-world development.

These objectives translate directly into the research questions that structure this dissertation:

- **RQ 1a:** What circular medical devices are already on the market, and what can we learn from their strategies to drive future circularity?
- **RQ 1b:** What barriers to the circular transition can be found, how likely do they occur, and what are potential opportunities to overcome them?
- **RQ 1c:** What circular design guidelines can we identify based on the outcomes of RQ 1a and 1b?
- **RQ 2:** How can circular healthcare flows be systematically mapped and visualized to provide conceptual clarity and support stakeholders in applying circular strategies within healthcare constraints?
- **RQ 3a:** To what extent can the 10R-strategies be applied in the redesign of electronic health devices to generate feasible and viable circular concepts?
- **RQ 3b:** How can circular strategies, applied through the 10R-framework, contribute to environmentally sustainable solutions in healthcare devices?
- **RQ 4:** How can trade-offs and synergies between circularity, safety, functionality, usability, and regulatory compliance be systematically assessed and managed in the design of complex medical devices?
- **RQ 5:** How can the insights from this research be synthesized into a practical, adoptable Circular Design Guide for medical devices, supporting designers, engineers, and other stakeholders in systematically implementing circular principles across product and system levels?

Electronic medical devices were chosen as the focus of this dissertation because devices containing electronic components have much higher lifecycle environmental impacts than simple metal or plastic devices, including the energy and materials required for manufacturing, distribution, use, and disposal [10]. By concentrating on these devices, the research targets a part of healthcare that is particularly environmentally consequential while still supporting essential patient care.

Together, these objectives and questions shape a research journey that bridges analysis and design, seeking not only to understand why circularity is difficult in healthcare, but also to show how it can be implemented safely and practically.

1.4 The Approach Taken

To investigate these questions, this dissertation combines iterative design, prototyping, literature review, stakeholder interviews, and case study analysis. This combination allows the research to tackle challenges that span technical, clinical, and regulatory dimensions—problems that cannot be resolved through theory alone. By integrating hands-on design work with empirical research, the dissertation examines how circular strategies perform in healthcare contexts and evaluates their feasibility, implications, and practical applicability.

Four design case studies were conducted, each exploring different types of devices and circular strategies. These included a smart pillbox, a laparoscopic surgical instrument, an electronic label used in clinical trial medicine kits, and a complex wearable sensor for patient monitoring. While all four informed the research, only two are presented in detail in the scientific papers included in this dissertation. These two were chosen to illustrate contrasting scenarios: one focused on every day, high-volume devices such as smart pillboxes, and the other on high-criticality surgical instruments like laparoscopic tools. Presenting these cases allows the dissertation to demonstrate how circular strategies interact with different levels of risk, patterns of use, and material complexities. Each experiment explored the trade-offs between circularity, safety, usability, and regulatory compliance, and the lessons learned were iteratively refined into conceptual frameworks and practical tools for real-world application.

Collaboration was central throughout. Designers, engineers, clinicians, and patients were involved at every stage, many through the Digital Health in a Circular Economy (DiCE) project. Their feedback ensured that emerging concepts were grounded in real-world needs and could be implemented effectively in practice.

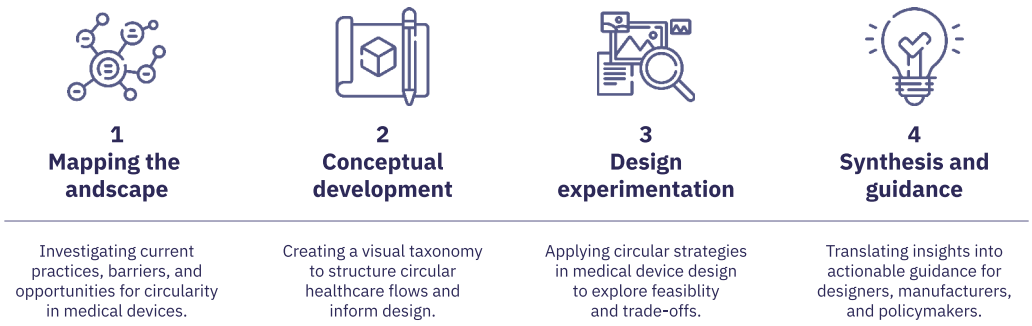
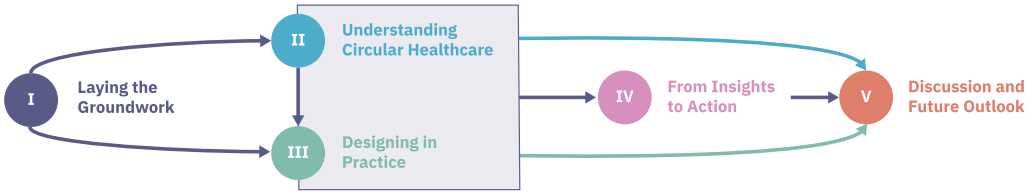


Figure 1: Research Process Stages

1.5 How This Dissertation Unfolds

This Dissertation follows a clear trajectory—from understanding the problem space, to experimenting with solutions, to translating findings into action. Each part builds on the last to form a coherent narrative from problem to practice to impact (Figure 2).



Laying the Groundwork	**Introduction: Saving Lives, One Landfill at a Time** — The introduction you are currently reading, introduces the environmental challenges of healthcare and sets out the rationale, objectives, and research approach of the study.			I
Understanding Circular Healthcare	**Chapter 2** Barriers, Opportunities, and Best Practices from a Design Perspective	**Chapter 3** Mapping Circular Economy Flows in Healthcare: A Visual Taxonomy	Addresses RQ 1a–c and RQ 2, establishing the conceptual and empirical foundation.	II
Designing in Practice	**Chapter 4** Redesigning Smart Pillboxes: Applying the R-strategies	**Chapter 5** Balancing Trade-Offs in Circular Medical Device Design: Laparoscopic Devices Case Study	Explores RQ 3a–b and RQ 4, translating theory into practice through case studies.	III
From Insights to Action	**Chapter 6** Circular Design Guide for Medical Devices: Vision and Practical Application		Synthesizes insights and develops a practical design guide (RQ5).	IV
Discussion and Future Outlook	**Chapter 7** Discussion and Implications		Reflects on the implications for research, policy, and design practice, and outlines future work	V

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PART II

understanding circular healthcare

PART II, Chapter 2

Strategies for designing more sustainably are being developed across the globe. While many industries are increasingly adopting circular design practices, the healthcare sector still appears to lag significantly behind. To better understand the current state of affairs — and to identify existing products that exemplify the kind of change envisioned — the field was first explored through a combination of literature review and expert input.

This study not only outlines the current "state of the art," but also highlights the limited integration of circularity principles in healthcare. In addition, it identifies key barriers to implementation and presents opportunities for overcoming them.

This article forms the foundation for the remainder of the dissertation, which delves deeper into specific design challenges and potential solutions.

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Chapter 2

Circular Economy for Medical Devices: Barriers, Opportunities and Best Practices from a Design Perspective

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Abstract—In an era of electronics-driven healthcare, the disposability of many medical devices raises environmental concerns. Transitioning these devices towards a circular economy, involving practices like reuse, remanufacturing, and recycling, holds promise. Our paper explores this transition through desk research, literature review, and expert interviews, examining the current state of circular design in electronic medical devices. We unveil barriers, opportunities, and design recommendations for circularization. First, we highlight the circularity potential of medical devices currently on the market, implementing e.g. refuse, reuse, recycle, etc. Second, we present barriers for circular medical device design, (e.g. (perceived) safety and infection risks, (perceived) regulatory difficulties, financial constraints, and difficulties in collection and separation) and opportunities to overcome these barriers. Finally, we present 29 design-specific recommendations for creating circular medical devices. Our insights into circular healthcare practices urge design engineers to integrate sustainable principles into medical device development without compromising safety, quality, or functionality.

Keywords: circular economy, circular design, medical devices, sustainable healthcare, active medical devices

2.1 Introduction

Circular economy principles hold the potential to transition the medical device industry towards a more sustainable future. This is important, as healthcare's current global climate footprint is greater than all aviation and shipping combined [1]. An increasing number of medical devices are designed for single use, a development that coincides with the rapid advancement of digitization in the field [2], [3]. While those technological advancements appear promising in improving clinical outcomes [4] and single-use devices may minimize cross-contamination risks and increase manufacturers' profits, e-waste is one of the fastest-growing types of waste and awareness about this in healthcare is low [5].

Our research focuses on mitigating the environmental impact linked to active medical devices, which are defined by the European medical device regulations (EU-MDR) [6] as "any device, the operation of which depends on a source of energy other than that generated by the human body for that purpose, or by gravity, and which acts by changing the density of or converting that energy". In this paper we use the term to describe any electronics-based device that is intended

by the manufacturer for specific medical purposes for human use. The strong market growth of electronics-based medical devices underscores the timeliness of this research; when considering medical wearables, for example, 83 million new units were brought to the market in 2020 alone [7]. At the same time, recycling of non-infected healthcare waste is still very limited, and infectious medical waste is routinely incinerated, owing to safety concerns and regulatory restrictions [8]. This leads to a considerable loss of valuable materials.

The healthcare industry is becoming increasingly mindful of the need for practices, procedures, and devices that fit in a circular economy and are environmentally sustainable. A circular economy is a restorative or regenerative system that aims to circle materials and products back into the economy for reuse and recycling, in an effort to 'design out waste' [9]. Circular designs are products designed to fit into a circular economy [10] using strategies like reuse, remanufacturing, and recycling. A comprehensive inventory and assessment of the current state of circularity in medical devices and manufacturer practices is currently lacking. Such an inventory and assessment could be used by the medical industry as a benchmark to improve the circularity of their current offering.

While some research has examined the barriers and opportunities to healthcare's circular transition [10], [11], [12], [13], most of the identified barriers and opportunities are based on reviews of non-healthcare-related literature. Examples of barriers to circularity that may apply to active medical devices are: insufficient product traceability [14], lack of data privacy and security [14], [15], and the lack of realistic business models [16], [17]. Notably, although literature describes a lack of circular product design as a barrier to circularity [11], [18], [19], specific circular design guidelines for medical devices are yet to be developed.

These research gaps need to be bridged to enable successful circular design of active medical devices. Our research aims to offer insights into the current state of circularity¬ in medical device design, improve understanding of challenges and opportunities of making medical devices more circular, and provide design-specific recommendations. We do so by answering the following research questions:

- What circular medical devices are already on the market, and what can we learn from their strategies to drive future circularity?
- What barriers to the circular transition can be found, how likely do they occur, and what are potential opportunities to overcome them?
- What circular design guidelines can we identify based on the outcomes of these two research questions?

In this paper, we first describe a list of 346 active medical devices from all over the world that employ circular strategies [20]. Thereafter, we share the most common barriers that make circularity challenging in the healthcare context, and opportunities to overcome them. Our final contribution is a list of design-specific recommendations that help medical device engineers and designers drive the medical circular transition through their expertise.

2.2 Method

The research was divided into three phases: the best practices inventory, the barriers and opportunities, and the consolidation of all findings into a list of design-specific recommendations.

2.2.1 Best Practices Inventory

We used desktop research (combining multiple data sources), field research, and expert interviews, with the goal to identify active medical devices that were on the market in 2023. We selected those devices that employed at least one circular strategy (as defined in Table 1: refuse, rethink, reduce, reuse, remanufacture, repurpose, recycle, or renew) and stored them in an Excel database [20].

For the field research we interviewed circular economy experts, medical device manufacturers and healthcare workers and we visited a major MedTech trade fair, looking for active medical device innovations that used circular strategies. Additionally, we queried LinkedIn to find additional device examples. For our desktop research, we reviewed relevant trade journals and catalogues of medical device manufacturers.

To ensure a good representation of worldwide medical device examples, we selected 13 countries (representing various income levels) from different continents for catalogue review: Norway, Australia, Mexico, USA, Germany, India, China, Japan, South Africa, Kenya, Brazil, Sweden, and the UK. These countries were chosen based on the location of major medical corporations and each country's export rate of active medical devices, obtained from OEC statistics [21] and through desk research.

For each country, we examined the medical device catalogues of several manufacturers. For feasibility reasons, we limited our search to a maximum of 10 manufacturers per country and 10 devices per manufacturer. However, due to the size of the USA, we doubled the manufacturer limit for this country. When more than 10 device examples were available for one manufacturer, our focus shifted to achieving a wider variety of device categories. Our country sample covered eight of the top 10 medical device companies in the world [22]. Therefore, we analysed the resulting two, Philips and Medtronic, separately.

All selected devices were stored in an Excel sheet mentioning the company name, country, device name, device description, URL, use location (in healthcare facility, at home, or both), medical criticality (based on the MDR-EU745 medical device regulations device classifications), device size, used circular strategies, number of strategies used, circularity rating, and explanation of circularity rating. We assumed (based on [10]) that the degree of circularity would be influenced by the economic value of a device; i.e., the more expensive a device, the more likely that circular strategies would be implemented because of value retention and cost savings. However, economic value (or sales price) was hard to determine through desktop research. We therefore categorized devices based on size, recognizing that size is not a direct proxy for economic value, as it does not consider factors such as, for instance, device complexity.

To determine which devices had the highest circularity potential, we developed a circularity scoring method based on the hierarchy and original definitions of the R-strategies [23]. The most important adaptations we made to the definitions of the circular strategies hierarchy:

- For refuse, we added the notion that the replacement device must not only be radically different, but also more environmentally sustainable.
- We introduced renew (regenerate, compost, biodegrade), akin to the bio cycle in the Butterfly Diagram [24], as an option for parts unsuitable for 'techno cycle' strategies.

- We merged refurbish and remanufacture despite distinct definitions, driven by identical processes due to the high-quality standards for medical devices.
- We merged reuse and repair. While recognizing repair as a distinct R-strategy, in our research we found repair and maintenance frequently mentioned together without further clarification. As we consider maintenance to be an intrinsic part of reuse, we categorized repair and maintenance under reuse, awarding bonus points for maintenance and repair to address this issue.

In the R-strategies hierarchy, refuse is considered the most and recover energy the least favourable strategy. The further up the hierarchy, the more points the device was given. Based on Table 1, the circularity score was calculated in the following way: Circularity score = (sum of points from strategies) + (number of strategies - 1). Devices do not only score higher based on which strategies they address, but also on the number of strategies. The argumentation is that e.g. if device A can be remanufactured, repurposed, and recycled, it should have a higher circularity score than device B that only addresses rethink (even though rethink is further up the hierarchy). In this example, device A receives two bonus points for addressing more than one strategy (1 point for each strategy without counting the first strategy). Although we strive for as many circular strategies as possible, we are aware that not all strategies can be combined. For example, recycle and renew are often mutually exclusive and repurpose and remanufacture are often not easily combined.

Table 1: R-Strategies Definition and Circularity Scoring Method

Circular strategy *(strategy type)*	**Definition**	**Max score**	**100% score is given when ...**	**50% score is given when ...**
Refuse (Design)	Make device redundant by abandoning its function or by offering the same function in a radically different, more sustainable device. Example: replacing a hearing aid device by a mobile application that amplifies sound, making the hearing aid device redundant in certain situations or scenarios.	**7**	The device functionality could eliminate the use of one or more other devices and does so in a radically more environmentally sustainable way.	The device eliminates only parts of medical devices, or only for certain use scenarios, and does so in a radically more environmentally sustainable way
Rethink (Design)	Make device use more intensive (e.g. through sharing products, or by putting multi-functional products on the market). Example: adapting the function of a wearable sensor by adding user profiles, making it shareable among multiple users instead of using one device per user.	**6**	Device is made to be used more intensively than its counterparts by using multiple strategies, such as: • Being used by multiple users at a time. • Providing multiple functions. • Being able to be used at locations that previously was not possible.	Device is made to be used more intensively than its counterparts by using only one of the strategies presented for the 100% score.

Reduce (Design)	Increase efficiency in product manufacturing or use by consuming fewer natural resources and materials. Example: Minimizing the amount of electronics used in laparoscopic devices, as some laparoscopic procedures can safely be performed with mechanic instruments.	**5**	Device reduces its environmental impact, in comparison to equivalent devices, through both: • Using less materials/ resources in the manufacturing and/or use stage. • Minimizing energy consumption during the manufacturing and/or use stage.	Device reduces its global warming potential in just one way of the strategies presented for the 100% score.
Reuse (Technical)	Reuse by another customer (or for another patient in healthcare) of discarded product which is still in good condition and fulfils its original function (in healthcare, often after cleaning processes) Example: partly reuse a heart catheter after removing infectious parts, cleaning, disinfecting and sterilizing the reusable parts, and preparing them for the next use.	**4**	Device is made with the purpose of being reused (which may include decontamination) for the same purpose without reduction of performance or quality of patient care. Maintenance/repair of the device is part of the service to extend the devices life even further.	Only one part of the device can be reused while the rest is single use, or the reusable device does not have maintenance/repair services.
Remanufacture (Technical)	Restore a discarded product and bring it up to date or use parts of a discarded product in a new product with the same function. Example: perform high level disinfection and functionality tests on all components of a used pacemaker, and restore the device to a better than new condition for the next user.	**3**	At least 50% of the parts of the discarded device are brought back into manufacturing to develop a remanufactured device with the same function and a device quality that is similar or better than the original device.	Some, but less than half or the parts of the discarded devices are used in the remanufacturing cycle.
Repurpose (Technical)	Use discarded product or its parts in a new product with a different function Example: updating the software of an ECG monitor to make it suitable to be used as a monitor or screen for any other type of device.	**2**	The entire discarded device is being reused for a different purpose or function. This may be intended by design or initiated by the user at EoL.	Only part of the discarded device is being reused for a different purpose or function. This may be intended by design or initiated by the user at EoL.
Recycle (Technical)	Process materials to obtain the same (high grade) or lower (low grade) quality Example: make disposable bags of a dialysis machine of safe but recyclable material and enable the process to create recycled granulate for production.	**1**	The device is made to be easily recyclable. There is a recycling program in place.	The device is made for easy recycling. There is no recycling program, but recycling is encouraged with detailed instructions.

Renew (Bio-cycle)	Materials that can safely be returned to the biosphere are used in the production of the device, to enable processes that together help regenerate natural capital, such as composting and anaerobic digestion. Example: make the lid of a smart pillbox of PLA, removing the electronics after use, and letting it biodegrade in days at a composting plant.	**1**	At least 50% of the parts are suitable for (tissue) regeneration, composting, or biodegradation and has a renew program in place.	Device parts are suitable for renew strategies, but this is only true for less than 50% of all materials and/or there is no renew program in place.
Recover energy (Waste)	Incineration of materials with energy recovery Example: in the incineration of a laparoscopic device, capture energy while burning non-infectious and non-hazardous parts (excluding batteries).	**0**	Device is incinerated upon EoL.	Not applicable

2.2.2 Interviews and Literature Review to Identify Barriers and Opportunities

To uncover barriers to the circular design of active medical devices and opportunities to overcome these barriers, we employed two methods: expert interviews and a systematic literature review. Prior to the expert interviews and systemic literature review, we performed an initial search of literature using Google Scholar to help identify key concepts to explore further (i.e. potential safety, financial, systemic, regulatory, technological, and social barriers and opportunities). This helped us develop our interview protocol and systemic literature review search string. In this initial search, we utilized various search keywords related to sustainability and healthcare, including terms such as 'barriers', 'challenges', and 'limitations'. Initially, our focus was on industrial design, but we broadened our search to include medical literature using keywords suggested by [10]. In this section, we further explain the approach taken for the expert interviews and systematic literature review.

2.2.2.1 Interviews Approach

We conducted 21 expert interviews with participants from diverse backgrounds, selected based on their profession and expertise (Table 2). Interviews included 1 to 3 individuals, and no individuals were present in more than one interview. Semi-structured interview questionnaires (Appendix A) were used and adapted based on the expertise of the participant. The interviews were video or audio recorded, transcribed and proofread using Sonix.ai. Coding was done in ATLAS.ti. Interesting quotes were highlighted and labelled as 'barrier' or 'opportunity' and additionally labelled with a code describing the main topic of the quote. Examples of such codes are 'safety risks' and 'terminology confusion' for barriers and 'traceability' and 'innovation investment' for opportunities. All codes with similar meanings were merged into one overarching code (e.g. 'device contamination' and 'patient infections' were merged into one barrier: 'safety, infection, and contamination risks'). To enhance the reliability of our coding process, we engaged

two independent researchers who reviewed and checked the codes prior to merging them. Discrepancies identified during the review were discussed in iterative sessions until full consensus was reached. As the scientific articles of the literature review were being coded simultaneously (by two independent researchers), we took steps to align the interpretations of the interview codes with those derived from the literature review. This alignment further fortified the robustness and coherence of our coding framework.

Table 2: Interview Participants

#	Participant category	Expertise	Number of people in each interview
P1	Sterilization facilities	External sterilization	2
P2	Sterilization facilities	Internal sterilization	1
P3	Manufacturers	Engineering, supply chain, and parts harvesting	2
P4	Manufacturers	Design Engineering	2
P5	Manufacturers	Strategy and design engineering	3
P6	Manufacturers	Research and development	1
P7	Hospital procurement	Academic hospital procurement	1
P8	Hospital procurement	Non-academic hospital procurement	1
P9	Hospital procurement	Non-academic hospital procurement, and intensive care	2
P10	(International) foundations	Sustainable use of natural resources	3
P11	(International) foundations	E-waste responsibility	3
P12	(International) foundations & (hazardous) waste handling	E-waste handling, and recycling	2
P13	Collection systems developer	Circularity collection systems	1
P14	Collection systems developer & recycling facilities	Recycling & collection	1
P15	Recycling facilities	Metal and electronics recycling	1
P16	Recycling facilities & (hazardous) waste handling	Plastics recycling	1
P17	(Hazardous) waste handling	Waste handling policies & practices, and handling sharps	3
P18	Remanufacturing experts	Remanufacturing of construction machines, and circular business concepts	1
P19	Remanufacturing experts	Remanufacturing of devices and components, and relevant regulations	1
P20	Bio cycle / reduce experts	Design engineering, bio-design and biomaterials	1
P21	Bio cycle / reduce experts	Expert on bio cycle processes, and material choices	1

2.2.2.2 Literature Review Approach

The literature review was done in PubMed and was limited to scientific articles published in or after 2018, as our initial search yielded limited relevant articles predating that timeframe. We employed the search string below.

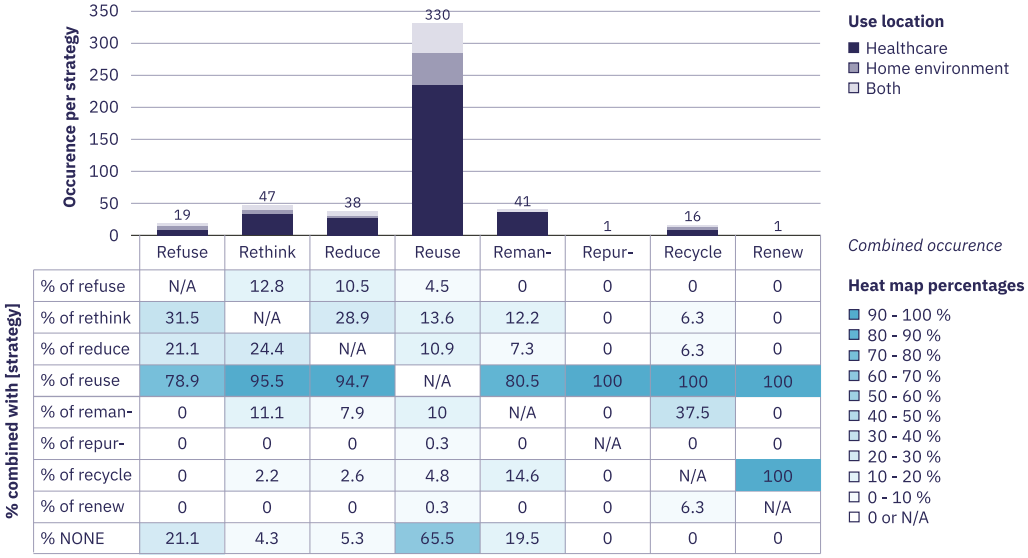
((device AND (healthcare OR "health care" OR medical OR hospital OR surgical OR "intensive care" OR ic) AND (("sustainable design" OR "circular economy" OR "circular design" OR recycl OR "environment* sustainab*" OR reuse OR "carbon footprint" OR resterilizat* OR repurpos* OR reproces* OR "eco design" OR "environment* friendly") AND (barriers OR obstacles OR hurdle* OR limit* OR boundar* OR hamper))) AND ("2018/01/01"[PDAT] : "2023/02/24"[PDAT]) AND (English[lang]) AND (Journal Article[ptyp]))*

The search string focused on healthcare devices, circular economy, barriers, and (eco)design. To prevent the misinterpretation of "circularity" as e.g. circular RNA, drug delivery systems were excluded. Initially, 377 abstracts were screened, with 101 meeting inclusion criteria (articles related to both circular economy and healthcare devices/materials written in the English language). For 96 out of 101 articles, we were able to gain access to the full text PDFs. A systematic approach was applied, noting the paper's topic, identified barriers and opportunities based on a full-text search using predefined synonyms of the words 'barrier' (e.g. challenge, limitation, obstacle) and 'opportunity' (e.g. advantage, benefit, alternative). The analysis involved detailed reading while evaluating whether the searched terms related to actual circularity barriers when viewed in-context and coding them accordingly. Synonyms that brought up no results (e.g. achieve, combine) or too many irrelevant results (e.g. increase and change) were excluded. The literature was coded in the same ATLAS.ti file and in the same way as the interview transcripts. As the analysis of two of the 96 papers did not reveal any relevant results, the final number of included articles was 94.

2.3 Results

2.3.1 Current State of Circularity in Healthcare

Our search strategy allowed us to review more than 1400 active medical devices. Of these, 346 devices (about 25%) used at least one circular strategy. The full dataset of 346 devices can be found in the online data repository of Dutch Universities of Technology [20]. On average, the 346 devices had a circularity score of 4.5, ranging from 2 (minimum score) to 20.5 (maximum score). Two thirds (67%) of the devices only implemented one strategy, while only 18 devices (5%) had a circularity score ≥ 10. Some devices implemented two strategies (25%); but three (7%) or four (1%) strategies in one device seemed uncommon. However, all 8 circular strategies we searched for were found at least once. Strikingly, as displayed in Figure 3, from all 346 active medical devices, 95% was reusable for more than one product life cycle. (e.g. an active surgical instrument that can be reused for a next surgery on a different patient after going through decontamination processes (e.g. cleaning, decontamination, and sterilization)). For 49% of these reusable devices, this also included maintenance/repair services. Other circular strategies were implemented to a much lesser extent, although rethink (13%), remanufacture (12%), reduce (10%), refuse (7%), and recycle (5%) were more common than repurpose (0.2%), and renew (0.2%).



% combined with [strategy]

	Refuse	Rethink	Reduce	Reuse	Reman-	Repur-	Recycle	Renew
% of refuse	N/A	12.8	10.5	4.5	0	0	0	0
% of rethink	31.5	N/A	28.9	13.6	12.2	0	6.3	0
% of reduce	21.1	24.4	N/A	10.9	7.3	0	6.3	0
% of reuse	78.9	95.5	94.7	N/A	80.5	100	100	100
% of reman-	0	11.1	7.9	10	N/A	0	37.5	0
% of repur-	0	0	0	0.3	0	N/A	0	0
% of recycle	0	2.2	2.6	4.8	14.6	0	N/A	100
% of renew	0	0	0	0.3	0	0	6.3	N/A
% NONE	21.1	4.3	5.3	65.5	19.5	0	0	0

Figure 3: Occurrence per Strategy and Use Location and Combined Occurrence of Multiple Strategies

Based on the outcomes of our desktop research, we conclude that the following circular strategies are most common for the top 15 devices:

- Introducing devices that eliminate the use of other less environmentally sustainable devices (refuse).
- Enabling sharing among users or offering multiple functions in one device (rethink).
- Minimizing the use of material and energy consumption (reduce).
- Reusing devices (after decontamination) for multiple use cycles (reuse).
- Designing devices to be remanufactured at the end of life (remanufacturing).

Our results also indicate that the use of circular strategies seems to depend on the size, use location, and medical criticality of the device. As can be seen in Figure 4, most circular active medical devices we identified are small devices (60%), most devices are used in a healthcare setting (71%), and have a low/medium or medium/high medical criticality (IIa or IIb MDR classification, each 38%). Overall, as also displayed in Figure 4, based on our circularity rating, smaller devices with a low/medium medical criticality (class IIa) seems to score higher than devices from other categories.

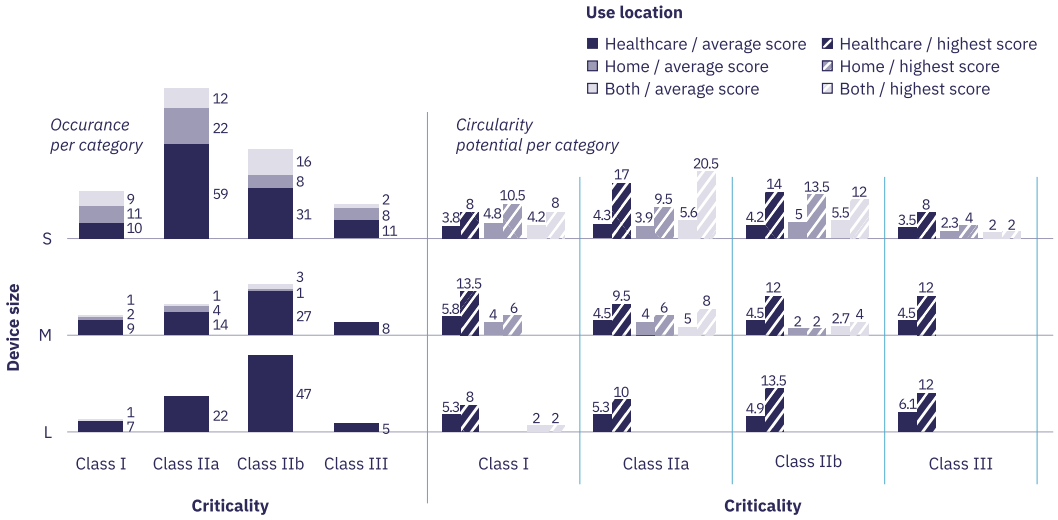


Figure 4: Occurrence and circularity potential per category

2.3.2 Barriers to Circular Transition of Medical Devices

The set of 94 articles covered the following topics: reuse and decontamination (62%), environmental impact and LCA (12%), (tech) innovation (6%), (reverse) logistics / strategies (6%), repurpose (4%), environment friendly material (3%), engagement / attitudes (2%), recycling (2%), and circular design (2%). This underlines the finding of section 2.3.1 that currently healthcare has a large focus on the strategy of reuse. Additionally, 24.5% of the work was related to the COVID-19 pandemic, discussing the difficulties of mitigating cross-contamination risks in a circular economy.

In total, we highlighted 1,948 quotations from 21 interview transcripts and 94 articles, which were sorted under 102 unique codes related to barriers, opportunities, and/or design specific guidelines. Table 3 shows the 31 barriers to the circular transition of medical devices that resulted from the coding of the interviews and scientific articles. The barriers are divided in six categories, and numbered and sorted based on their occurrence.

Our results indicate that (perceived) safety risks, e.g. infection and decontamination concerns, emerge as the most common barrier to circularity in medical devices. Other significant barriers are challenges with collecting and sorting devices, (perceived) regulatory constraints, financial limitations, unsuitable device characteristics, and lack of awareness about the circular economy. In general, overcoming ingrained linear norms and addressing stakeholder issues, such as social acceptance, collaboration, and terminology confusion, seems to be challenging. Implementing circularity introduces new barriers like scalability and maintaining device quality. Although some barriers are typical to circular economy transitions in general, barriers like (perceived) safety risks, (perceived) regulatory constraints, focus on clinical outcomes, and problems surrounding decontamination processes (e.g. careless decontamination adherence and unsuitable device characteristics for decontamination) are more specific to medical devices.

Table 3: Overview of Barriers

#	Barrier		Finding based on analysis of …		
	Category: Safety barriers	**Times mentioned**	***Interviews***	***Literature***	**Example Quote**
1.1	Safety, infection, and contamination risks	**171**	P2, P3, P5, P7, P9, P11, 13, P14, and P16-P20	[11], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41]	". . . it can be dangerous . . . if you come into contact with certain pharmaceutical substances, sharps, lots of types of things, they can be contaminated with viruses from other persons" (P13).
1.2	Focus on use and clinical outcomes, opposing circularity	**36**	P3, P4, P7-P10, and P14	[11], [29], [30], [33], [35], [36], [39], [43], [46], [82], [87]	"Regulators, accreditors, and professional societies focus almost exclusively on individual patient risk. Thus, they have tended toward the default position that patient safety is optimized by eliminating reuse of medical devices" [11].
1.3	Dangers of hazardous components such as batteries and toxins	**23**	P3, P6, P8, P9, P12-P17, P19, and P21	[46], [47]	"Some chemicals may be toxic and may also leave stain or odor on the equipment post sterilization, . . ." [46].
1.4	Careless adherence to decontamination method (human factor)	**23**	n.a.	[11], [28], [48], [49], [50], [51], [52], [53], [54]	"insufficient drying before storage was identified as a possible reason for contamination" [49].
	Category: Systemic barriers	**Times mentioned**	***Interviews***	***Literature***	**Example Quote**
2.1	Practical difficulties related to collection and separation logistics	**145**	P1-P4, P6, P8-P16, P19, and P21	[30], [32], [33], [35]–[38], [42]–[59]	"There are unlimited logistic issues. There is no return flow in place" (P5).
2.2	Difficulty to move away from linear norms	**60**	P2-P5, P7-P13, P17, P19, P20, and P21	[11], [26], [36], [38], [59], [61]	"A linear supply chain minimizes liability and complexity for hospitals" [11].
2.3	Scalability problems and scarcity of materials, devices, equipment, and resources	**40**	P9, P14-P18, P20, and P21	[26], [28], [36], [44], [51], [57], [61], [70], [77], [81], [85], [86]	"None of the hospitals had dedicated tools and equipment or reprocessing surgical instruments" [26].
2.4	Global market boundaries	**32**	P7, P10, P11, P13, P14, and P17	[28], [66], [74], [75]	"When it comes to battery-based device, it is also essential to take into consideration the limitations of local contexts, such as the extreme environmental conditions" [75].

2.5	Time constraints of all stakeholders	**29**	P9, P14, P17-P21	[26], [35], [42], [76]	"it takes ten years to change the cap, even though it doesn't really need to have that quality requirement" (P14).
2.6	Specialization / different norms and practices medical/ recovery facilities	**20**	P1, P2, and P14-P16	[25], [58], [75]	"The basic surgery set of hospital A is not necessarily the same as the basic set for hospital B" (P1).
	Category: Regulatory barriers	**Times mentioned**	***Interviews***	***Literature***	**Example Quote**
3.1	Regulations that complicate the process	**125**	P1-P6, P8, P9, and P11-P21	[11], [27], [28], [29], [29], [34], [35], [36], [37], [44], [55], [56], [71], [77], [78]	"Brazilian legislation prohibits the reuse and reprocessing of CIED, such as pacemakers, defibrillators, and CRT devices" [44].
3.2	Limited device knowledge of external parties	**6**	P6, P12, P18, P19, and P21	n.a.	"Our engineering team needs to reverse engineer devices to understand key requirements and specifications, and make sure we are testing to those specifications" (P6).
3.3	Concerns surrounding data and privacy	**6**	P3 and P13	[36], [60]	"LCAs may rely on estimates of proprietary manufacturing processes that companies may not readily share with researchers" [36].
3.4	Loss of warranty	**1**	n.a.	[56]	"Another concern is the loss of coverage under the original manufacturer's warranty when using third-party reprocessing" [56].
	Category: Financial barriers	**Times mentioned**	***Interviews***	***Literature***	**Example Quote**
4.1	Financial constraints of different stakeholders	**108**	P2-P11, and P13-P21	[26], [27], [32], [34], [35], [36], [37], [39], [42], [47], [50], [57], [58], [59], [76], [79], [80], [81]	"You need economies of scale to be economically successful in something" (P17).
4.2	Differences in device value (high value gets circular priority)	**22**	P3, P6, P7, P10, P11, P13, P15, and P16	[31], [37]	"You need lots of the very small devices to make recycling profitable" (P11).
4.3	Circular economy competition	**6**	P6, P14, and P16	n.a.	"The cost and complexity of collection needed for circularity creates a barrier to somebody new that's entering the market" (P6).

	Category: Techn- barriers	Times mentioned	*Interviews*	*Literature*	Example Quote
5.1	Unsuitable device/material characteristics for circular strategies	**81**	P1-P4, P8, P10-P12, P14-P18, P20, and P21	[26], [30], [31], [34], [36], [37], [44], [46], [53], [55], [58], [62], [68], [72], [80], [81], [82], [83], [84], [85], [86], [87], [88]	"The design team strictly adhered to the glued solution, as that was the only way to create a completely water tight devices that are still hygienic" (P3).
5.2	Focus on and need for high quality and function of the device	**65**	P3-P9, P11, P12, and P14-P21	[34], [36], [42], [44], [45], [76]	"We are really stressing the material strength envelope to make it lightweight. It ends up bending, creating deformation that is really hard to take from one patient to the next" (P4).
5.3	(Outdated) designs not intended for circular strategies (+ forced obsolescence)	**18**	P3, P4, P6, P14, P18, and P21	[11], [30], [36], [51]	"We need to design these circular systems for current linear products because they will be here for a long, long time" (P14).
5.4	Inability to perform device updates in circular devices	**3**	P3	n.a.	"Normally in a life cycle you also see engineering changes. In circularity this must be discontinued, unless you offer a repaired part for the change" (P3).
5.5	Unmanageable device sizes	**2**	P16	n.a.	"The smallest materials we don't recycle, we don't have the technology for that yet, and also the bigger items are returned . . ." (P16).
	Category: Social barriers	**Times mentioned**	***Interviews***	***Literature***	**Example Quote**
6.1	Unawareness about and complexity of the circular economy	**78**	P2-P11, P13-P15, P17-P19, and 21	[26], [28], [35], [45], [50]–[52], [65], [81]	"People are often not aware of the impact of everything we use. Locally, but also in the supply chain" (P8).
6.2	Unclarities in or lack of taking responsibility	**65**	P1-P5, P7-P11, and P13-P19	[11], [26], [35], [36], [39], [42], [51], [52], [64], [69]	"Regulation and oversight of the medical device industry occurs via a complex network of organizations, within which roles and responsibilities are sometimes ill defined" [11].

6.3	Terminology confusion	**50**	P1-P3, P5-P9, P11, P14, P15, and P17-P20	[54], [65]	"Nobody seems to think about whether someone has the same interpretations. . . . this [is] very problematic, since we often think we are talking to each other, while we are not really having a conversation" (P7).
6.4	Lack of trust/social acceptance that leads to favorable behaviors (partly due to greenwashing)	**48**	P7-P9, P11, P11-15, and P18-P21	[25], [26], [35], [36], [39], [43], [50], [51], [55], [57], [59]	"A large percentage, about 24%, said they didn't trust remanufacturers. They just didn't think they were the sort of people they wanted to do business with" (P19).
6.5	Lack of or problems with stakeholder interactions	**42**	P1-P3, P5, P7, P8, P10, P12, P13, P18, and P19	[33], [60], [69]	"It is a question to collaborate in a different way for lower environmental impact, . . . but we just don't have those kinds of conversations" (P7).
6.6	Attitudes, preferences (or differences between), and lack of support	**39**	P18-P20	[11], [26], [28], [30], [35], [36], [43], [50], [51], [55], [57], [59], [65], [81], [82], [87], [88]	"That [use of biological materials] is something people are not willing to accept" (P20).
6.7	(Expected) limited environmental benefits of actions	**20**	P7, P8, P10, P18, P20, and P21	[35], [36], [58]	"We're driving trucks all over the state and interstate to get these [circular] devices to us. I think it would be interesting to understand what the carbon footprint of that is [transporting circular devices]" [36].
6.8	Interpretation of regulations	**3**	P17	[11]	"Lack of clear and consistent guidelines has resulted in confusion around standards for reusable device reprocessing. In this environment, many device consumers have resorted to single-use disposables to avoid the potential for error, citation, and liability" [11].
6.9	Approaching customers	**1**	P18	n.a.	"How to reach customers [that would purchase remanufactured items]; that is probably also a barrier" (P18).

2.3.3 Opportunities for Circularizing Healthcare

We identified opportunities across the general healthcare ecosystem, social acceptance, manufacturer suggestions, and product development. However, it should be noted that the product development opportunities are not included in Table 4. In Table 4, opportunities within the first three categories are ranked based on their frequency in interviews and literature. Additionally, the product development opportunities were assessed separately by comparing them with findings from desktop research on the current state of circularity in medical devices market. These findings were then transformed into design-specific recommendations, detailed in section 2.3.3.1.

Table 4: Circularity Opportunities

#	Opportunity		Finding based on analysis of ...		
	Category: General (circular) healthcare ecosystem	**Times mentioned**	***Interviews***	***Literature***	**Example Quote**
1.1	Develop circularity-enabling and -stimulating regulations, guidelines, and standardizations.	**67**	P2, P3, P5, P7, P9, P11, 13, P14, and P16-P20	[11], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41]	"If right-to-repair were applied to original equipment manufacturers, it could be considered illegal to design devices that preclude reprocessing" [11].
1.2	Increase and improve reuse and decontamination (cleaning, disinfection and sterilization) of devices and their electronics.	**35**	P1, P2, P4, P6, P15, P16, and P17	[25], [28], [29], [34], [37], [48], [49], [50], [55], [60], [69], [77], [80], [89], [90], [91], [92], [93], [94], [95], [96]	"If such items [like syringes] could be reused and not just thrown away, it would be good" (P16).
1.3	Develop a large variety of new return solutions (e.g. collection point communication systems, smart drop-off points, easy and clear return infrastructure, and centralized collection and separation).	**15**	P5, P6, P12-P14, and P17	[11], [27], [36], [55], [65], [97]	"There will not be one solution that fits all here. . . . you would probably need to have a large variety of collection solutions" (P14).
1.4	Make use of existing collection infrastructure.	**12**	P6, P12, P14, and P17	[34], [35], [47], [61]	"There are synergies to make use of the existing collection methods for waste from hospitals" (P12).

1.5	Categorize and sort devices per type to enable efficient collection and transport.	**10**	P10, P13, P15	[60]	"There is a need to find these different categories of devices and how you can process them" (P13).
1.6	Take inspiration from other/existing waste streams or methods.	**5**	P12, and P13	[61], [97]	"Expertise and learnings from existing and previous recycling schemes can be used to develop and to enhance any future initiatives" [61].
1.7	Consider chemical recycling as an option for polymers that are not suitable for mechanical recycling.	**4**	P16, P21	[98]	"A lot of plastic that we cannot recycle in our plants you could, in theory, recycle chemically" (P16).
1.8	Enable the execution of circular strategies close to the use site for efficiency (e.g. in-hospital decontamination, repair, and remanufacturing).	**3**	P20	n.a.	"You could use it and clean it, and already sort of reuse it at the same time. You could have a super local loop because a lot of the materials are already in that environment" (P20).
	Category: Social acceptance	**Times mentioned**	***Interviews***	***Literature***	**Example Quote**
2.1	Increase stakeholder motivation by enabling circularity and creating commitment.	**64**	P1- P3, P5, P7-P14, and P16-P20	[11], [25], [26], [28], [32], [35], [36], [39], [40], [43], [49], [55], [60], [64], [69], [97], [99]	"We can also come up with a sustainability challenge and have manufacturers come up with solutions; that is called creative procurement" (P7).
2.2	Circularity-related education or training.	**62**	P9	[26], [28], [30], [31], [32], [33], [34], [35], [36], [40], [48], [49], [51], [56], [58], [60], [61], [64], [69], [74], [79], [97]	"Surgical instrument reprocessing is a complicated procedure and requires training, infrastructure, supplies, and strong organizational principles to be successful"[28].
2.3	Creating transparency about environmental and safety impacts of (circular) medical devices by means of benchmarking.	**34**	P7, P9, P12, P19, and P21	[11], [25], [27], [32], [34], [35], [36], [40], [51], [60], [65], [69], [100]	"As hospitals and healthcare providers move toward more sustainable or 'green' practices, publicly available, transparent environmental information is needed to support product decisions" [100].

2.4	Use environmental benefits as a motivator for change.	**20**	P1, P6, P9, P17-P20	[11], [32], [34], [60], [69], [100]	"You can remanufacture to reduce waste, which is a visible moral aspect" (P18).
2.5	Normalize the use of environment-friendly and/or recovery-suitable materials	**8**	P14, and P20	[34], [39], [60], [62], [83]	"Reducing material quality, in favor of recyclable and ecofriendly materials, could be a way to save energy while ensuring patient safety" [34].
	Category: Manufacturer suggestions	**Times mentioned**	***Interviews***	***Literature***	**Example Quote**
3.1	Enable financial benefits for customers or for manufacturers through good circular business models.	**54**	P1-P3, P5-P8, P10, P13, P14, and P17-P20	[11], [26], [27], [36], [39], [56], [58], [60], [69], [80], [90], [95], [100]	"For high end equipment circularity as already been planned for a long time . . . that is because there circularity and business models go together quite well" (P3).
3.2	Improve and intensify collaboration among stakeholders.	**41**	P3, P7-P9, P15, P17, P19, and P21	[30], [32], [34], [36], [40], [48], [53], [55], [56], [60], [61], [65], [69]	"It is not only about product level. It is about daring to design a completely different collaboration" (P7).
3.3	Invest in innovation (for all stakeholders).	**35**	P3, P7, P9, P13, P14, P16, P17, P20, and P21	[9], [18], [30], [33], [33], [45], [51], [56], [60], [66], [67], [70], [72], [73]	"If [company] develops a circular concept . . . then you must also be daring to invest in this as a hospital" (P7).
3.4	Let producers take responsibility and ownership over their wastes.	**29**	P2-P4, P6, P8, P11, P14-P16, P18, P19, P21	[11], [34], [36], [43], [56]	"If they would return to the manufacturer, they would have a larger chance of being recycled because they will know what to do with it" (P16).
3.5	Improve circular design and engineering practices.	**24**	P3, P19, P20, and P21	[11], [26], [34], [49], [60], [62], [69], [81], [83], [90], [97]	"To make sure this effort continues to extend the life of products, design them better" (19).
3.6	Introduce system thinking and service concepts.	**12**	P3, P7, P18, and P20	[11], [32], [40], [100]	"Adding the life cycle of other textile and non-textile items found in healthcare facilities, such as gloves, wipes, or masks, would further strengthen the environmental benefits of reusable systems" [100].

3.7	Use scarcity of materials (or the prevention thereof) as a motivator to perform circular practices.	**8**	P3, P5, P18, and P21	[36]	"Remanufacturing is … something that comes from the aim to deal smartly with scarce resources" (P18).
3.8	Break the linear pattern and utilize first mover advantage.	**7**	P7, P17, P20, and P21	[32], [43], [44], [56], [78], [95], [98]	"It definitely provides you with a first mover advantage, if you're the first in the market. So that is definitely a reason to do it" (P17).
3.9	Make use of contracted recovery facilities.	**6**	P3, and P19-P21	[27]	"The second business model is when the OEM appoints a third party . . . [The third party] is licensed to operate by the OEM" (P19).
3.10	Donate devices to low-income countries or charity. [1]	**3**	P2, P3	[69]	"Other sustainability efforts in Canadian ORs included donating unused medical equipment and supplies to medical missions" [69].
3.11	Create circularity-related employment opportunities.	**1**	P1	n.a.	"There's a huge benefit to having more reusable devices: it ensures employment opportunities for this work field" (P1).

Our list of opportunities indicate that the circular transition of medical devices could be realized through policies, human factors, and (technological) innovations (such as enabling systems, e.g. related to efficient collection and circular procedures). Circularity can be stimulated through different regulations, guidelines, and standards that manufacturers and users should adhere to. Additional motivation could be driven through creating circularity-related financial benefits, enabling practices, ensuring transparency about environmental benefits, highlighting material scarcity, stimulating normalization, and offering education and training. To make the circular economy work, we also need to establish better stakeholder collaborations, implement system thinking, and improve (circular) design practices. Apart from all this, we need to find a way to ensure successful collection and separation of devices, for example, by sorting devices per type, implementing collection point communication systems, and making use of already existing and centralized collection methods. However, our research also presents an alternative approach: avoiding the need for complicated collection systems by providing circular strategies locally, close to the use site.

2.3.3.1 Design-Specific Recommendations

Based on the identified best practices, the barriers and opportunities, and on the results of our interviews and literature review, we developed a set of design-specific recommendations that may help drive medical device design towards a more circular future (Table 5). Some recommendations were directly mentioned in interviews or literature, while others were interpreted based on a

1 Donating used devices to low-income settings is a potential opportunity to explore. However, it is important to take ethical considerations and additional environmental impacts that may come with this strategy into account.

combination of the other results (e.g. the notion that mixed plastics cannot easily be recycled, which falls under barrier 5.1, was interpreted as a need to avoid the use of mixed plastics for recycling, which falls under design recommendation 28). Table 5 also indicates which circular strategies the design recommendations apply to. They are ordered based on their relevance in line with the hierarchy of the R-strategies and the number of R-strategies they apply to.

Table 5: Design-Specific Recommendations

#	Design recommendation	Concluded from analysis of ...			CIRCULAR STRATEGIES							
		Best practices	Barriers and opportunities		Refuse	Rethink	Reduce	Reuse	Remanufacture	Repurpose	Recycle	Renew
			Interviews	Literature								
1	Maintain (or improve) quality, function & usability of the original device when introducing circular strategies.	n.a.	P2, P3, P5-P8, P10, and P14-P21	[76]								
2	Aim to combine different circular strategies as much as possible (while prioritizing the strategy higher in the hierarchy).	We had already assumed this to be true in our circularity rating method	P1-P5, and P10-P12	n.a.								
3	When integrating circular strategies, make sure to mitigate safety risks for intended use of the device/material/system.	n.a.	P8, P10, P15, and P21	n.a.								
4	Make sure the device has sustainability certificates.	n.a.	P9, and P21	n.a.								
5	Consider the device EoL from the start of the design process.	10% of reusable devices we found are designed for remanufacturing upon EoL	n.a.	n.a.								
6	Be careful not to unjustly prioritize the selection of biomaterials when other options are more sustainable.	n.a.	P21	n.a.								
7	Design devices for local manufacturing and distribution to minimize transportation emissions.	n.a.	Based on findings from opportunity 1.8, e.g. P20	n.a.								
8	Enable both extensive testing and simplified assessment of device and/or material quality and circularity.	n.a.	P6, P8, P18, and P21	[11], [27], [28], [32], [36], [43], [58], [66], [90]								

9	Ensure quick, efficient procedures needed for the different circular strategies (such as collection, decontamination, etc.) that fit within the current workflow (where this is possible).	n.a.	P1, P3-P5, P8-P10, P12, P14, P15, and P17	[26], [27], [48], [58], [60]								
10	If needed, make device good and easy to clean, (suitable for various decontamination methods – water/heat/chemicals resistant).	n.a.	P1, P2, P8, P9, P17, P18, and P20	[46]								
11	Minimalize the needed (and performed) decontamination processes.	Some circular devices improve sustainability by avoiding sterilization in their reuse cycle.	P4, P5, and P20	n.a.								
12	Provide clear and easy-to-understand instructions on the execution of the steps in the different circular strategies.	n.a.	P1, P10-P12, and P14	n.a.								
13	Enable easy disassembly (for cleaning, removing hazardous materials, and sorting materials).	Most reusable and remanufacturable devices are easy to disassemble	P1, P3-P6, P8-P10, P12, P15-P18, and P20	[83]								
14	Enable traceability of devices and materials during their circular life cycles, for example through a digital device passport	Many reusable devices have limited allow use cycles, which needs registration.	P1, P3, P6, P9, P13, P14, and P17-P21	[27], [36]								
15	Aim to increase device value and lifetime where possible.	n.a.	P4, P16, and P20	[11], [28], [32], [36], [44], [60], [75], [98]								
16	Provide clear information about circular principles and proper maintenance to enhance longevity of devices.	n.a.	Based on findings from barrier 6.1, e.g. P10	[60]								
17	Assure a simplification of shapes and parts to enable disassembly, decontamination, and separation.	n.a.	P2, P8, P14, and P16	n.a.								
18	Try to refuse (prevent the use of the device or materials where possible).	A small number of circular devices applies this strategy successfully.	n.a.	[32], [39], [60], [90], [98]								

19	Save spare parts from partly reuse devices that cannot be reused in whole to use them in other circular processes, such as remanufacturing.	In some circular devices, some parts have more use cycles than others.	P3-P5, P12, P17, and P21	[11], [75]									
20	Align the battery life (and point of assembly thereof) with the device life.	Long-lasting circular devices tend to have longer battery life.	P4, and P12	[36], [44]									
21	Aim to design a modular device with standardized connections compatible with different parts and systems.	Some circular devices have “add-ons” that fit on different systems.	n.a.	Based on findings from opportunity 3.5, e.g. [34], [60]									
22	Aim to design a (portable) device that can be used in different locations, such as the home and healthcare setting.	This is an example of “rethink”, which may make a device more circular.	n.a.	n.a.									
23	Aim to design a device that can be used by multiple users (at the same time) to minimize the need for individual ownership.	This is an example of “rethink”, which may make a device more circular.	n.a.	n.a.									
24	Aim to design a multifunctional device, able to be used for multiple purposes (at a time).	This is an example of “rethink”, which may make a device more circular.	n.a.	n.a.									
25	Minimize material use in both device and packaging while maintaining device quality, longevity, and functionality (design for dematerialization).	This is an example of “reduce”, which makes devices more circular.	P8, and P9	[32], [60], [90], [95]									
26	Minimize energy consumption (refuse/ reduce) electronics, increase efficiency, or introduce energy saving features.	This is an example of “reduce”, which makes devices more circular.	n.a.	[60], [66], [69], [90], [11]									
27	If possible and useful, consider repurposing the device for different functions upon EoL.	“Repurpose” is underrepresented in the best practices.	P6, and P18	[11], [32], [34], [41], [60], [98]									
28	Make materials easy to separate, by avoiding combining different materials and mixed materials such as fancy plastics.	Recyclable devices typically have minimal material variance and complexity.	P3, P10, P12, and P14-P17	[37]									
29	Consider biobased, bioactive, and/or biodegradable materials where possible (but always check whether those options actually increase sustainability).	n.a.	P6, P12, P20, and P21	[47], [62], [66], [97], [102]									

Firstly, we recommend engineers to look beyond the circular strategy of reuse: in terms of circularity it may be worthwhile to look into refuse, rethink, and reduce, or to determine whether a device could be made suitable for repurpose or remanufacture once it has reached its maximum number of reuse cycles (as is illustrated by guidelines 2, 18, 21, 22, 23, 24, 25, and 26). Our findings indicate that to develop a circular active medical device, at least 29 different recommendations need to be considered. This underlines a need for further design guidance to help designers and engineers take into account so many guidelines and account for contradictions and exceptions. The most important guidelines are numbers 1-5, as they apply to all circular strategies we investigated. These five guidelines stress that circular medical devices should not be inferior to their (non-circular) predecessors in terms of quality, function, and usability. Another recommendation is to combine as many circular strategies as possible, while prioritizing strategies higher in the hierarchy. Implementation of circular strategies may in some cases lead to increased safety risks (e.g. because of access to batteries or functionality risks after sterilization). It is important to take all possible hazards and risks into account and make sure to mitigate those risks for the intended use of the device, material, or system. Successful circular designs should ideally be supplied with sustainability certificates. It is therefore important to already start thinking about circular strategies and EoL scenarios in the early stages of the design process, as this allows designers to embed circular principles into the product's foundation, optimizing resource use, durability, and EoL recovery. This proactive approach minimizes the need for costly retrofits, fosters sustainable design practices, and aligns with broader environmental goals.

2.4 Discussion

Our inventory of best practices revealed that out of at least 1400 medical devices, only 346 implemented at least one circular strategy. Of these 346 devices, only 33% implemented more than one circular strategy. Most circular devices we found were reusable medium-criticality devices used in a healthcare setting. This underscores the need to improve circularity in active medical devices, particularly for low and high-criticality devices used in patients' homes.

While our interviews and literature review indicated that reusability and decontamination practices could still be increased and improved (also e.g in terms of environmental impact [25]), looking beyond reuse is advisable, as in our best practices search all other circular strategies were found to a much lesser extent. Especially repurpose, recycle and renew were uncommon. It is particularly noteworthy but not unexpected that the fundamental recycle strategy is scarcely found in medical device design: this finding was confirmed by the interviewed recyclers, who are not allowed by law to recycle potentially contaminated devices (i.e. all devices falling under the medical device directive).

The difficulty of finding good circular examples was not very surprising, considering the extensive list of barriers to the circularity of active medical devices we provided. Barriers were divided into six categories: safety, systemic, regulatory, financial, technological, and social barriers. Although safety concerns made it to the top of our list, interview participants indicated that in practice this sometimes leads to an unhelpful overemphasis on infection prevention. For example, some devices are thrown into the medical waste bin 'just to be safe' even though they are not contaminated. This is unfortunate because both our best practices inventory and existing literature [103], [104] have shown that well-performed circular practices can result in efficient, reliable and safe medical devices. A similar situation is true for regulations; they are often interpreted extra strictly to prevent possible business risks. A potential way to equate perception with reality was

presented as the most-mentioned opportunity: circularity-enabling regulations, guidelines and standardizations could minimize safety risks while further clarifying needed regulatory adherence.

Despite identified barriers and somewhat disappointing results in the best practices inventory, we showed that circular design of active medical devices is feasible. Notable circular practices included eliminating the need for unsustainable devices (refuse), reducing energy consumption (reduce), offering multiple functions in one device (rethink), and eliminating electronic components without compromising functionality (reduce). Surprisingly, rethink emerged as the second most prevalent strategy, following reuse. However, our definition of rethink encompassed sharing devices among users or patients, and portable devices that can be used in various locations. Therefore, developments in this direction could be motivated by considerations such as enhanced adaptability, improved user experience, and increased accessibility, rather than circularity. This in itself underlines the opportunity to connect circular practices to e.g. functionality, scarcity, business or regulation-related incentives, as was also proposed in our list of opportunities.

Our research resulted in a unique set of specific circular design recommendations for active medical devices, presented in Table 6. This represents a novel, pioneering representation of design guidelines that builds on the previously unexplored topic of design strategies for medical devices.

2.4.1 Limitations

In our research, we ranked barriers and opportunities based on their frequency of occurrence in the literature review and interviews. However, it is important to note that the order of importance of barriers may vary per device. Participants highlighted for instance that for devices storing patient data, privacy concerns in reuse, repurpose, and remanufacture, influenced by recent developments in European privacy regulation, was a major barrier that could significantly hinder the circular transition.

The best practices were ranked by means of our circularity rating method. We made use of the hierarchy of circular strateigies based on two assumptions: that certain strategies are always superior to other strategies and that the more strategies a device uses, the higher the circularity score of a device is (based on [105]). This was necessary to make our circularity rating easy to apply to a large number of devices. However, the reality is somewhat more nuanced. While certain strategies may be prioritized from an environmental perspective, strategies like refuse or reduce may seem counterintuitive from an economics point of view, as they can lead to economic challenges such as cannibalization issues [106].

Also from a sustainability perspective, strict adherence to the hierarchy must be avoided, as demonstrated by the example of reusing an old device with hazardous substances, which may be worse than remanufacturing it and replacing those unsafe components. Although our assumption that more circular strategies in one device is better was endorsed by our interview participants, it is crucial to consider that circularity depends not only on the number of strategies but also on their quality of execution (e.g., maximizing reuse cycles, minimizing sterilization impact, and recycling into similar or higher-quality materials). Furthermore, it is unlikely for one device to employ all strategies, as some are mutually exclusive (e.g., recycle and renew).

The circularity scores were based on manufacturer-provided claims, with efforts made to verify reliability through expert input. The subjective nature of these assessments may introduce some degree of uncertainty and may have posed some limitations, e.g. in capturing devices repurposed in developing world markets after use (as manufacturers often lack knowledge of such practices), or the inability to analyse the use of the repair strategy separately due to limited data availability. Additionally, we were unable to verify sustainability claims made by the company due to time constraints. This may lead to unintended consequences like burden shifting, as seen when transitioning a device like a hearing aid to an app format, potentially reducing smartphone lifespan or encouraging more frequent upgrades. Despite the assumptions made in our circularity rating method, we are confident that our final list provides accurate findings that can help understand the current state of circularity in medical devices.

We identified some common themes in high scoring devices, such as remanufacturing after reuse, replacing devices with more sustainable alternatives and reducing energy consumption. However, we identified another interesting strategy that is worth mentioning: the elimination or minimization of the need to use infection prevention materials such as disposable alcohol wipes or sterile sleeves (refuse), which is for example applied in device 22 and 270 of the full list of best practices. The reason this strategy is found in devices with a lower circularity score, is because we scored the devices specifically on the circularity of the device itself, while this strategy addresses the overall sustainability of the full care pathway.

Apart from the scoring of the devices, we also aimed to categorize them based on their use location, economic value, and criticality. As data about economic value was unavailable, size was used as a value indicator. This size-based evaluation yielded conflicting findings: while the best practices inventory included numerous smaller devices, the interviews indicated a greater likelihood for high-value devices to implement circular strategies. We expect this to be the case due to our search and selection method: there being more small devices in our best practices inventory likely means that more small devices exist, rather than low value devices being more circular.

Lastly, although we present opportunities that apply to different parts of the supply chain, it is important to keep in mind that we have conducted this research from a design point of view. For this reason, different perspectives related to e.g. circular business models, supply chain logistics and regulatory constraints may be underexposed in our analysis. We acknowledge that for a successful circular transition, effort is needed from all supply chain stakeholders.

2.4.2 Future Research

Future research on circularity in medical devices should include users' needs, the care pathway, and the entire product life cycle. Adopting a systemic approach during the development of circular design guidelines will help ensure that circular practices do not compromise the functionality, usability, and safety of the devices. Additionally, integrating circularity recommendations in successful business models and evaluating their compatibility with existing regulations (or suggesting regulatory adaptations) is essential for practical implementation. Further research is also needed to assess the applicability of the recommendations in real-life contexts, considering existing medical device design practices through testing by experienced medical device engineers across a range of design cases.

2.5 Conclusion

The aim of our research was to investigate the extent to which circular design principles are currently employed in the development of active medical devices, to create a concise overview of the barriers and opportunities to the transition towards circularity, and to create a set of circular design-specific recommendations tailored to active medical devices.

The analysis of the current state of circularity in healthcare revealed limited circularity of active medical devices. However, reusing devices is relatively common, as is minimizing material and energy consumption. The identified barriers to circular design encompass safety concerns, challenges in device collection and separation, regulatory constraints, financial limitations, and a lack of awareness. Opportunities for promoting circularity in healthcare include policy interventions, technological innovations, financial incentives, stakeholder collaboration, and system thinking. Design-specific recommendations, derived from the analysis of the best practices and interviews and literature review used to identify the barriers and opportunities, emphasize the importance of maintaining device quality, function and safety when implementing circular strategies. Additionally, we recommend early consideration of circular potential, prioritizing reuse, and addressing potential safety risks. The recommendations encompass 29 guidelines, reinforcing the need for comprehensive design guidance to navigate the complexities of circular medical device development. The findings of this study offer valuable insights for design engineers, providing actionable recommendations to navigate the complexities of circular medical device development, ultimately contributing to sustainable and innovative healthcare solutions.

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PART II, Chapter 3

Chapter 2 highlighted the urgent need for more sustainable medical devices, as well as the main barriers preventing the adoption of circular strategies. One key barrier that emerged is inconsistent or conflicting terminology. Terms such as “reuse” or “recycling” are often used differently across disciplines, which can fragment collaboration and impede the practical implementation of circular strategies.

Chapter 3 addresses this barrier by developing a visual taxonomy of circular healthcare flows. The taxonomy was co-created with stakeholders across the healthcare supply chain and clarifies how circular strategies are defined, applied, and connected in practice. By providing a shared understanding of terminology and operationalization, this chapter builds directly on the findings from Chapter 2 and prepares the ground for applying circular strategies in design.

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Chapter 3

Mapping Circular Economy Material and Product Flows in Healthcare: A Visual Taxonomy

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Abstract—Background: The healthcare sector contributes substantially to environmental pollution, affecting ecosystems and public health. Circular economy (CE) strategies offer potential solutions, but existing frameworks provide limited guidance for healthcare, overlooking factors such as infection control, decontamination, and staff workload.

Methods: We developed the Circular Healthcare Flows visual, a taxonomy of CE strategies for medical devices, using observations in sterilization departments, recycling facilities, and manufacturing plants; 21 expert interviews; and a systematic review of 1104 studies (68 full-text reviews). Additional stakeholder feedback validated and refined the taxonomy.

Findings: The taxonomy identifies 13 CE strategies—refuse, replace, rethink, reduce, reuse, maintain, repair, refurbish, remanufacture, repurpose, recycle, renew, and recover—and organizes them in a healthcare-specific framework. Iterative feedback ensured that the taxonomy is clear, practically applicable, and addresses sector-specific regulatory, clinical, and operational constraints.

Interpretation: The Circular Healthcare Flows visual provides a practical tool to standardize terminology and guide the implementation of CE strategies in healthcare. By offering conceptual structure and actionable guidance, it supports informed decision-making, facilitates collaboration among stakeholders, and encourages consistent application of circular strategies across the sector.

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3.1 Introduction

The healthcare sector is essential for improving and maintaining health, yet it contributes 4-5% of global greenhouse gas emissions [1], paradoxically undermining societal health. A 1% increase in carbon emissions can increase inpatient visits by 0.162% and outpatient visits by 0.298%. [2] According to the 2024 Quantifying the Impact of Climate Change on Human Health report [3], climate change is projected to cause 14.5 million additional deaths worldwide by 2050, further exacerbating the strain on global healthcare systems.

Healthcare systems themselves are major contributors to environmental degradation due to energy-intensive operations, high material throughput, and complex waste streams. Studies by Eckelman and Sherman (2016) [4], Eckelman and McGain (2020) [5], and others have quantified healthcare's carbon footprint and emphasized the need for systemic mitigation strategies across supply chains, clinical operations, and procurement. Initiatives such as Health Care Without Harm and Practice Greenhealth demonstrate that integrating environmental management principles—energy efficiency, waste minimization, and product life extension—can reduce emissions while maintaining quality of care. These approaches form a theoretical and practical bridge between sustainability science and circular economy thinking within healthcare.

This study tackles how circular economy (CE) principles can be made workable within healthcare, a field where sector-specific and operationally detailed CE frameworks remain limited. CE strategies, which promote the reuse, remanufacturing, and recycling of products and materials [6], shift away from linear production and consumption toward regenerative systems that reduce waste, preserve product value, and support economic resilience. While CE overlaps with environmental sustainability, it is distinct: CE focuses on closing material loops and retaining product value, whereas sustainability addresses broader issues like carbon footprint reduction and biodiversity conservation. In this study, "circular economy (CE)" or "circularity" is used to engage with the broader discourse on resource recovery and waste reduction.

To operationalize CE in healthcare, it is necessary to examine existing CE frameworks and assess their applicability to sector-specific challenges. Among the most recognized frameworks is the Ellen MacArthur Foundation's (EMF) Butterfly Diagram [7], which divides CE into a technical cycle (reuse, repair, recycling) and a biological cycle (composting, anaerobic digestion). Similarly, the Netherlands Environmental Assessment Agency's (PBL) 10R-strategies framework [8] categorizes circular strategies from "refuse" (R0) to "recover" (R9), providing a structured hierarchy. In contrast, The Value Hill model [9], developed by Nuovalente, Circle Economy, Sustainable Finance Lab, TU Delft, and Het Groene Brein, examines value retention across product lifecycles. Additionally, the "Re-defining Value" report from the United Nations Environment Programme (UNEP) and International Resource Panel (IRP) [10] complements these frameworks by providing insights into material and product lifecycle management.

When applying circular economy (CE) models to healthcare systems, these general frameworks must be adapted to address sector-specific sustainability challenges such as infection control, contamination risk, and regulatory barriers to reuse. These issues are extensively discussed in the literature on sustainable healthcare management. Applying CE in healthcare requires a systems-thinking approach that considers interactions across material flows, clinical operations, stakeholder behaviour, and regulatory frameworks. For example, MacNeill et al. (2020) [11] highlight barriers such as assumptions about infection prevention and the behaviours of healthcare professionals, while Hoveling et al. (2024) [12] identify perceived safety and infection

risks, as well as regulatory difficulties, as major obstacles to circular medical device design. Together, these studies emphasize that healthcare requires tailored CE strategies that reconcile sustainability goals with patient safety and regulatory compliance, and that provide clear, practical guidance for safely reintegrating medical materials and devices into circular loops. Viewed within hospital sustainability literature, these studies indicate that circular strategies can extend existing environmental management efforts, improving material retention and waste reduction.

In addition to the just-mentioned conceptual frameworks, non-healthcare related regulatory and standardization efforts have also attempted to define CE principles more formally. ISO 59004:2024 [13] provides standardized definitions for key CE terms while emphasizing systemic thinking, value retention, and stakeholder collaboration. Meanwhile, the Waste Framework Directive (WFD) [14] establishes a waste hierarchy prioritizing prevention, reuse, recycling, and recovery. However, neither ISO 59004:2024 nor the WFD directly address the management of hazardous and bio-contaminated waste, which is a critical consideration in healthcare settings. Healthcare regulatory frameworks like the US Food and Drug Administration (FDA) [15] and the EU Medical Device Regulations (MDR) [16] impose strict guidelines on medical device safety and reuse. Interestingly, both refer to "reprocessing" as a CE strategy—a term that is absent from several widely recognized non-healthcare CE frameworks, including the Butterfly Diagram [7], Value Hill model [9], 10R framework [8], ISO 59004:2024 [13], and Waste Framework Directive (WFD) [14].

Moreover, the instance of terminology confusion surrounding "reprocessing" is just one example among many documented in the literature. Chang et al. note that "inconsistent terminology regarding sterilization cycles has led to confusion among ambulatory surgery centres," highlighting how such discrepancies can disrupt operational clarity.[17] Similarly, Peters et al. propose using emojis to bridge language barriers in respirator reprocessing guidelines, underscoring the need for more precise language.[18] While innovative, such approaches may be limiting in spoken language and when conveying the nuanced distinctions between CE strategies. The lack of standardized terminology complicates communication among stakeholders and may hinder transdisciplinary research, which, according to Uiterkamp and Vlek (2007), is crucial for advancing circularity. [19] These examples illustrate a broader challenge: divergent language across disciplines hampers interdisciplinary collaboration and the successful implementation of circular economy strategies. This is important, as the practical application of CE strategies in healthcare is further challenged by conflicting stakeholder priorities—such as safety, sales, and regulatory approval—which can overshadow environmental objectives. [6] Effective collaboration among these diverse groups is therefore essential for aligning interests and implementing circular strategies.

This terminology challenge extends beyond text-based definitions. Use of visualisation (including e.g. emojis, as was suggested by Peters et al [18]) could offer benefits in overcoming language barriers and improving collaboration. As described by Eppler and Bresciani in 2013, using qualitative visualisations such as conceptual diagrams, metaphors and sketches could in fact enable effective and seamless collaboration across disciplinary boundaries. [20] In 2019, Bresciani developed a framework for collaborative dimensions of visualizations. [21] While focused on developing visuals in smaller group collaborations (in comparison to the circular healthcare sector), her framework does detail seven dimensions that can be relevant for constructing conceptual visualizations to support collaboration: structural restrictiveness (extent to which the design process is guided or constrained by the visualisation), content modifiability (extent to which the items of a visualisation can be dynamically changed), directed focus (extent to which the main item(s) of the discussion is visually emphasized), perceived "finishedness" (extent to

which visual cues suggest whether an object appears finished), outcome clarity (extent to which a visual representation is self-explanatory and easily understandable with low cognitive effort), visual appeal (extent to which a visual representation is attractive and pleasant to the eyes), and collaboration support (extent to which a visualisation controls the flow of group discussion).

Some attempts have been made to develop visualizations of the CE, such as the previously-discussed butterfly diagram [7]. Likewise, the European Union's interactive Sankey diagrams[17] provide a visual tool with insights into CE material flows, mapping extraction, consumption, and recycling pathways. However, both visualizations could be improved based on the collaborative dimensions of visualizations framework. For example, the Butterfly Diagram seems to unintentionally draw attention to regeneration of waste in the biosphere and is not fully self-explanatory due to the lack of detail. Likewise, the Sankey diagrams are very focused on material flows alone, while also not being very intuitive to use with low cognitive effort. Additionally, like other general CE frameworks, they fall short of addressing sector-specific needs in healthcare, such as balancing circular strategies with infection control and clinical effectiveness.

To address these challenges, this study aims to develop the Circular Healthcare Flows visual—a visual taxonomy that applies established circular economy principles within healthcare-specific constraints. The visual taxonomy is designed as both a conceptual and practical tool for healthcare stakeholders—including designers, clinicians, procurement teams, remanufacturers, and policymakers—to apply circular strategies while safeguarding patient safety, infection control, and regulatory compliance. It was developed iteratively, drawing on field observations, expert feedback, and a systematic review of how circularity is discussed in healthcare literature. The framework also draws inspiration from Bresciani's collaborative dimensions to strengthen clarity, adaptability, and usability in multidisciplinary settings. Together, these elements aim to create a visual that is genuinely usable in healthcare practice rather than a generic circularity model.

3.2 Method

The Circular Healthcare Flows visual was developed through a stepwise, iterative process (Table 6). Initially, internal circular economy (CE) expertise at TU Delft was used to draft a first version of the system visual, forming the basis for further iteration. This initial version was refined through observational research, which helped map procedural steps for each CE strategy and incorporate healthcare-specific nuances, informing early iterations (3–4, Table 6).

The visual at that stage was used as a research probe in expert interviews, allowing participants to provide practical feedback and highlight areas needing improvement (iterations 5–7, Table 6). During these interviews, it became clear that there was no consensus on CE strategies, terminology, or definitions, indicating a need for a systematic literature review to ensure standardization and evidence-based terminology.

The systematic literature review was then conducted to standardize terminology, clarify definitions, and refine the sequencing of CE strategies in the visual (iterations 9–10, Table 6). After revising the visual based on the literature review findings, it was validated again with the same and additional experts, ensuring both accuracy and practical relevance (iterations 13–14, Table 6).

Finally, once content-related aspects were finalized, the visual was refined and evaluated using the Collaborative Dimensions Framework, optimizing clarity, focus, modifiability, usability, and collaboration support across seven clearly defined dimensions: visual impact, clarity, perceived finishedness, directed focus, inference support, modifiability, and discourse management. Insights from each stage informed subsequent iterations, linking evidence collection directly to design refinements.

The development combined observational research, expert interviews, systematic literature review, and stakeholder validation, with each method feeding into the next in a clearly sequenced, iterative process that informed the final visual taxonomy. Each method's contribution to the iterative development is explicitly linked to the corresponding updates in Table 6.

Table 6: Overview of Circular Healthcare Flows visual iterations

#	Intention of specific iteration	Developed based on
1	Exploration and defining literature and observation strategy	Internal knowledge TU Delft
2	Update based on new findings	Initial literature search
3	Update based on new findings	Observational research (see paragraph 3.2.1)
4	Update graphical design for final research probe	Internal consultations
5	Corrections based on new findings	Expert interviews (see paragraph 3.2.2)
6	Corrections based on new findings	Expert interviews (see paragraph 3.2.2)
7	Corrections based on additional feedback	Expert interviews (see paragraph 3.2.2)
8	Improve clarity and identify additional knowledge gaps	Internal consultations
9	Adapt terminology and definitions used	Early literature review findings (see paragraph 2.2.3)
10	Adapt terminology and definitions used	Final literature review findings (see paragraph 3.2.3)
11	Add additional contextual information where needed	Internal consultations
12	Improve graphical design to fit newly added strategies	Internal consultations
13	Corrections based on additional feedback	Validation with experts (see paragraph 3.2.4)
14	Final validated version (minimal final corrections)	Validation with experts (see paragraph 3.2.4)

3.2.1 Observational Research

Observational research aimed to map procedural steps for each CE strategy and identify healthcare-specific nuances, ensuring that the visual taxonomy reflects real-world operational practices. Site visits included a recycling facility (~2 hours), a medical device production site (~2 hours), various clinical procedure areas in hospitals (~10–12 hours total across multiple departments), and three internal and two external hospital sterilization departments (~1 hour per facility). Notes and photographs from these visits were analysed and translated into visual representations, informing both content and design decisions in the taxonomy. A total of 8 site visits were conducted, covering diverse healthcare and industrial settings. This number was considered sufficient to capture the key procedural variations across different settings, allowing the development of a first version of the visual taxonomy that could then be iteratively refined based on expert interviews. These observations ensured that the visual accurately reflected real-world processes and practical considerations across multiple healthcare contexts. To enhance consistency, observations were documented systematically through structured notes and photographs, with key patterns discussed among the research team before translating them into visual representations.

3.2.2 Expert Interviews

Expert interviews aimed to gather sector-specific insights to refine and validate the visual taxonomy, ensuring practical relevance and clarity per CE strategy. The visual probe (Appendix A) was used to elicit feedback on content, terminology, and usability. Procedural details (e.g., transcription tools, platforms) have been summarized here; full protocols are in Appendix B. The research probe was developed by combining observational research findings with internal knowledge from the Sustainable Design Engineering department at TU Delft and further refined using literature and observations. Literature sources included general CE principles and strategies, such as the PBL 10R-strategies framework and the EMF butterfly diagram, which informed the initial visual overview.

The interview participants (Table 7) were those previously published in [12], which reported the second part of the same interview, which will not be repeated in this paper. Thirty-four experts divided over twenty-one interviews, from a variety of EU countries (The Netherlands, Switzerland, Spain, Norway, Slovenia) and the USA took part (Table 7). Interview participants were selected to represent a diverse range of backgrounds and expertise. For each of the categories—sterilization facilities (internal and external), manufacturers, hospital procurement, (international) foundations, (hazardous) waste handling, collection systems experts, recycling facilities, remanufacturing experts, and biocycle or renewable energy experts—the goal was to conduct at least two interviews, with each interview including one to three individuals. No participant took part in more than one interview. Participants (hereafter referred to as 'experts' or 'stakeholders' depending on context) signed consent forms, and interviews lasted ~30 minutes via face-to-face or online video call. All sessions were recorded, transcribed with Sonix.ai, and proofread. Coding was performed in ATLAS.ti. Highlighted statements from the interviews were translated into actionable updates to the visual. Although no formal intercoder procedure was applied, the coding reflects the literal statements of the interview participants. Reliability of the coding and interpretations was ensured through a multi-step process: the coded data were visualized in an updated taxonomy, discussed with participants for corrections and refinements, and reviewed again during the formal validation stage (section 3.2.4).

Table 7: List of Expert Interview Participants

#	Participant category	Expertise	Number of people in the interview
P1	Sterilization facilities	External sterilization	2
P2	Sterilization facilities	Internal sterilization	1
P3	Manufacturers	Engineering, supply chain, and parts harvesting	2
P4	Manufacturers	Design Engineering	2
P5	Manufacturers	Strategy and design engineering	3
P6	Manufacturers	Research and development	1
P7	Hospital procurement	Academic hospital procurement	1
P8	Hospital procurement	Non-academic hospital procurement	1
P9	Hospital procurement	Non-academic hospital procurement, and intensive care	2
P10	(International) foundations	Sustainable use of natural resources	3

P11	(International) foundations	E-waste responsibility	3
P12	(International) foundations & (hazardous) waste handling	E-waste handling, and recycling	2
P13	Collection systems developer	Circularity collection systems	1
P14	Collection systems developer & recycling facilities	Recycling & collection	1
P15	Recycling facilities	Metal and electronics recycling	1
P16	Recycling facilities & (hazardous) waste handling	Plastics recycling	1
P17	(Hazardous) waste handling	Waste handling policies & practices, and handling sharps	3
P18	Remanufacturing experts	Remanufacturing of construction machines, and circular business concepts	1
P19	Remanufacturing experts	Remanufacturing of devices and components, and relevant regulations	1
P20	Bio cycle / reduce experts	Design engineering, bio-design and biomaterials	1
P21	Bio cycle / reduce experts	Expert on bio cycle processes, and material choices	1

3.2.3 Systematic Literature Review

The systematic literature review aimed to address inconsistent terminology and definitions of CE strategies in healthcare and to inform evidence-based development of the Circular Healthcare Flows visual. In total, 1,104 articles were screened, including 68 full-text review articles analysed in detail. The review had three main objectives:

1. Map terminology usage: Bibliometric analyses were performed to identify term frequency, co-occurrence, and topic clusters, revealing common concepts and knowledge gaps.
2. Compare with frameworks: Terms and definitions were compared to regulatory and CE frameworks—including the 10R framework, EMF Butterfly Diagram, ISO standards, and EU/FDA regulations—to ensure healthcare-specific relevance.
3. Inform visual taxonomy: Insights guided standardization of definitions, alignment of CE strategies with healthcare contexts, and sequencing of steps in the visual taxonomy.

This review was registered at https://osf.io/8psdh and conducted following Cochrane Collaboration methods and PRISMA guidelines [22], [23]. The search strategy was developed and duplicates removed by an information specialist [WB], initially optimized in Embase.com, then adapted for Medline ALL and Web of Science.

3.2.3.1 Search Methods

Searches were conducted in three databases:

- Medline ALL (Ovid, 1946–Daily Update)
- Embase.com (1971–present)
- Web of Science Core Collection (1975–present, including various indexes)

The initial search was performed in January 2023, updated on 23 February 2023 following Bramer's methods [24], and a second update was conducted on 15 August 2024 to incorporate additional terms identified during synthesis. Conference abstracts prior to 2020 and articles focused on DNA or tissue repair were excluded. Full search strings are detailed in Appendix D.

3.2.3.2 Eligibility Criteria

Studies were included if they addressed circularity or environmental sustainability of materials, devices, consumables, or products used clinically. Only review articles were analysed in full text; other study designs were included for preliminary bibliometric mapping. Exclusions applied to regenerative materials, tissue repair, and non-environmental sustainability topics.

3.2.3.3 Study Selection

References were imported into EndNote, and duplicates were removed by the information specialist following Bramer's methods[25]. Title and abstract screening were performed in Rayyan, a web-based systematic review tool.

- A pilot screening was performed collectively and individually on a subset of titles/abstracts to refine inclusion and exclusion criteria.
- Two researchers independently screened all remaining titles/abstracts, with discrepancies resolved by a third reviewer.
- Articles with uncertainty were discussed in team meetings to ensure consensus.
- Reasons for exclusion at the title/abstract phase are presented in the PRISMA chart (Figure 1).

Full-text review was conducted for 68 articles meeting inclusion criteria. Studies not meeting inclusion criteria during full-text review (e.g., reuse of surgical sites instead of materials) were excluded.

3.2.3.4 Data Extraction and Synthesis

A multi-stage data extraction process ensured accuracy and reliability:

- One researcher reviewed the full dataset.
- Two additional extractors performed quality assurance checks.
- A fourth extractor randomly verified 10% of studies.
- Discrepancies were resolved through team discussion.

Extracted data included:

- Article characteristics (title, year, journal, authors)
- Review method and objectives
- Object of interest (e.g., medical device, consumable, product)
- Sustainability or circularity terms and definitions

Prior to full-text synthesis, bibliometric analyses were conducted on all 1,104 articles using VOSviewer to visualize term occurrences, topic clusters, and co-authorship networks. A thesaurus was applied to standardize terms, remove irrelevant nouns, and identify co-occurrence patterns

For full-text review, two researchers independently recorded terms and definitions in an Excel file, labelling them as ‘clear definition’, ‘unclear definition’, or ‘no definition’. Terms with unclear definitions were counted but excluded from detailed analysis. Discrepancies were resolved in team meetings until 100% consensus was achieved.

All extracted terms and definitions were compared to established healthcare regulations (MDR-EU 2017/745 [16], FDA [26]), standards (Waste Framework Directive [27], ISO 59004:2024 [13], UNEP-IRP [10]), and circular economy frameworks (Butterfly Diagram [7], 10R framework [8], Value Hill [9]). Overlapping terms were merged, divergent definitions were reevaluated, and insights directly informed the sequencing and development of healthcare-specific definitions in the visual taxonomy.

3.2.4 Validation with Experts

Validation aimed to confirm that the final visual taxonomy is accurate, operationally relevant, and aligned with stakeholder perspectives. The visual taxonomy (version in Appendix E) was validated with 11 stakeholders across diverse domains, including circular economy project management, circular business models, circular design, medical device sterilization, and sustainable procurement. All feedback was collected via email, stored, and analysed in a local file. Conflicting feedback from stakeholders was resolved through team discussions, prioritizing alignment with healthcare-specific requirements, CE principles, and patient safety considerations. Iterative validation cycles ensured that the final visual taxonomy integrated all relevant input while maintaining conceptual consistency. The Circular Healthcare Flows visual was updated iteratively and re-shared with the same stakeholders until no further comments remained. After finalizing all content-related aspects, the graphic design was refined and evaluated using the collaborative dimensions framework [21] to optimize clarity, focus, modifiability, and usability.

The combination of observational research, expert interviews, systematic literature review, and stakeholder validation produced a healthcare-specific, evidence-based visual taxonomy. Iterative refinement cycles and structured evaluation using the Collaborative Dimensions Framework strengthened both conceptual rigor and the visual’s practical clarity.

3.3 Results

3.3.1 Observational Research and Expert Interviews

Observations helped identify process steps per CE strategy and their variations, particularly in decontamination processes (cleaning, disinfection, sterilization). Despite location differences, a consistent pattern emerged, shaping the initial Circular Healthcare Flows visual (Appendix A), later refined through expert interviews.

Analysis of the 214 coded quotations from the expert interview transcripts revealed key insights. The responses were categorized as follows: 60 general comments, 10 related to collection, 9 on depollution processes, 4 on part recovery, 18 discussing recycling, 4 focused on repurposing, 80 on sterilization, and 29 addressing terminology. Overall, participant feedback was largely positive, but experts emphasized the need to clarify how decision-making and hierarchy were represented after collection, stating that “it should better reflect the hierarchy of flows to aid decisions.” Several

also highlighted the importance of step sequencing, e.g., “disinfection happens after collection,” “melting is always the final recycling step,” and “repairs occur after sterilization.” Terminology confusion was a recurring issue, mentioned in all but one interview, with comments such as “we don’t use ‘reprocessing,’ we just say sterilization,” and “definitions are not yet uniform.” One participant remarked, “it is really easy to use the wrong definition,” highlighting the ambiguity of CE terms in healthcare.

These insights directly informed refinements to the Circular Healthcare Flows visual (Appendix C), guiding adjustments to process sequencing, hierarchy representation, and incorporation of clearly defined, standardized CE terminology. This also motivated the subsequent systematic literature review, which aimed to resolve terminology inconsistencies and support evidence-based updates to both the visual and its strategy definitions.

3.3.2 Systematic Literature Review

As shown in the PRISMA chart in Figure 5, for the bibliometric analysis, 1,104 articles were included for bibliometric analysis, and 68 review articles were analysed in full to clarify terminology inconsistencies in CE strategies.

3.3.3 Preliminary Bibliometric Analysis in VOSviewer

A bibliometric analysis of 1,104 articles from the first search phase provided an overview of key terms, co-occurrence patterns, and author networks in healthcare circular economy literature. Figure 6 visualizes term co-occurrence, revealing three distinct clusters: red (right), focusing on the environmental footprint, industrial production, waste disposal, and recycling; green (upper left), centring on cleaning, decontamination, and reprocessing; and blue (lower left), relating to specific medical devices, specialties, and adverse events associated with reprocessing. Reprocessing, reusability, and recycling as the most prevalent circular economy strategies. The interactive term graph is available here: https://tinyurl.com/yoqxqoys.

The author network analysis showed many distinct research groups, with prolific contributors such as F. McGain, R.A. Kozarek, and M.Th. Linner. While some authors bridge groups, the network remains fragmented. The interactive author graph can be accessed here: https://tinyurl.com/yusqnwff.

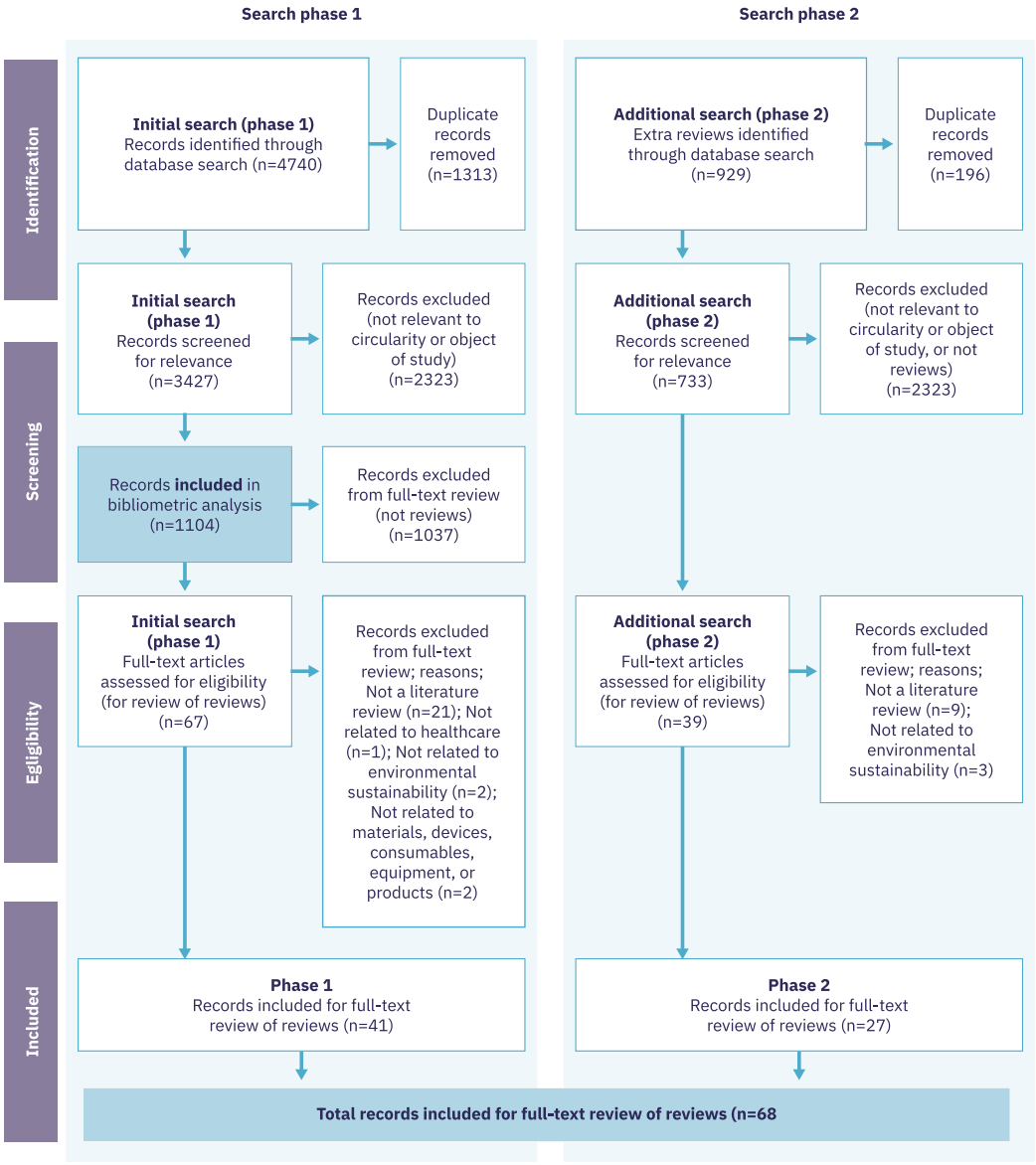


Figure 5: PRISMA Flow Diagram for the Scoping Review Process. Adapted from: Peters et al. 2015; Joanna Briggs Institute Reviewers' Manual

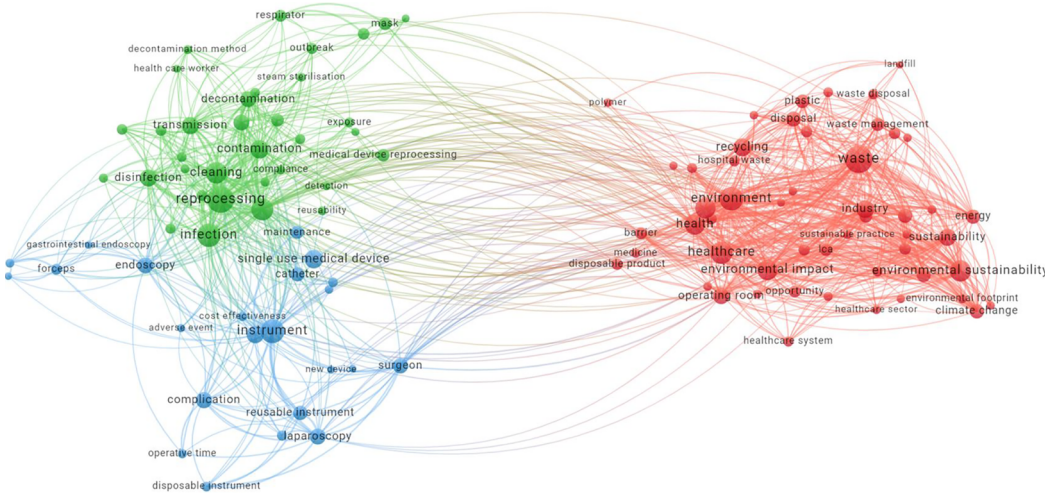


Figure 6: Co-Occurrence of Terms Visualised in VOSviewer

3.3.4 Full-Text Analysis of Review Articles

The 68 review articles covered various topics, with some addressing multiple subjects (see Appendix F). The analysis identified 27 CE strategy terms and labelled them according to frequency, definitions, and overlaps. Only terms with full team consensus were included for comparison. A summarized version of these terms is presented in Table 8, showing the term, frequency (n=68, as also displayed in Figure 7), key elements from healthcare literature definitions, established definitions, and integration into the final visual taxonomy. The full set of all extracted definitions for each term, including all variations from healthcare literature, healthcare bodies, non-health organizations, and circular economy frameworks, is provided in Appendix G. Table 8 illustrates that common strategies—such as reuse, reduce, recycle, repair, and maintain—are frequently discussed and directly included in the visual taxonomy, whereas other terms, including prevent, (re)design, closing loops, and research, were either too broad, overlapping, or lacked clear standalone definitions, and were therefore scaled under other strategies or excluded as independent strategies.

While some strategies, such as recycle, are frequently mentioned in the literature, their priority in established CE frameworks (e.g., the 10R hierarchy, Butterfly Diagram) does not always align with frequency. To address this, the final Circular Healthcare Flows visual balances the frequency of terms in literature with framework-based prioritization. Strategies like refuse and reduce are positioned higher in the hierarchy to reflect sustainability impact and practical relevance, even if they are less frequently cited. This ensures that the taxonomy represents both evidence from literature and operational priorities in healthcare CE decision-making.

Table 8: Condensed Summary of 27 Healthcare Circular Economy (CE) Strategy Terms Identified from 68 Review Articles.

Frequency (n=68), key elements from healthcare literature definitions, established definitions (healthcare bodies / non-health organizations / circular economy frameworks), and integration into the final visual taxonomy are shown. Abbreviations used: FDA = U.S. Food and Drug Administration, MDR = EU Medical Device Regulation, WFD = Waste Framework Directive, ISO = International Organization for Standardization, EMF = Ellen MacArthur Foundation, PBL = Netherlands Environmental Assessment Agency, VH = Value Hill.

Term used for CE strategy	Mentioned by # of articles; n=68	Key elements from healthcare literature definitions	Established definitions (healthcare bodies / non-health organizations / CE frameworks)	Integration into visual taxonomy
Reuse	62	Reuse devices/materials after decontamination; multiple patients; single-patient reuse; materials reuse	FDA/MDR: reusable devices can be reprocessed and reused; WFD/ISO/UNEP/EMF/ PBL: similar definitions	Included: 5th strategy
Reduce	54	Reduce waste, resources, environmental impact, unnecessary care, unsustainable devices, chemicals/toxins	PBL: increase efficiency, consume fewer resources	Included: 4th strategy
Recycle	53	Recover raw material through processing: decontaminate, shred, melt, remould	FDA/WFD/ISO/UNEP/ EMF/PBL/VH: processing of waste into new products/materials	Included: 11th strategy
Reprocess	48	Decontaminate, clean, sterilize; prepare used devices for reuse	MDR/FDA: safe reuse including cleaning, disinfection, sterilization	Overarching term: reuse, maintain, repair, refurbish, remanufacture
Prevent	32	Prevent unnecessary care, device use, waste, infection, environmental impact	WFD: measures to reduce waste/impact before product becomes waste	Partially grouped: under refuse, replace, reduce; not independent
(Re)design	32	Design for sustainability/ circularity, sterilization, waste reduction, recyclability, durability, eco-design, modularity, maintenance, refurbishment, end-of-life	ISO: eco-design and circular design; VH: design for end-of-life	Partially grouped: under other strategies (too broad)
Replace	31	Substitute devices, materials, or procedures with more sustainable alternatives, digitization, parts replacement	No formal definitions	Included: 2nd strategy
Maintain	23	Preventive/corrective maintenance, lifetime extension, maintain value, clinical environment	FDA/EMF/PBL/VH: service, repair, retain product value	Included: 6th strategy

Repair	22	Recover functional obsolescence, extend product life, corrective maintenance	FDA/ISO/UNEP/EMF/PBL/VH: restore product to intended function	Included: 7th strategy
Remanufacture	19	Restore used equipment to “as new” or better condition, cleaning, renovation, quality control	FDA/ISO/UNEP/EMF/PBL/VH: industrial restoration to like-new condition	Included: 9th strategy
Rethink	18	Make systems/processes more environmentally sustainable, e.g., patient transport, purchasing, telemedicine, packaging; change beliefs/practices	PBL: increase product use intensity (sharing, multifunction)	Included: 3rd strategy
Renew	17	Renewable energy, biodegradable materials, remanufacturing	ISO/EMF: renewable energy/materials	Included: 12th strategy
Repurpose	15	Use discarded products for different purposes, contexts, locations; maximize product life	ISO/PBL: adapt product or parts for different function	Included: 10th strategy
Refurbish	13	Transform obsolete products to contemporary standards while maintaining intended use	MDR/ISO/UNEP/EMF/PBL/VH: restore functionality, quality, performance	Included: 8th strategy
Biodegrade	11	Biodegradable polymers, coatings, medications, energy recovery	EMF: natural breakdown into CO_2, water, biomass	Grouped: under renew
Refuse	10	Avoid unnecessary devices, procedures, consumption, disposal	PBL: make product redundant, abandon function or radically change product	Included: 1st strategy
Restore	9	Restore value, repair product/material, restore trust	None	Grouped: under repair
Closing loops	9	Develop value from waste, minimize waste, circular analogy	ISO: closed-loop system	Excluded: encompassed by other strategies
Research	8	Life cycle analyses, green device development, cost comparisons, renewable energy, lean & 6-sigma methods	None	Excluded: too broad
Retain	5	Retaining value, recycling, product use over time	None	Partially grouped: under maintain; remainder disregarded
Regenerate	4	Regenerative medicine, regenerating natural systems	ISO/EMF: improve/restore ecosystems, regenerative production	Grouped: under renew
Redistribute	4	Divert product to other customers or contexts	EMF/VH: enable reuse at high value	Grouped: under reuse/remanufacture

Share	3	Shared use of products or equipment	EMF/VH: multiple users sequentially, increase utilization	Grouped: under rethink
Resterilise	2	Sterilizing again for reuse	None	Grouped: under processes requiring sterilization
Slowing loops	1	Durable design, product longevity	None	Excluded: broad, overlapping
(Bio)remediate	1	Chemical recycling by microbial action; shared use (note: healthcare literature example included)	EMF: shared use; chemical recycling	Grouped: under renew

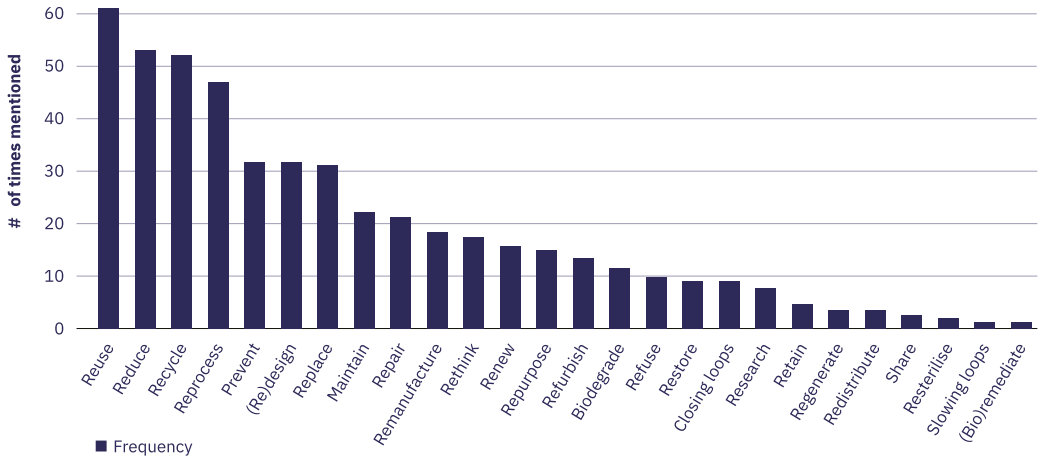


Figure 7: Term Mentioned by # of Reviewed Articles (n=68)

3.3.4.1 Synonymous use of terms

The reviewed articles often indicated an overlap of definitions for the terms found, as shown in Table 9 and Figure 8. Examples of citations labelled as synonymous use of terms are: "medical device reprocessing, or 'remanufacturing', refers to …" [28], "… and remanufactured (a.k.a. reprocessed) medical devices …" [29], and "repair/refurbishment" [30]. For the terms not included in Table 9, no synonymous use was detected. For reprocess and repair, up to four alternative terms were used as synonyms. Notably, reuse, remanufacture, repair, and recycle were also used interchangeably with reprocess. Similarly, repair was described as synonym of maintain, prevent, and refurbish, and retain and recover were frequently used interchangeably. Additionally, some articles labelled specific terms as "R-strategies," including reduce (6 mentions), research (5), rethink (4), reuse (2), and renew (1).

3.3.4.2 Congruence with Established Definitions

Healthcare literature definitions were compared with previously established ones. No definitions were found for terms like replace, restore, research, retain, resterilise, slowing loops, and (bio) remediate. Terms with fewer than four occurrences or unclear definitions, like closing loops and biodegrade, were not compared. Among terms with multiple definitions, most shared key elements with established definitions but varied in emphasis or context. High congruence was found for repair, recycling, and renew, while reuse and refurbish were largely consistent, though healthcare-specific nuances exist.

For example, healthcare reuse often refers to use of a device across multiple patients, where each patient counts as a separate reuse even if the same healthcare worker uses the device multiple times. In contrast, established CE definitions consider reuse as occurring only when a device is used by different users; multiple patients served by the same user typically count as a single reuse event. Refurbish definitions mostly align with established ones, except for the EU-MDR 2017/745 [16] definition, which is closer to remanufacturing.

Table 9: Terms Utilized as Synonyms in Healthcare Literature, with Darker Squares Representing Where More Synonymous Use Was Found.

	Reuse	Reduce	Recycle	Reprocess	Prevent	(Re)design	Replace	Maintain	Repair	Recover	Remanufacture	Rethink	Renew	Refurbish	Refuse	Restore	Retain	Regenerate	(Bio)remediate
Reuse	NA	0	1	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reduce	0	NA	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recycle	1	0	NA	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Reprocess	6	0	1	NA	0	0	0	0	1	1	2	0	0	0	0	0	0	0	0
Prevent	0	1	0	0	NA	0	0	2	1	0	0	0	0	0	1	0	0	0	0
(Re)design	0	0	0	0	0	NA	0	0	0	0	0	2	0	0	0	0	0	0	0
Replace	0	0	0	0	0	0	NA	0	0	0	0	0	0	0	1	0	0	0	0
Maintain	0	0	0	0	2	0	0	NA	6	0	0	0	0	0	0	0	0	0	0
Repair	0	0	0	1	1	0	0	6	NA	0	0	0	1	1	0	2	0	0	0
Recover	0	0	1	1	0	0	0	0	0	NA	0	0	0	1	0	2	5	0	0
Remanufacture	0	0	0	2	0	0	0	0	0	0	NA	0	1	3	0	0	0	0	0
Rethink	0	0	0	0	0	2	0	0	0	0	0	NA	0	0	2	0	0	0	0
Renew	0	0	0	0	0	0	0	0	1	0	1	0	NA	0	0	0	0	2	0
Refurbish	0	0	0	0	0	0	0	0	1	1	3	0	0	NA	0	0	0	0	0
Refuse	0	0	0	0	1	0	1	0	0	0	0	2	0	0	NA	0	0	0	0
Restore	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	NA	0	0	0
Retain	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	NA	0	0
Regenerate	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	NA	0
(Bio)remediate	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NA

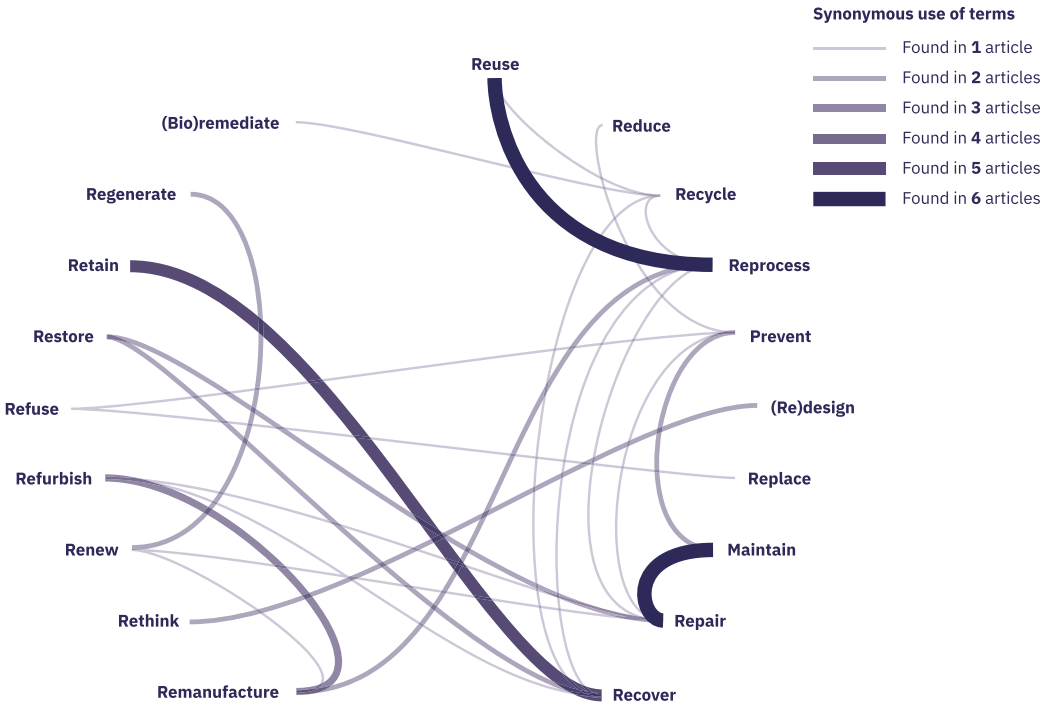


Figure 8: Visualization of Synonymous Use of Terms in Healthcare Literature.

The term recover generally aligned well with established definitions, which focus on energy recovery or resource collection, rather than retaining products or product value. Terms with medium congruence included reprocess, reduce, (re)design, prevent, maintain, remanufacture, and repurpose. Established definitions for reprocess found in healthcare regulations (e.g. MDR-EU 2017/745 [16] and FDA medical device regulation [15]) describe decontamination as a part of reprocessing but do not specifically address single-use devices, whereas healthcare literature does. Other terms, like reduce and (re)design, show healthcare-specific contextual differences. For instance, (re)design often includes decontamination considerations, and prevent encompasses infection and unnecessary procedures. Remanufacturing definitions were covered by established definitions despite variability in usage. Repurpose definitions vary in healthcare literature, describing changes in product function, context, or location, while established definitions focus solely on function changes.

Lastly, some terms showed low congruence among established definitions themselves. For example, in the Butterfly Diagram, remanufacturing can be interpreted as the re-engineering of products to an as-new condition [31], while in the 10R-strategies, remanufacturing refers to using parts of a discarded product in a new product [8], which the MDR-EU 2017/745 [16] describes as refurbishment.

3.3.4.3 CE Strategy Process Timeline and Hierarchy

In addition to highlighting the divergence in the use of terms and definitions surrounding CE strategies in healthcare literature, the analysis provides insights for the visual taxonomy regarding timing and sequence of strategies. These details, however, exhibit notable variability across

sources. For example, one article states that "Reprocessing is decontamination using disinfection or sterilization methods followed by reuse" [32], suggesting that reuse follows reprocess, while other sources describe reprocess as including reuse or occurring as part of recycle and remanufacture processes. Similarly, repair is sometimes described as part of refurbish, repurpose as an enabler of reuse, refurbish as an enabler of recover, redistribute as part of reuse and/or remanufacture, and recycle as a method to retain value. Terms like closing loops and slowing loops are also mentioned in conjunction with other strategies, but their relationship to reuse and recycling varies across sources. Additionally, the hierarchy of strategies in CE frameworks does not always align with term frequency in literature. For example, the Value Hill [9] prioritizes prevent, while the 10R-strategies[8] emphasize refuse and reduce. While prevent and reduce occur frequently, refuse, the highest strategy on the 10-R hierarchy [8], does not. Conversely, recycle, a commonly used strategy term in literature, is considered a lower priority in frameworks such as the Butterfly Diagram [7].

3.3.5 Final Visual Taxonomy

Based on observational research, expert interviews, a systematic literature review, and expert stakeholder validations, the final visual taxonomy was developed (Figure 9). A practical application of this visual taxonomy to a real-world healthcare device—the endoscope—is provided in Appendix H, demonstrating how the framework can guide circular economy decision-making across a device lifecycle. During content validation, the Circular Healthcare Flows visual iteration refined through the literature review (Appendix E) was validated and adjusted using expert feedback. For example, hospital sterilization staff refined decontamination steps, supply chain experts verified sequencing, and a designer integrated seven dimensions from the Collaborative Dimensions of Visualisations framework [21].

The taxonomy presents 13 healthcare-specific CE flows, each with steps and explanations. It introduces a standardized set of CE strategy definitions to reduce terminology inconsistencies in healthcare. These definitions are provided in Table 10, which aligns the strategies with established sustainability principles and incorporates healthcare-specific nuances. The visual depicts a linear economy supply chain (grey boxes) with 13 hierarchical flows connected by arrow loops. Each step includes explanations, likely stakeholders, expected transport needs, potential material leakage, and possible transitions between flows.

Table 10: Proposed Healthcare-Specific Definitions for CE Strategies

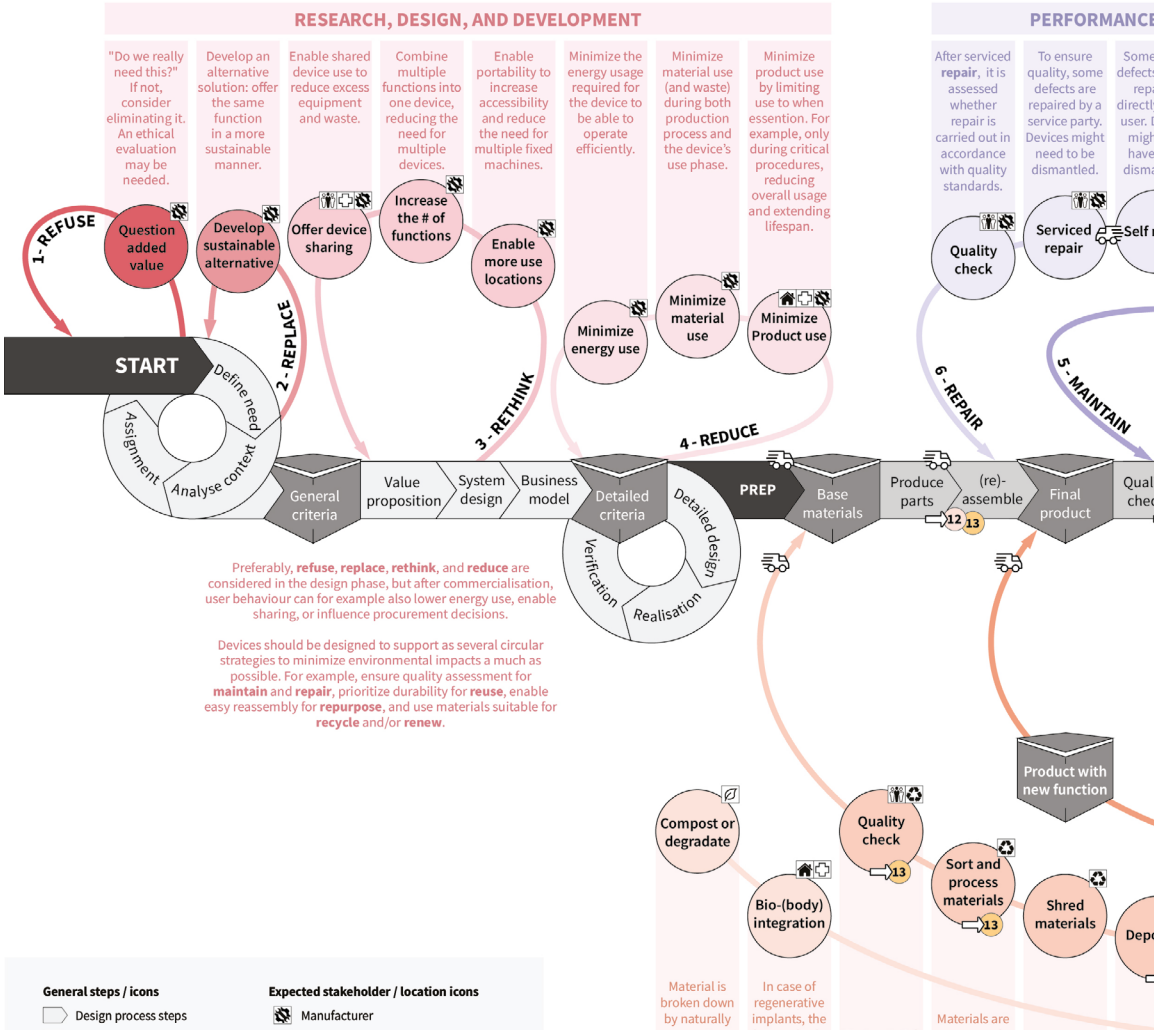
Terms	Healthcare-specific definitions
Refuse	The intentional act of rejecting the production, consumption, or use of a medical product, material, or procedure, particularly those that are unnecessary, unsustainable, or harmful.
Replace	Substituting a medical product or procedure with an alternative that serves the same purpose but significantly reduces environmental impact.
Rethink	Systemically enhancing the procedures surrounding product use to drive environmentally sustainable practices, such as through rethinking patient transport and telemedicine, sharing products or introducing multifunctionality.
Reduce	Increasing efficiency in healthcare delivery and medical product manufacturing by minimising energy use, resources use and waste generation at the source, avoiding unnecessary production or consumption, limiting hazardous substances, and carefully minimising (unnecessary) procedures to meet healthcare needs.

Reprocessing	Reuse	Repeated use of a medical device on multiple patients for the same intended purpose, after decontamination when needed, and without significant modification.
	Maintain	Preserving the quality, function, and safety of medical products and clinical environments to ensure reliable performance, extend their lifespan, and reduce the risk of malfunctions that could lead to potential treatment failures.
	Repair	Restoring a faulty or broken product or component to a usable state to fulfil its intended use, which typically involves corrective maintenance, ensuring that safety and performance specifications are met for an extended period of time.
	Refurbish	Restoring a product to good working condition through decontamination, repairs, upgrades, cosmetic changes, performance checks, reinstallation, warranty assurance, and parts replacement.
	Remanufacture	Restoring products and components, often utilizing parts from discarded products for the same function, to achieve as-new condition through disassembly, decontamination, quality control, certification, repackaging, and redistribution.
	Repurpose	Using discarded products or parts for different purposes than originally intended, such as in varied contexts (e.g. veterinary care procedures), purposes (e.g. different human procedures) and locations (e.g. developing countries).
	Recycle	Transforming waste materials from used products or resources into new raw materials, either of the same or lower quality, through e.g. decontamination, shredding, and moulding
	Renew	Transforming waste materials, energy sources, and other substances into basic elements like carbon dioxide, water, biomass, or human tissue (for regenerative medicine) through natural processes.
	Recover energy	Incineration (or medical incineration) of waste materials with energy recovery.

The process of developing the definitions in Table 10 is further explained in section 3.3.5.1. The table presents terms and definitions derived from literature, aligned with sustainability principles while reflecting healthcare-specific nuances. While the hierarchy is informed by the 10R-strategies, which prioritize sustainability actions based on impact and product integrity [8], it also reflects the timeline of processes in practice. In healthcare, maintenance and repair were placed higher than reuse because they often occur periodically during the use cycle rather than after use. Additionally, section 3.3.5.2 explains how insights from the collaborative dimensions framework [21] were integrated into the graphic design of the visual.

3.3.5.1 Development of Healthcare-Specific CE Strategy Definitions

To minimize confusion, several terms were not directly included in the list of definitions: prevent, research, closing loops, slowing loops, and redistribute. These terms were either too broad, overlapping with other strategies, or lacked a clear, standalone definition in the context of sustainability. For example, while preventive healthcare is essential for reducing environmental impact, the term prevent was deemed too broad to represent a single sustainable strategy, as it could also encompass preventing environmental damage and waste. Similarly, (re)design could apply to various contexts, such as redesigning a product for any strategy, replacing a product, or reducing energy consumption, making it too vague. Research and redistribute were also part of other strategies rather than being standalone. Finally, closing loops and slowing loops were excluded because they encompass multiple strategies.



1 - Refuse

The intentional act of rejecting the production, consumption, or use of a medical product, material, or procedure, particularly those that are unnecessary, unsustainable, or harmful.

2 - Replace

Substituting a medical product or procedure with an alternative that serves the same purpose but significantly reduces environmental impact.

3 - Rethink

Systemically enhancing the procedures surrounding product use to drive environmentally sustainable practices, such as through rethinking patient transport and telemedicine, sharing products or introducing multifunctionality.

4 - Reduce

Increasing efficiency in healthcare delivery and medical manufacturing by minimising energy and resource use, avoiding unnecessary production or consumption, limiting hazardous substances, and minimising (unnecessary) procedures.

5 - Maintain

Preserving the quality, function, and safety of medical products and clinical environments to ensure reliable performance, extend their lifespan, and reduce the risk of malfunctions that could lead to potential treatment failures.

6 - Repair

Restoring a faulty or broken product or component to a usable state to fulfil its intended use, which typically involves corrective maintenance, ensuring that safety and performance specifications are met for an extended period of time.

7 - Reuse

Repeated use
device on mul
for the same i
purpose, after
decontaminati
needed, and w
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AR HEALTHCARE FLOWS (CHF)

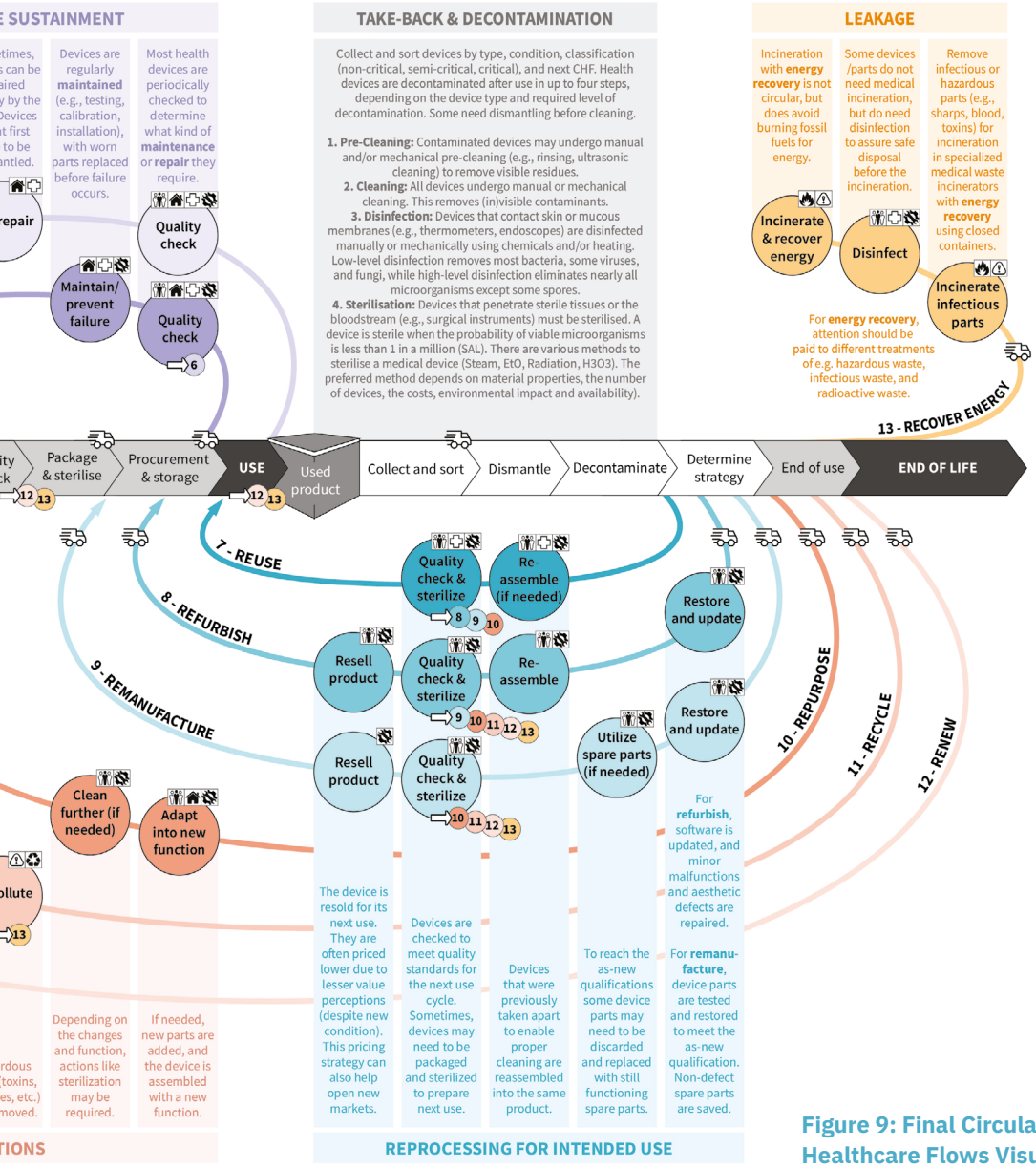


Figure 9: Final Circular Healthcare Flows Visual

8 - Refurbish
Restoring a product to good working condition through decontamination, repairs, upgrades, cosmetic changes, performance checks, reinstallation, warranty assurance, and parts replacement.

9 - Remanufacture
Restoring products and components, often utilizing parts from discarded products, to achieve as-new condition through disassembly, decontamination, quality control, certification, repackaging, and redistribution.

10 - Repurpose
Using discarded products or parts for different purposes than originally intended, such as in varied contexts (e.g. veterinary care procedures), purposes (e.g. different human procedures) and locations (e.g. developing countries).

11 - Recycle
Transforming waste materials from used products or resources into new raw materials, either of the same or lower quality, through e.g. decontamination, shredding, and moulding

12 - Renew
Transforming waste materials, energy sources, and other substances into basic elements like carbon dioxide, water, biomass, or human tissue (for regenerative medicine) through natural processes.

13 - Recover energy
Incineration (or medical incineration) of waste materials with energy recovery.

To further improve comprehension of definitions in the visual taxonomy, terms with similar meanings were consolidated. For instance, based on the review analysis, part of retain was scaled under maintain, share under rethink, and restore under repair. All processes that referred to the bio-cycle as described by EMF [33] (renew, biodegrade, regenerate, and (bio)remediate), were scaled under renew.

Despite its frequent use in healthcare literature, reprocess has significant divergence in its meaning. Likely derived from processing, as defined in ISO 17664:2021 (preparing new or used healthcare products for intended use), reprocessing typically refers to preparing used products after the use cycle for the same purpose in a next use cycle.

This includes processes like reuse, refurbish, and remanufacture but not maintain and repair (as those take place during the use cycle), or repurpose and recycle (as those will not result in a product used for the same purpose). This aligns with established definitions and review findings, where decontamination is emphasized in healthcare but is not the only step. Due to its widespread use, reprocess was included as an overarching term in the framework. More specific subcategories are recommended to reduce terminology confusion and foster interdisciplinary collaboration.

3.3.5.2 Improvement of Visual Communication

The Circular Healthcare Flows visual was optimized for utilization in multidisciplinary collaboration following the different dimensions of the Collaborative Dimensions of Visualisations framework [21]. Table 11 explains the meaning of each dimension and how it was adopted into the design of the visual taxonomy.

Table 11: Design Integration of Collaborative Dimensions Framework (based on Bresciani et al [21])

Dimension	Original definition	Contextual Translation	Application in Visual
Structural restrictiveness	Extent to which the design process is guided or constrained by the visualization.	Visual design should enable healthcare professionals and stakeholders, including medical device developers, to uncover new insights about interconnections and potential process optimizations within the circular economy framework, specifically highlighting hierarchical flows and critical CE steps in healthcare contexts.	Integrated visual cues, such as hierarchical, iterative arrow loops and transition icons, encourage users to draw conclusions about possible systemic steps and process enhancements, effectively bridging theory and practical implications.
Content modifiability	Extent to which the items of a visualization can be dynamically changed.	Visual is intentionally designed with low modifiability to ensure consistency, reliability, and standardization in healthcare CE discussions. It is a fixed reference that cannot be altered by individual users. Instead, users can customize which steps are relevant to the device being considered, but the overall structure remains unchanged.	The visual is a structured, validated reference that prevents ad-hoc modifications while still allowing periodic expert-driven updates. This ensures users rely on a stable framework for decision-making rather than making individual, unverified alterations.

Directed focus	Extent to which the main item(s) of the discussion is visually emphasized.	Visual should highlight the most critical elements of the CE strategies—such as key decision nodes that determine circularity success—to guide stakeholder focus during discussions. Emphasis is placed on post-use decision points relevant to both healthcare workflows and medical device lifecycle decisions.	Strategic use of contrasting colours and focal markers (for instance, accentuating the start of the timeline) directs attention to essential steps and facilitates focused dialogue on process improvements.
Perceived finishedness	Extent to which visual cues suggest whether an object appears finished.	Visual must appear professionally refined (and thus "finished") to build trust among healthcare stakeholders, reflecting the rigorous validation by hospital, MedTech, and design experts. A polished appearance reassures clinical, administrative, and device development audiences of reliability.	The visual design is highly refined, with consistent use of design elements such as colour, font, and layout. There are no unfinished sketches or ambiguous elements. The design appears as a finished, standardized product that inspires confidence.
Outcome clarity	Extent to which a visual representation is self-explanatory and easily understandable with low cognitive effort.	Visual should be clear and intuitive, providing a straightforward representation of the CE process for medical devices with minimal explanation required. Healthcare staff and medical device developers can quickly interpret processes and decision points without specialized CE training.	Simple icons, colour coding, and a logical flow from one step to the next help viewers quickly understand the CE process without confusion. Minimal attention is drawn to the explanatory texts and clear labelling is used to ensure ease of understanding.
Visual appeal	Extent to which a visual representation is attractive and pleasant to the eyes.	Visual must be visually compelling to effectively engage stakeholders and support their understanding of CE processes for medical devices. This includes clear, intuitive layout and colour coding for different flows.	Iconography (e.g., for stakeholder location and need for transportation) is used alongside dynamic arrow loops connecting 13 flows, ensuring key messages are memorable.
Collaboration support	Extent of the control over the flow of the group discussion which is exercised by a visualization.	Visual should facilitate structured discussions among healthcare stakeholders by providing a shared reference point for decision-making. Supports interdisciplinary alignment in hospital, MedTech, and device development CE initiatives.	The standardized visual ensures consistent terminology and process clarity, reducing misinterpretation. Its structured layout guides CE discussions without the need for modifications, using icons and color-coded segments to highlight key stages for easy reference.

3.4 Discussion

While circular economy (CE) strategies are increasingly discussed in the healthcare sector, existing models—such as the Butterfly Diagram[7]—often lack the specificity needed for contexts with strict regulatory and operational constraints. This, together with inconsistent use of terms

like reuse, reprocess, refurbish, and remanufacture, creates confusion and can hinder effective implementation. To address this challenge, this paper aimed to provide conceptual clarity by harmonizing terminology in healthcare contexts. It introduced the Circular Healthcare Flows visual taxonomy: an operationalization of CE frameworks that categorizes strategies for the physical flow of products and materials in healthcare.

Observational research, stakeholder interviews, bibliometric analysis, and literature review each informed the Circular Healthcare Flows visual. Observations in hospitals and production sites uncovered healthcare-specific process nuances, such as sterilization steps and material handling, which guided the inclusion of key workflow elements in the visual. Expert interviews highlighted inconsistencies in terminology and practical usability challenges, shaping updates to definitions, labelling, and visual layout. Insights from the bibliometric analysis helped clarify relationships between CE terms and highlighted sector-specific interpretations in healthcare literature. The systematic literature review enabled standardization of definitions and alignment with established CE hierarchies. By linking these insights with the other data sources, the taxonomy was iteratively refined to be conceptually clear, practically usable, and tailored to the specific regulatory, clinical, and operational requirements of healthcare. The results highlighted confusion between the terms. For example, in interviews and healthcare literature, terms like reprocess were often used interchangeably with reuse, repair, and remanufacture, despite representing distinct processes in established sustainability frameworks. Additionally, the bibliometric analysis highlighted inconsistencies in how CE terms are used across healthcare literature, further supporting the need for a standardized set of definitions. These observed inconsistencies directly guided the categorization and definition of terms in the Circular Healthcare Flows visual, ensuring that the taxonomy reflects both conceptual clarity and practical applicability. For example, the taxonomy treats reprocessing as an overarching category encompassing reuse, repair, refurbish, and remanufacture, while remaining distinct from processes like repurpose or recycle.

The final visual taxonomy builds on and refines existing CE frameworks, including the Butterfly Diagram [7], 10R framework [8], Value Hill model [9], and UNEP's Re-defining Value report [10]. It extends these frameworks by adapting their CE strategies to healthcare, clarifying terminology, and mapping flows to reflect operational, clinical, and regulatory considerations. This underscores that CE strategies cannot be applied uniformly across sectors but must be adapted to incorporate sector-specific processes and requirements to balance circularity with safety and compliance. Additionally, although hierarchical models like the 10R framework [8] or Butterfly Diagram [7] suggest higher-order strategies such as refuse or rethink are always preferable, previous work [34] shows they do not consistently achieve lower environmental impacts than downstream options like repair or remanufacture. Therefore, while the Circular Healthcare Flows visual does present a hierarchy to organize strategies conceptually, it is not intended as a strict ranking of environment or operational benefit. Rather, it supports context-sensitive decision-making based on operational, clinical, and regulatory factors.

Beyond its conceptual value, the Circular Healthcare Flows visual has the potential to hold practical contributions, depending on the taxonomy being widely accepted and adopted. For medical device designers, it offers a structured approach to integrate circularity principles early in the design process, ensuring that products are circularly designed from the outset. Hospital procurement teams can use it to distinguish between suppliers offering reuse, refurbishment, or remanufacturing services, reducing ambiguity and aiding regulatory compliance. Clinical staff, such as nurses and sterile services technicians, gain a clearer understanding of reprocessing responsibilities and

steps, helping to standardize practices and ensure patient safety. Remanufacturers and third-party reprocessors can better align quality control documentation and compliance protocols with clearly defined categories, ensuring consistency across the sector. Policymakers and regulators can leverage the taxonomy to develop clearer, more targeted guidelines and regulations, reducing uncertainty around the application of CE strategies in healthcare. Finally, it can help facilitate collaboration between all these disciplines by helping create a common language.

By combining conceptual structure with practical guidance, the Circular Healthcare Flows visual connects theory and practice, addressing infection control, material flows, the roles of diverse stakeholders, and regulatory requirements in healthcare.

3.4.1 Limitations

While this study develops and validates a visual taxonomy framework for circular economy (CE) strategies in healthcare, several limitations should be acknowledged. The analysis primarily relied on literature synthesis and expert input, which, although valuable, may not fully capture real-world complexities. Feedback from healthcare professionals, policymakers, and sustainability experts enhanced the framework's robustness, yet its transferability across different healthcare systems requires further empirical validation. Therefore, the described use cases represent projected applications based on expert input rather than empirically tested outcomes. The review was limited to English-language sources, potentially excluding relevant insights. Moreover, the initial search strategy may have shaped the concepts identified; future studies could broaden these parameters and assess the framework across diverse contexts.

The study also does not fully account for contextual barriers to CE implementation, particularly in settings with limited infrastructure, resource constraints, or unclear regulatory environments. Restricted access to clean technologies and institutional capacity may further constrain adoption and scalability. In addition, behavioural and organizational dynamics—such as procurement practices, staff training needs, and resistance to reuse—pose further challenges to circular implementation. Addressing these structural, institutional, and behavioural barriers is essential for translating CE strategies into practical, context-sensitive solutions within healthcare.

3.4.2 Future Research

Future research could focus on validating the framework through real-world applications and expanded stakeholder engagement. Delphi panels are particularly suitable for this purpose, as they enable structured consensus-building among diverse expert stakeholders across healthcare, regulatory, and design domains [35], [36]. Building on this foundation, the framework is intended to serve as the conceptual backbone for developing a Circular Design Guide for healthcare, supporting decision-making on sustainable procurement, asset management, and waste reduction. Future studies should include pilot implementation studies in hospital procurement, device lifecycle management, and clinical workflows to empirically evaluate the usability, adoption, and operational impact of the taxonomy. This guide could be integrated into decision-support systems, such as public procurement guidelines, hospital management software, or regulatory assessment frameworks, to enable actionable implementation of circular strategies. Future studies should therefore explore pathways for such integration and evaluate the usability, policy relevance, and operational impact of these tools in diverse healthcare settings. Empirical

research should also assess how adoption of the framework influences collaboration, decision-making, and compliance with circular economy objectives across healthcare systems. Additionally, the potential of the Circular Healthcare Flows visual as an educational and training tool could be explored, helping staff across clinical, operational, and administrative roles to understand and apply circular economy strategies in daily practice.

3.5 Conclusion

This study addresses an important gap in healthcare: the confusion created by inconsistent and conflicting terminology around circular economy (CE) strategies. It proposes a sector-specific visual taxonomy to standardize CE terminology for healthcare. Grounded in a systematic review, expert interviews, and observational research, it clarifies terms such as reuse, repair, reprocess, remanufacture, and refurbish to improve communication and decision-making. Inspired by broader frameworks such as the Butterfly Diagram or 10R model, this taxonomy translates CE principles into a healthcare-specific framework that reflects regulatory and clinical considerations. It supports policy development, practical implementation, and stakeholder awareness, enabling consistent integration of circularity into design, procurement, and use. Ultimately, if widely adopted in practice, it provides a foundation for measurable and scalable implementation of circular economy strategies across global healthcare systems.

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Author contributions

Hoveling led the conceptualization of the paper, developed the visual taxonomy, conducted stakeholder interviews, contributed to data analysis, and drafted the manuscript. Bakker and Faludi provided critical input in refining the taxonomy based on expert feedback. The systematic literature review was conceptualized by Hoveling, Diehl, van Raaij, and Hinrichs-Krapels, with Bramer leading the search strategy. Ijzenbrandt screened abstracts and conducted the initial review sample, while van Raaij performed the VOSviewer analysis. Article screening and analysis were carried out by Hoveling, Ijzenbrandt, van Raaij, Hinrichs-Krapels, Ritzen, Diehl, and Bramer.

All authors contributed to manuscript revisions and approved the final version.

Declaration of interests

The authors declare that there are no financial or personal relationships with other people or organizations that could influence the work presented in this manuscript. No conflicts of interest exist for any of the authors.

Declaration of generative ai in the manuscript preparation process

During the preparation of this work, the author(s) used ChatGPT (OpenAI) to find appropriate phrasing and improve clarity. After using this tool, the author(s) thoroughly reviewed and edited the content and take full responsibility for the scientific content and accuracy of the published article.

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PART III

designing in practice

PART III, Chapter 4

Chapter 3 clarified a major barrier to circular design: inconsistent terminology and fragmented understanding of circular strategies. By establishing a visual taxonomy of circular healthcare flows, it provided a shared framework for operationalizing circular principles across stakeholders.

Building on this foundation, Chapter 4 explores how these strategies can be applied in practice. A research-through-design case study was carried out using smart pillboxes. While these products are considered medical devices in some contexts (e.g., in the US), they are not classified as such under the EU Medical Device Regulation (EU-MDR). This lower-risk context allowed the study to experiment with circular strategies without the complexity and safety risks of higher-risk medical devices.

This chapter translates the insights from Chapter 3 into actionable design recommendations. It demonstrates how R-strategies — reduce, reuse, and recycle — can be embedded in medical device design, while also highlighting practical considerations and trade-offs, paving the way for the deeper exploration of trade-offs in Chapter 5.

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Chapter 4

Redesigning Health Devices for the Circular Economy: A Case Study on Smart Pillboxes

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Abstract—Like many health devices, smart pill boxes designed to enhance medication adherence often incorporate electronic components and smart sensors. However, the production and disposal of these rising numbers of electronics contribute significantly to the global e-waste crisis, exacerbating the negative climate impact of the healthcare industry. To minimize the impact of such electronic health devices, redesign based on circular economy principles is crucial. However, currently no clear circular design methodology exists to apply those principles in the healthcare domain. This paper discusses a case study in which we propose conceptual redesigns that aim to mitigate the environmental impact of smart pill boxes and help align them with circular economy principles. We employ a research-through-design approach in which we attempt to apply the well-known "10R strategies" (i.e. refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover) as a design method. While doing this, we assessed their applicability in a design process and added value in making the device circular through reflective journalling, and their estimated effectiveness on minimizing environmental impacts by comparing fast-track LCAs for each design decision. In this way, we were able to provide insights into the intricacies of designing a more sustainable and circular device in this manner, and subsequently formulate recommendations for designing similar devices in the future.

Keywords: Circular Economy, Sustainable Design, Life Cycle Assessment, Medication Adherence

4.1 Introduction

In 2022, the Dutch National Institute for Public Health and Environmental Protection (RIVM) calculated that the healthcare sector accounts for approximately 7% of global greenhouse gas emissions [1]. There are several causes for this high impact, one of them being the rapid digitalization of health devices. A worrying development, with electronic waste (e-waste) being one of the fastest growing waste streams in the world [2]. This not only poses immediate hazards but also undermines long-term sustainability efforts.

To ensure the long-term benefits of electronic components integrated into healthcare devices, it is imperative to mitigate the environmental impact of digitization. A possible opportunity in achieving this is embracing the principles of the circular economy, which minimize waste and environmental impact through "an economic system that replaces the 'end-of-life' concept with

reducing, alternatively reusing, recycling and recovering materials" [3]. However, the transition of health devices to such a system requires a fundamental shift in design practices. While literature underscores the significance of design in facilitating the circular economy transition [4], and even provides some potential "strategies for recovery of circular medical products" [5], due to mostly safety-related challenges it is currently hard to apply circular design methods in the healthcare domain.

Existing sustainable design strategies such as life cycle assessment and eco-design offer valuable guidance focused on minimizing environmental impacts [6], but may overlook critical healthcare-specific considerations, such as contamination risks, patient safety concerns, and the complex regulatory landscape. Therefore, it is vital to adapt those existing methods to the specifics of medical device design. A first attempt to this was done by [5], which categorizes and analyses existing instances of circular economy in the medical sector, identifying device criticality and sterilization requirements as key factors influencing the design.

To further contribute to the adaptation of existing circular design methodologies to the healthcare domain, we aim to build on this previous work by conducting a circular design case study on smart pill boxes. These devices represent an example of rapid digitization of healthcare and the environmental sustainability challenges associated with it. Formerly, medication storage relied solely on simple plastic containers, but today, smart pillboxes equipped with sensors and reminders are entering the medication adherence market. By exploring the circular design 'solution space' of such devices, we aim to extrapolate circular design recommendations that can be applied to similar electronic health devices. In this way, we contribute to future application and normalization of circular design in this context, with the aim to ultimately enhance its sustainability.

A widely recognized hierarchy of 10R-strategies outlines various approaching to enhance the sustainability and circularity of products [7]. This hierarchy encompasses the following strategies: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover. In [8], it is suggested that that the 10R strategies can be used as a starting point for circular interventions by healthcare staff. While the 10R-strategies were originally conceptualized as a framework for resource management within a circular economy, rather than specifically for product redesign, we utilize our case study to explore their potential applicability in the redesign process of an electronic health device. By considering all steps needed in the process for each R-strategy, such as e.g. cleaning methods, we aimed to adapt the R-strategies to ensure that healthcare-specific requirements are incorporated. By structuring our design iterations around this hierarchy, we assess the strategies based on the key aims of this paper:

1. Evaluate the extent to which applying the R-strategies allows us to come up with feasible and viable circular concepts in the healthcare context.
2. Ascertain that circular strategies also result in sustainable solutions by assessing their environmental impact.

2.1 Method

4.2.1 Research Through Design Method

We conducted a research through design study, by deliberately introducing the R-strategies into our design method, while questioning their adaptability and effectiveness for our specific design case. The research through design method was split-up in five different stages:

1. Estimation of environmental impact hotspots of the current pillbox through a fast-track LCA.
2. Design sprints and concept development for each R-strategy separately, considering the impact hotspots.
3. For each design sprint, performing an in-between qualitative assessment of the integration of each R-strategy in the design method through reflective journalling.
4. Fast-track LCA comparison of design concepts to estimate the effectiveness of designing for each R-strategy in mitigating environmental impact.
5. Development of a final design that combines different R-strategy-based concepts and additional evaluation thereof through fast-track LCA.

Following the conclusion of the design case study, we used an inductive approach to derive circular design recommendations for similar electronic health devices.

4.2.2 R-Strategies Utilization

Several design sprints were performed based on the 10R-strategies. However, due to applicability of the specific strategies to our case study, we made two adaptations:

1. Refurbish and remanufacture were combined into one design sprint, as due to the high quality and safety requirements of many health devices we expect design requirements for both strategies to often be similar.
2. No design sprint was performed for the strategy of recover, as this is defined as "incineration of material for energy recovery" [7], which we argue is not a strategy we can design for, as literally anything can be incinerated.

After the two adaptations made, we came to the following list of 8 R-strategies utilized in our Research through Design approach: refuse, rethink, reduce, reuse, repair, remanufacture/ refurbish, repurpose, and recycle. Table 12 displays how we defined those strategies based on [7], adapted to make them suitable for design purposes (e.g. adding examples of how product use can be intensified for rethink) and to make them fit the narrative of the healthcare industry (e.g. merging remanufacturing and refurbishing and including cleaning processes in reuse).

The design sprints resulted in eight different redesign concepts, one for each R. However, as we argue that products that address multiple R-strategies are more environmentally sustainable, we also aimed to combine the concepts. We did so by viewing the R-strategies as if they were the different product functions in a morphological chart, combining ideas while considering the hierarchical nature of the strategies. This resulted in one final concept that could subsequently be assessed on its environmental impact.

Table 12: Definitions of the R-strategies

R-Strategy	Definition
Refuse	Making product redundant by eliminating its function or by offering the same function with a more sustainable, dissimilar product.
Rethink	Making product use more intensive through e.g. product sharing, device portability, standardized product architecture, and/or multifunctionality
Reduce	Use of fewer resources throughout the whole product life cycle (on product level minimize product, material, and electricity use).

(Direct) reuse	After cleaning, use of previously used product by another or the same user, while the product is still in working condition and the original functionalities are still present.
Repair	Bringing a defective product back to a working condition, so that it can be used for its original function.
Refurbish	Restoring an old product to as good as new or better than new condition, bring it up to date and if needed adding new parts in the product reassembly.
Repurpose	Use discarded product or its parts for a new function or in a new context, or use parts of the device in a new product with a different function.
Recycle	Processing materials to obtain the same or lower quality of materials (mostly done through sorting, shredding, and melting).

4.2.3 Reflective Journalling

After each design sprint, we wrote a reflective essay describing 1) the main design features of the concept, 2) its benefits and drawbacks, and 3) product and system changes that would enable the concept (compared to the original pill box). Additionally, we wrote a reflection on the ease of implementing each R-strategy into the design method. Finally, the writing for each R-strategy was analyzed and compared to derive useful design recommendations, considering the outcomes of the fast-track LCA comparisons.

4.2.4 Fast-track LCA approach

Several fast-track LCAs were performed in this study: we first assessed a smart pillbox as a baseline, and compared each design concept against that baseline. For all designs, the LCA boundaries included the production of the pillbox components (materials and manufacturing), transport, use, and end-of-life (EoL). While the device also uses a smartphone app, this was considered out of scope because we assumed users would already have a smartphone regardless of the pillbox, and the additional phone energy use from using the app would be negligible. As our research focuses on the development of health devices for the EU, EoL for everything was assumed to be incineration, or landfill when incineration data was unavailable. The functional unit was defined as a three-year average usage lifetime of a single smart pillbox, called one “use cycle”. All impacts were calculated per use cycle. The impact assessment method was IPCC 2021 GWP100, listed in kg of CO_2 equivalent emissions. Impacts were calculated using the Idemat2023 database in Excel.

As the redesigns are conceptual, we had to estimate the changes in, e.g., used components, material types, or material volumes, resulting in high uncertainty ratings. For both the baseline and new estimated designs, the rule of thumb used to set uncertainties was ±10% for precise data and perfect database match, ±30% for confident estimates or plausible database substitutions, and ±100% for unsubstantiated guesses.

For the baseline design, a bill of materials was available, but to protect intellectual property confidentiality, results were aggregated into material groups. Transport was assumed to be from production in China to a geographically average center in the EU, by a mix of container ship, train, and trucking, with ±100% uncertainty. Usage energy (charging the battery) was assumed to average 125 Wh/yr, with ±50% uncertainty, based on the manufacturer’s data. The assumptions we made for each new concept are explained with the results.

4.3 Smart Pillbox: Baseline LCA

For this study, we chose an existing smart pillbox currently on the market. The pillbox has several compartments that users can fill with different pills. It has a sliding lid and has electronics that register the opening of the lid to indicate medicine intake and remind the user to adhere to their prescriptions through auditive and visual cues that are enabled through a speaker and LED lights.

4.3.1 Fast-track LCA of the current pillbox

The fast-track LCA of the current pillbox determined environmental impact hotspots and set a baseline for later comparison. Although there were large uncertainties, the results clearly indicate the manufacturing stage has by far the largest impacts (Figure 10). As Figure 11 indicates, this is mostly caused by the manufacturing of the electronic components (PCB, battery, and LEDs). Again, despite the large uncertainties, the electronic components clearly cause higher impacts than all other components together, the latter having a combined impact of 1 to 2 kg CO_2-eq per use cycle. This is similar to the impact that the battery has on its own: 0.6 to 1.7 kg CO_2-eq per use cycle; it is likely slightly lower to much lower than the impact of the PCB (depending on the uncertainty), which is 0,7 to 6,1 kg CO_2-eq per use cycle (excluding the LEDs). Due to the large number of LEDs in the original pillbox, the impact of the manufacturing of the LEDs is also estimated to be relatively high, with an impact of approx. 0.2 to 1.9 CO_2-eq per use cycle.

Based on these outcomes, we estimated a current total impact between 2.6 and 12 kg CO_2-eq per use cycle, with the manufacturing of the electronic components (PCB, battery, and LEDs) being the main impact hotspot.

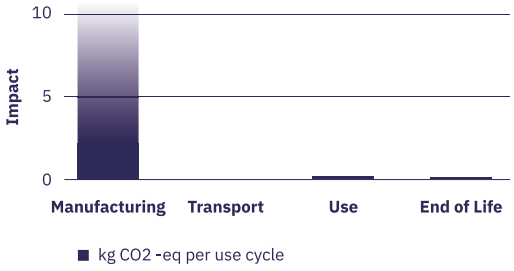


Figure 10: Impact of Smart Pillbox per Life Cycle Stage (Uncertainty is Displayed in Gradient)

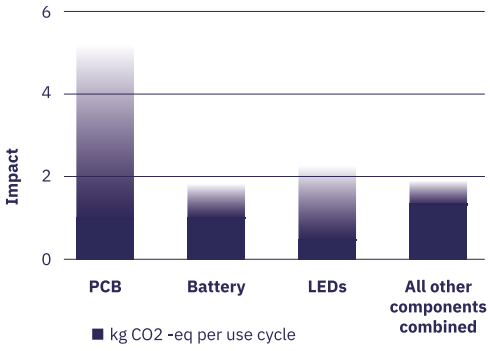


Figure 11: Impacts by Component in Manufacturing (uncertainty is displayed in gradient)

4.4 Results: Design Concepts Per R-Strategy

This research falls under the Digital Health in a Circular Economy (DiCE) project, which is funded by the Horizon Europe program of the European Union. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

In this section, we will shortly introduce the conceptual ideas we came up with through our design brainstorming for each R-strategy, highlighting their benefits and drawbacks.

4.4.1 Refuse Concept

The refuse strategy aims to render a product redundant by abandoning its function or replacing it with a more sustainable alternative. For the pillbox, which primarily enhances medication adherence through reminders and dosing instructions, we propose integrating all functionalities into the accompanying smartphone app, removing the need for electronics in the physical pillbox. Although we cannot be certain how this change affects the medication adherence, several studies suggest that there may be no significant difference in adherence between reminder methods [9], and it has been observed that turning off alarms on pillboxes could potentially even improve adherence [10]. In this concept, users keep a simple, non-electronic pillbox for storage and portability; we assume physical presence of the pillbox will function as the reminder [11], with an app for backup reminders and/or adherence tracking. See Figure 12 for the refuse concept illustration.

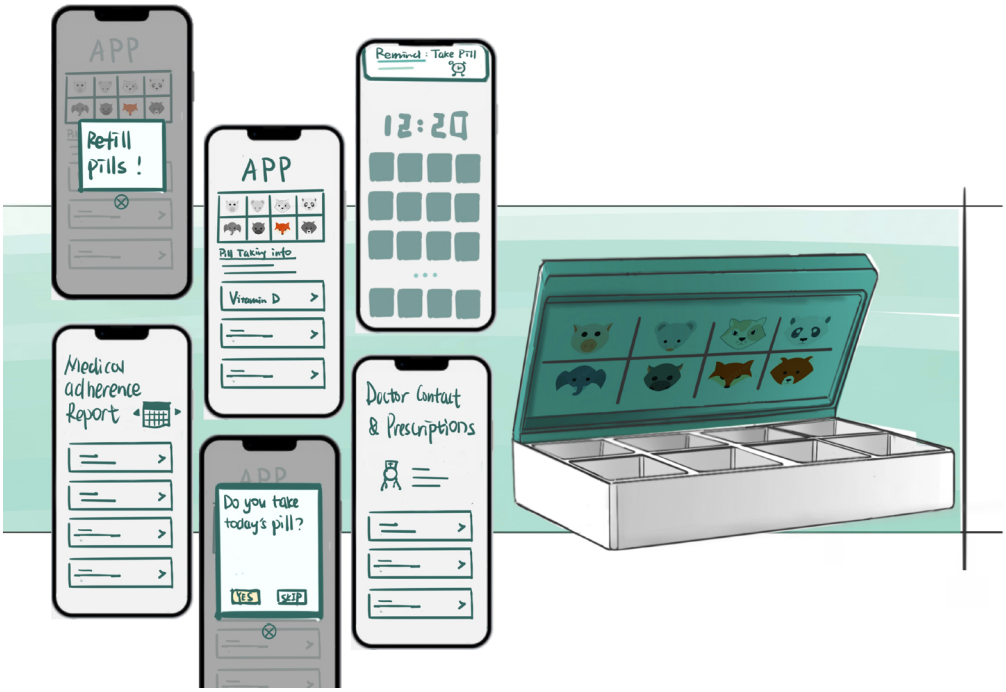


Figure 12: Refuse Concept

4.4.2 Rethink Concept

The rethink strategy we interpreted as a way of intensifying product use to ensure full utilization of the product functionalities. In this concept, patients receive a temporary pillbox as part of their medication purchase from the pharmacy without gaining ownership. This transformation of the ownership model requires patients to return the device to the pharmacy, which takes responsibility of refilling and medication management to prevent idle pillboxes at home. This shift encourages pillbox return, minimizing idle pillboxes at home and promoting efficient resource utilization through temporary usage. Encouraging return of the pillbox to a pharmacy may also benefit other circular strategies. Its versatile design includes a modular approach, with all electronics grouped in a separate and easily separable part, which allows attachment to various home containers, while the expanded app tracks health data and digital prescriptions, enhancing overall medication management and adherence (Figure 13).

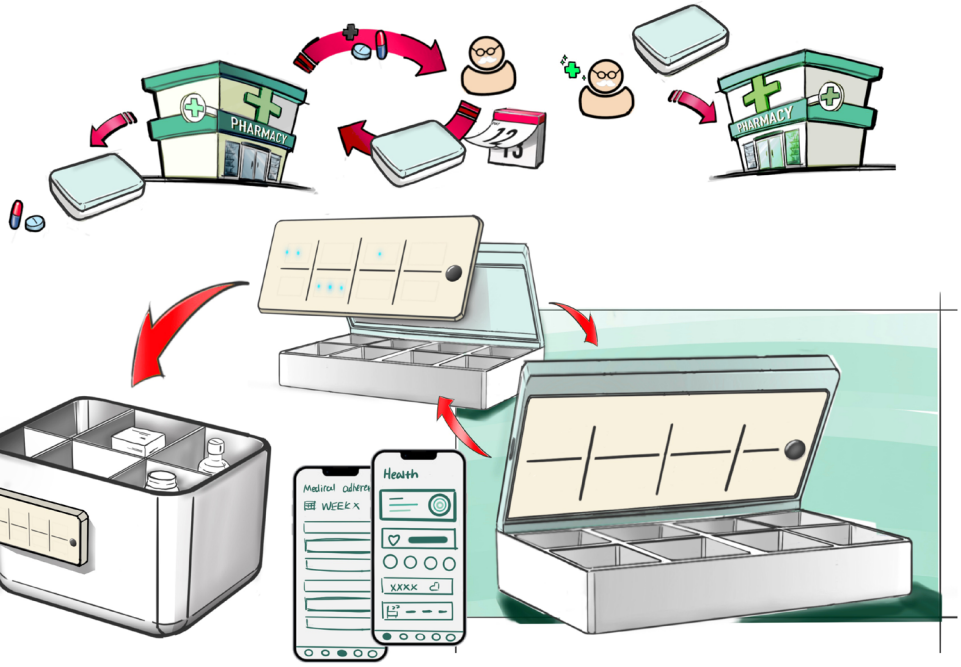


Figure 13: Rethink Concept

4.4.3 Reduce Concept

In the reduce concept, we aimed to minimize the need for electronics, addressing the PCB and LED impact hotspot. For the LEDs, we incorporated translucent material in the lid for light transmission, reducing LED intensity while maintaining visibility. Additionally, our concept has a modular approach, with all electronics grouped in a separate and easily separable part with snap connection that has only one LED per compartment. Additionally, standardization was enabled through integration of a USB C charging connector to be able to remove the charger from the packaging. Replacement of the speaker with a simpler, more energy efficient buzzer, and simplifying the opening mechanism with a flip design also minimized material use. Finally, to further reduce plastics usage and overall PCB size, since the average number of concomitant medications in the Netherlands is 4 [12], the full pillbox size is minimized by 50%, to just 4 compartments. The final reduce concept is displayed in Figure 14.

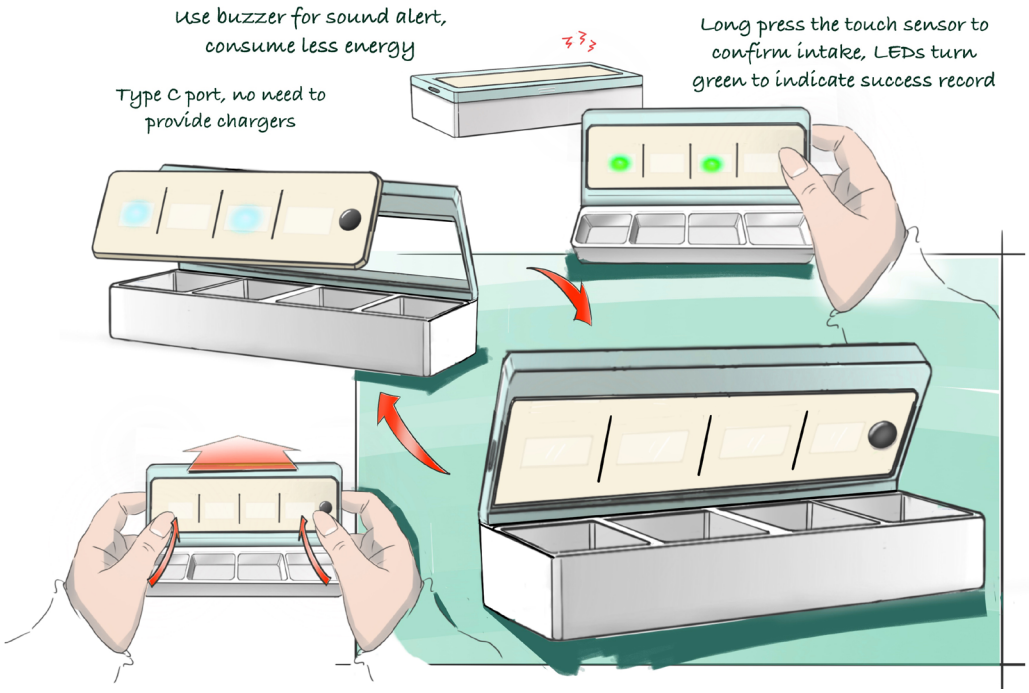


Figure 14: Reduce Concept

4.4.4 Reuse Concept

We interpret the reuse strategy as direct reuse, referring to products that are used again for their original purpose, without alteration, by a different user. For the pillbox, this entails maintenance for lifespan extension. To enable reuse, our concept entails a similar system as the rethink concept: the user obtains pills and the pillbox from the pharmacy, paying for the pills and adherence support instead of purchasing the pillbox. The pillbox design features a standard USB C charging port, with charging cable available for purchase at the pharmacy. Electronics are enclosed within a buckle lid, with waterproofing facilitated by screws and gaskets for cleaning. Materials are chosen for resistance to hot water, alcohol, and UV light, with a smooth, scratch-resistant surface to ensure device longevity. A physical reset button on the lid allows deletion of stored data. The app now generates a log of all medicines previously placed in the pillbox, aiding in decontamination. When users no longer receive pills, they can return the pillbox to the pharmacy or purchase it at low cost for reuse with other pills not prescribed by their doctor. Returned pillboxes are disinfected and quality-checked, receiving a ‘reused’ sticker if in good condition. The reuse concept is displayed in Figure 15.

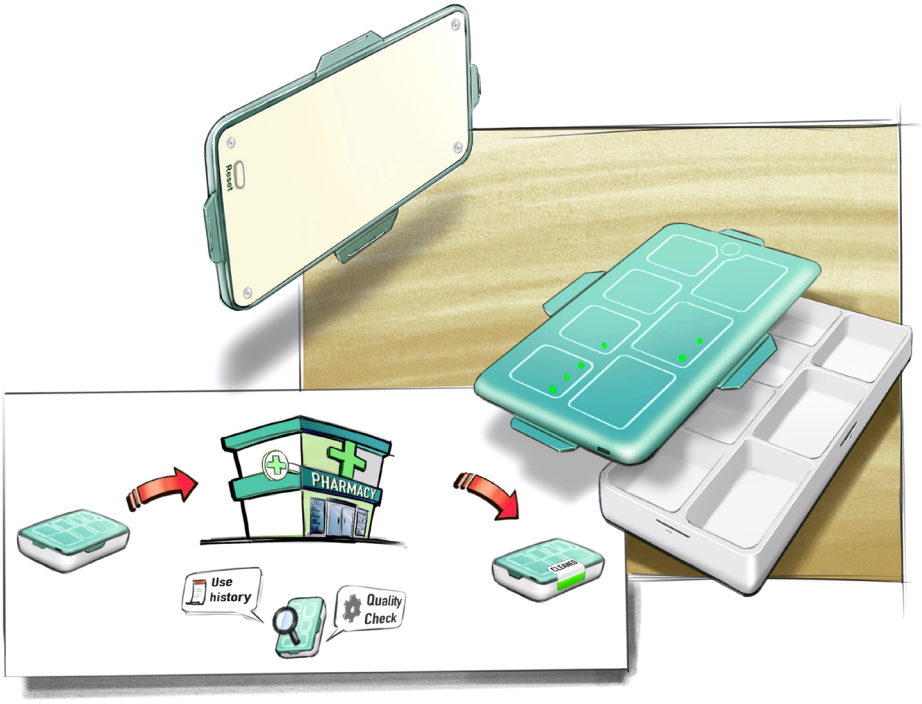


Figure 15: Reuse Concept

4.4.5 Repair Concept

Repair can be done by the user (“self-repair”) or professional repairers. For our low-cost, frequently used pillbox, our focus is on enabling self-repair. Our new concept includes a digital diagnosis mode in the app, allowing users to find and fix problems. They can request spare parts via the app for minor problems and return broken parts for a reward. The pillbox design features a buckle lid with internal electronics, screws, gaskets, and an easily replaceable battery. The repair concept is displayed in Figure 16.

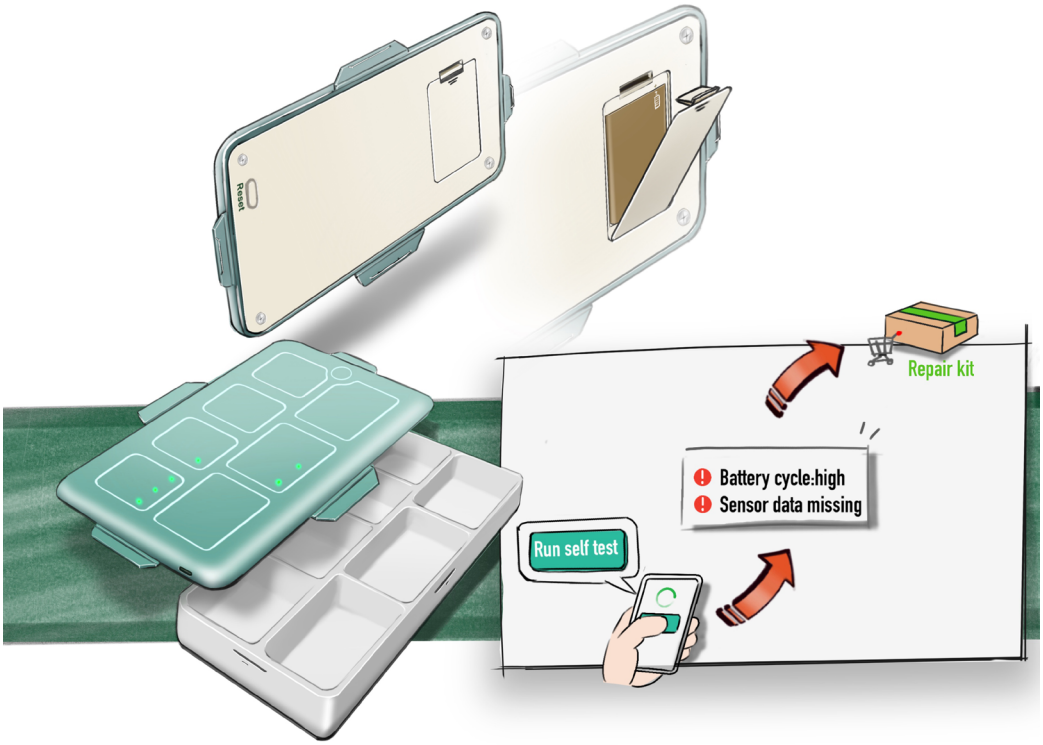


Figure 16: Repair Concept

4.4.6 Remanufacture/Refurbish Concept

Our approach for remanufacture/refurbish emphasizes durability, easy disassembly, and tracking systems for efficient operation, accommodating the needs of both remanufacturing and refurbishment. It features an independent electronic bundle and a durable box, facilitating separate quality checks and simultaneous inspections. Surfaces are hard, smooth, and suitable for disinfection, while screws secure the PCB and close the electronics bundle for repeated disassembly. The interchangeable battery and standard USB C charging port enhance longevity and compatibility, catering to the requirements of both processes. NFC tags aid in inventory management, while a digital checking program ensures functionality, benefiting both remanufacturing and refurbishment processes. To determine whether the PCB functions optimally, the engineer can write a log into the PCB to document usage history and update the NFC, enhancing component traceability. Refurbished products are identified with an embossed sign on the lid, streamlining identification and differentiation. The remanufacture/refurbish concept is displayed in Figure 17.

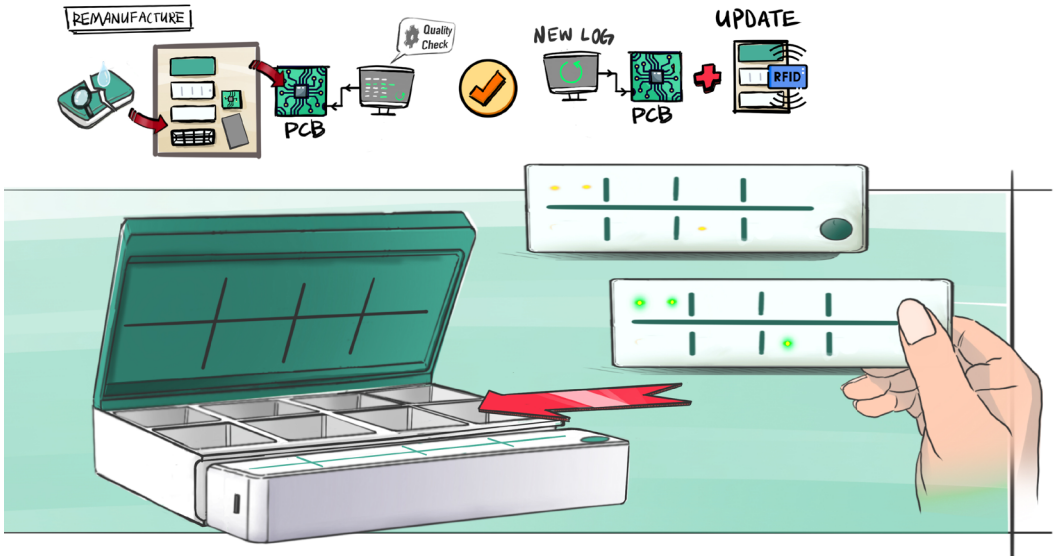


Figure 17: Remanufacture/Refurbish Concept

4.4.7 Repurpose Concept

In order to repurpose a product or product parts, new applications would need to be found for the device after use, to use it for a new function and/or in a different context. Unfortunately, deliberately designing for repurpose (without creating a multifunctional device) has proven to be complicated, as our influence on user behavior is limited. However, as the design features of the smart pillbox are naturally close to an organizer, our concept represents a modular design with standardized components, that enables the user to explore new functions and various use environments. The modular pillbox consists of an independent electronic bundle and a “dumb organizer”. Users can detach the electronic bundle to use it as an alarm clock The electronic bundle is equipped with a standard rechargeable cell battery (AA); the charger is optional. The pillbox contains flexible dividers that can help users create up to six compartments which can be customized when repurposing. In the app, a digital community function would be added in which people can share their “after-use-stories” of how they have repurposed the pillbox, to inspire others. The modular repurpose concept is displayed in Figure 18.

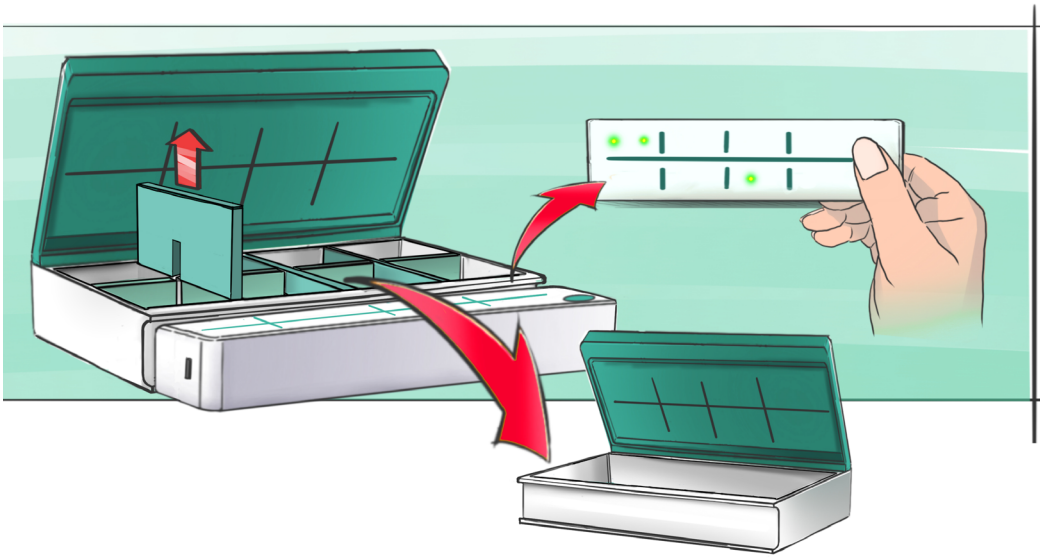


Figure 18: Repurpose Concept

4.4.8 Recycle Concept

To facilitate the recycle process, we focus on easy battery access, and efficient material separation. We prioritize mono-material design, disassembly ease, and avoidance of adhesives and screws for attachment. Return instructions are provided in the app, where users can also receive rewards upon product return confirmation. The product features screwless design with snap-fits in one mono-material, a USB C charging port eliminating the need for a charger (as users often do not return the charger with the product), and an interchangeable battery with a distinct cover for easy identification. Disassembly indications for the battery are printed on the pillbox, while all shell components are made of the same plastic. Lead-free soldering and conductive ink are used on the circuit board, with the original PCB color retained for machine sorting convenience. A QR code on the product provides access to its digital passport, detailing materials, recyclability, and recycling advice. The recycle concept is displayed in Figure 19.

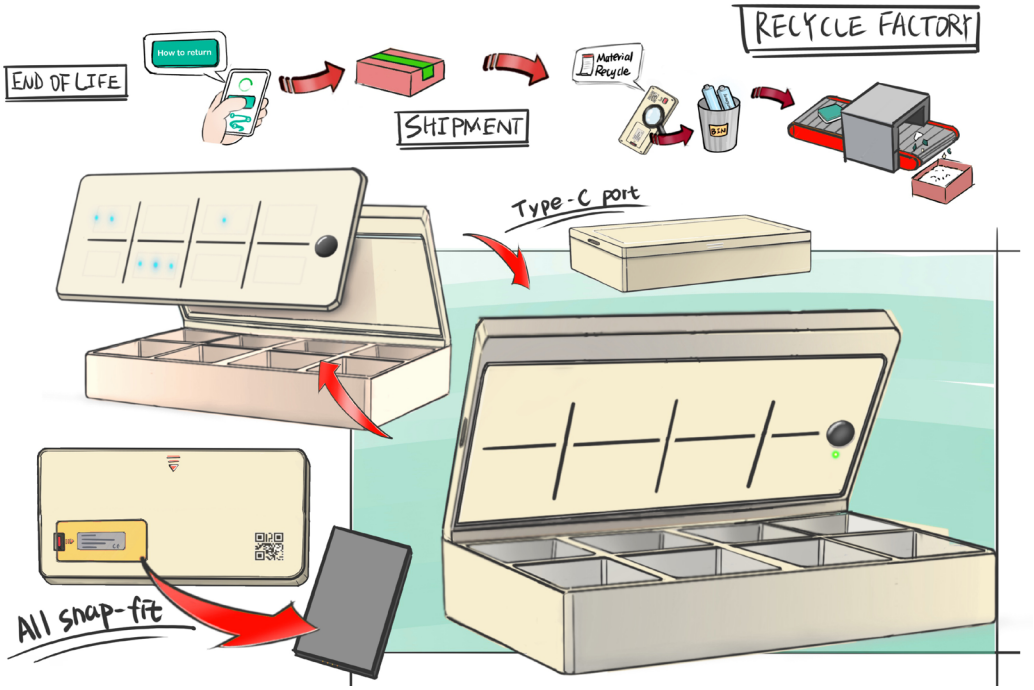


Figure 19: Recycle Concept

4.5 Comparison of the R-Strategies

In this section, we will compare the application of each R-strategy in our design method by detailing how the R-based brainstorms influenced circularity (through reflective journaling) and sustainability (via fast-track LCA comparisons). For the fast-track LCA comparison, we will also explain based on which concept-based adaptations and assumptions we made the calculations.

4.5.1 Reflective Journalling

For each R-strategy, we reflected on the benefits, drawbacks, and the ease of implementation. The benefits and drawbacks of the R-strategy-based design concepts compared to the original pillbox can be found in Table 13. When reflecting on the designs, we surmised that all R strategies have both benefits and drawbacks. Table 13 lists a number of these, without claiming to be complete. For instance, refuse can significantly reduce waste, but ensuring product functionality is essential. In the case of our refuse concept, it is crucial to examine how our design affects medication adherence. Additionally, while reuse shows much promise as a simplified method for extending product life cycles, concerns persist regarding the perceived value of second-hand products and the potential increase in labor intensity within the healthcare system, as the pharmacy becomes responsible for cleaning devices.

Another strategy with potential benefits seems to be repurpose. It is, however, quite challenging to design a product for repurpose without compromising its original functionality, and there is usually no way to ensure that the product is indeed repurposed by the user.

Strategies that seem more promising than repurpose are reduce, rethink, and remanufacture/refurbish. By reducing the materials and energy used, we easily obtain sustainability benefits with minimal drawbacks. Our rethink concept does the same thing, but on a system rather than a product level, aiming to intensify use, which often leads to new business models or value chain collaboration. Therefore, it seems to be important to retain supply chain efficiency. We believe rethink to be a crucial strategy that could enable other strategies to work. Also remanufacture/refurbish seems to hold promise. The benefit of this strategy is that it enables the manufacturers to ensure patient safety during the use phase as they retain their influence on product quality.

Table 13: Potential Benefits and Drawbacks for Each Design Concept, Based on Reflective Journalling

Benefits	Design sprint concepts it applies to							
	Refuse	Rethink	Reduce	Reuse	Repair	Repurpose	Reman/refurb	Recycle
Simplified logistics during manufacturing (less shipping)	■	■	■	■	■	■	■	■
Reduction of incinerated/landfilled waste	■	■	■	■	■	■	■	■
Enables disinfection, quality check, sorting	■	■	■	■	■	■	■	
Reduced consumption of raw materials in production and conservative use of resources	■		■	■		■	■	■

Easy disassembly (easy separation between different materials, interchangeable battery)	
Higher work efficiency in EoL system operation	
Lower labor intensity in manufacturing (easy assembly)	
Decreased energy consumption during use	
Extended product life cycle	
Encourage continuous use (add value)	
Prevention of idle usage at home (motivate return)	
Simplified reverse logistics	
Assured safety and quality of the product during use	
Drawbacks	
Diminished sense of product value, no ownership (may lead to careless treatment or disposal)	
Potentially shorter life cycle (higher learning curve, less durable, safety concerns in repair)	
Potentially affect functionalities negatively	
Increased labour intensity in manufacturing (complex assembly, more connections)	
Higher resource consumption during manufacturing (more moulds for different components)	
Increased labor intensity in healthcare system (more functions at pharmacy)	
May increase initial manufacturing costs	
Minimal influence on whether strategy will actually take place	
Potential poor waste collection (broken parts, shift in user perception of the product)	
Inventory management pressure	
Resource intensity of EoL process (complex system: log writing, NFC updating)	

Despite showing less benefits in our overview, we argue that designing for repair is vital in all instances, as other strategies such as reuse and remanufacture/refurbish also benefit from the easier disassembly, modularity, and standardization caused by designing for repairability. However, as we focused our design sprint on self-repair, the success of our specific concept was dependent on the behaviour of the user. Also, the adaptations to the design might complicate the manufacturing processes. Therefore, we expect repair would have had more benefits if we had designed the pillbox for professional repair, as it might be easier to ensure that users let their device get repaired under warranty.

Finally, the recycle strategy is the least environmentally sustainable, and it does not maintain product integrity. Nonetheless, it is crucial to incorporate it into product designs to address the inevitable EoL stage, regardless of the previously applied R-strategy.

4.5.2 Circularity Evaluation

We evaluated the R-strategies on their potential to enhance product circularity. We categorized strategies into three groups:

- Refuse and reduce minimize resource use but do not inherently facilitate the circular flow of materials.
- Rethink, while not directly a circular strategy, could enable circularity by promoting continuous use and extending product lifecycles.
- Reuse, repair, repurpose, remanufacture, and recycle are clear circular strategies. They extend product lifecycles and optimize EoL processes, closing the loop on resource utilization. However, prioritizing tighter circularity loops over recycling is crucial for optimal circularity.

Overall, these evaluations highlight the importance of combining diverse strategies to achieve comprehensive circularity in product systems.

4.5.2.1 Fast-track LCA comparison

In addition to reflective journaling, we conducted quantitative comparisons of design sprint outcomes using estimated fast-track LCAs. Our primary goal was to compare the CO_2 impact of each design concept relative to the original pillbox and to each other. Details on these comparisons are provided later in this section. Figure 20 illustrates the estimated impact of each concept compared to the original pillbox, with the uncertainty of each impact displayed in a gradient. It assumes only one use cycle for each design, even the ones designed for multiple life cycles. Notably, strategies like refuse and reduce show sustainability benefits by minimizing resource use in production and use stages. Other R-based concepts have CO_2 impacts well within the uncertainties of the original pillbox for one cycle; some may lower impacts slightly, but it is far from guaranteed if they only have one use cycle.

However, if the circular designs achieve five use cycles, as shown in Figure 21, the relative CO_2 impact of reuse and remanufacture/refurbish improve significantly, with repair showing a lesser improvement. The relative impacts of refuse, reduce, rethink, and recycle strategies remain consistent, because they still have only one use cycle. These findings align with our journalling about circularity: refuse and reduce improve sustainability, not circularity, rethink enables circularity but does not guarantee it, and the R-strategies of reuse, repair, and Remanufacture/Refurbish are clearly circular strategies. Recycle, though a circular strategy, may not fully reflect its circularity in our fast-track LCA. This is because the recycle concept mostly focused on recycling of plastic components, while the electronics, which have the highest impact, did not get recycled.

Further sections will detail how calculations for each R-strategy were derived, including adaptations from design concepts and additional assumptions in the fast-track LCA. As the calculations solely serve as an estimated comparison of the concepts with the original pillbox, we only provide estimates of how much better or worse they are than the original pillbox.

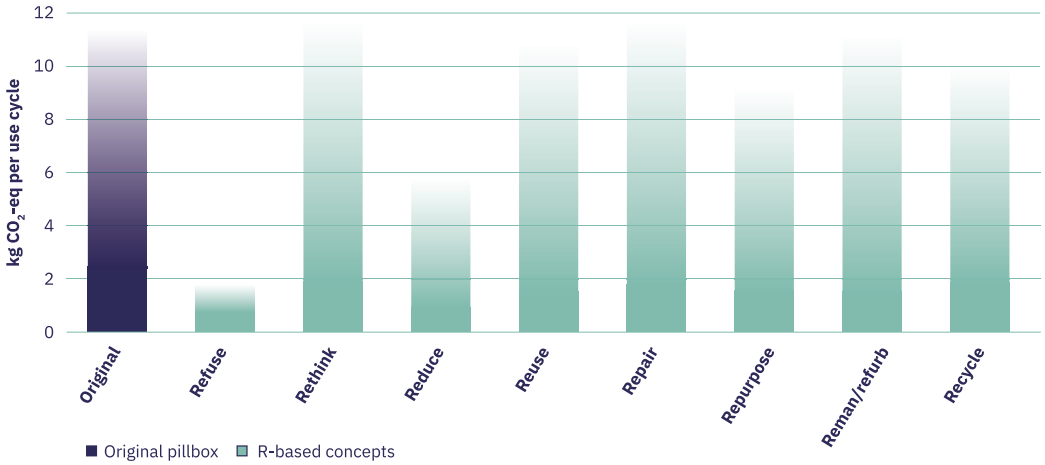


Figure 20: Comparison of Total Estimated CO_2-eq per R-Based Concepts with Only One Use cycle (3 Years).

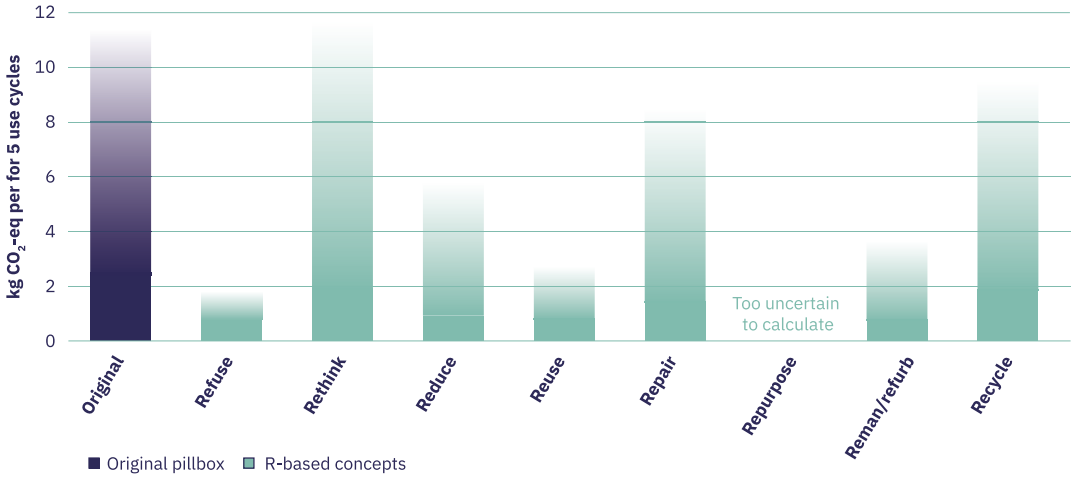


Figure 21: Comparison of Total Estimated CO_2-eq per R-Based Concept for Five Use Cycles (15 Years).

4.5.2.2 Explanation of Refuse Calculations

In the refuse concept, we remove all electronics from the fast-track LCA calculations. This includes the battery, PCB, speaker, and LED. As we still advise users to use the smartphone app with their own simple plastic pillbox, we kept all plastics for the tray and lid and the transportation thereof in the calculation. However, as most simple plastic pillboxes do not have a sliding lid, we also excluded the sliding mechanisms and the magnets. Additionally, we deleted the product-related electricity used in the use phase. Although electricity is still used through the smartphone app, these impacts were already out of scope for the original pillbox. As was to be expected, these adaptations decrease the CO_2 impact of the pillbox by 30 – 90% per use cycle. However, in this we do not consider possible influence of these adjustments on medication adherence. For the five use cycles scenario, its impacts per use are unchanged.

4.5.2.3 Explanation of Rethink Calculations

To enable the rethink concept, due to the strong system focus, not much product changes are needed. The same electronics are utilized, but an additional compartment needs to be produced in the same plastic, which was estimated to have a weight of 20% of the pillbox tray, with 20% uncertainty. Due to the lid being hinged instead of sliding, all components of the sliding mechanism are eliminated. The concept also eliminates the automatic recording or medication intake, replacing the recording sensor and magnet with a simple press button. We made the assumption that this would not alter the PCB weight used to calculate the PCB impact, but we did adapt the uncertainty of the PCB weight to 100%. The increase in the CO_2 impact caused by the user's travel to the pharmacy, which we estimated to be 470 km over three years, is so negligible that this is not visible in the final total impacts per use cycle. Taking into account the device changes and adding them in the fast-track LCA made for the original pillbox, this results in an estimated impact similar to the original pillbox's impact. Although the rethink concept might enable the reuse scenario, this concept does not necessarily assure long-term reuse beyond the initial use cycle. Therefore, for the five use cycles scenario, its impacts per use are unchanged.

4.5.2.4 Explanation of Reduce Calculations

For the concept, changes are implemented to eliminate combined materials in the lid for LED diffusion, switching to opaque PMMA material. Material mass is estimated by transferring mass and density from the original lid materials, with a 50% uncertainty. This inadvertently prevents the 2K injection molding used for the original lid. The reduce concept also reduces the overall pillbox size, halving plastic materials in the lid and tray. The PCB mass is also reduced by 50% (with 100% uncertainty), given the elimination of the sensor. LED count is reduced to four, one per compartment, and the speaker is replaced with a buzzer, assumed to have similar impact. We also assumed this would minimize energy use during the use stage by 40%, with 100% uncertainty. Sliding mechanisms, charger, and additional packaging are removed from the calculation. Based on these adjustments, we estimate the Reduce is likely to yield a significant improvement, perhaps cutting impacts in half. For the five use cycles scenario, its impacts per use are unchanged.

4.5.2.5 Explanation of Reuse Calculations

For the reuse concept, adjustments are made to eliminate the rubbery material materials in the lid, replacing it with the same durable material used in other parts of the original pillbox, and which is known for its longevity and resistance to water, heat, and scratches. Material weight calculations are based on the density and mass of the original pillbox's rubber material, with a 60% uncertainty. The sensor is removed by reducing PCB mass with 0.11 grams, which is the estimated weight of the sensor, with an increased uncertainty of 100%. Slider mechanisms and the need for a charger are also eliminated, assuming users possess a USB-C charger at home. However, four tiny stainless-steel screws and one gasket are added to the calculations. Due to reusability, the scenario of the user travelling to the pharmacy was copied from the rethink calculations. Accounting for these changes, the estimated impact is perhaps a bit lower than the original pillbox, but well within uncertainty ranges when only accounting for one use cycle. For the five use cycles scenario of reuse, we count the original transport, manufacturing in only the first of the five cycles; EoL impacts are only counted in the last cycle; impacts of the use stage, including user travel to the pharmacy, are counted in all five life cycles. With five life cycles, impacts are likely reduced by 10% - 85% less than baseline.

4.5.2.6 Explanation of Repair Calculations

To enable the repair concept we developed, a similar design is needed as the reuse concept. This means that we eliminated the sensor by minimizing the PCB mass with 0.11 grams, increasing the uncertainty to 100%, and removing all slider mechanisms as the lid was replaced with a buckle lid. Also, just as with the reuse concept, 4 stainless-steel screws and one gasket were added. As we do not expect the removable battery lid to change the design composition much, all other features of the pillbox remained the same, including the transport, use, and EoL stages. By adapting the fast-track LCA calculations based on this, this results in an estimated impact of the repair concept is perhaps slightly lower than the original pillbox, but well within uncertainty ranges. For the five use cycles scenario, we assumed with 100% uncertainly that the repair strategy would prolong each use cycle by one year, making one use cycle 4 years instead of 3. The impacts of replacement parts manufacturing, transport, and EoL were assumed to be included in this, as the product's life might be extended beyond 4 years but the impacts of replacement parts would make total impacts equivalent to a 4 year lifetime with no new parts. Therefore, we multiplied the impacts per use cycle by 75%.

4.5.2.7 Explanation of Remanufacture/Refurbish Calculations

Changes to enable the remanufacture/refurbish concept are similar to those of the reuse concept: the rubbery material was again removed in a similar way, but in this case not only for durability, but also to enable cleaning. Also, in the same way as the reuse concept, all sliding mechanisms and the need for a charger were eliminated while four tiny stainless-steel screws were added, in this case to ensure ease of disassembly. However, instead of minimizing the PCB mass to reduce the sensor, the PCB mass remained the same, as the remanufacture/refurbish concept would also need an NFC sensor to be added. Naturally, this mass comes with 100% uncertainty. This results in an estimated impact which is perhaps slightly lower than the original pillbox, but well within uncertainty ranges. In the five-use cycle scenario, we assumed critical components like the battery and LEDs are replaced half the time, calculating one full manufacturing impact for the first use cycle and half of the impacts for LEDs and the battery for the following four use cycles. EoL impacts are only counted in the last cycle. The use stage is counted for all five use cycles. The full transport is counted for the first use cycle, then the following four use cycles only count transport to a remanufacturing/refurbishment facility (1/3 of the full transport, ±100%). The resulting total impacts have enough uncertainty that in their worst case, they might potentially be worse than the best-case baseline, but in their best case, they might reduce impacts by 70% from the baseline worst case.

4.5.2.8 Explanation of Repurpose Calculations

For our repurpose concept, alterations to the original pillbox transition it into a modular design while abandoning the sliding mechanism. Symmetric design is crucial to facilitate modularity and minimize pill compartments, resulting in a 13% reduction in LED lights. Due to this, we also expect a reduction of energy use in the use stage of 5% ±100% uncertainty. Flexible compartments require separate production, with the pillbox tray using 20% less material, as this material will be used to produce five modular units via injection moulding. Similar to the rethink concept, the pillbox features a separate electronics compartment. Simplifying repurposing, the battery is replaced with two standard rechargeable cells (AA), and assuming only half of the users will make use of the optional charger, the charge volumes are reduced by 50%, with ±100% uncertainty. Accounting for these changes, the repurpose concept yields an estimated impact that might be

slightly lower than the concepts of e.g., reuse and remanufacturing. This reduction is primarily due to the change of battery and nonintentional reduction of LED lights. Since the outcome and duration of repurposing are highly uncertain, we excluded it from the five use cycles scenario calculations.

4.5.2.9 Explanation of Recycle Calculations

To enable our recycle concept, we first minimize the number of different materials by eliminating all sliding mechanisms again. Additionally, charging is eliminated. However, the most important change for this concept is that all plastic parts are changed into one recyclable material. In this case, we chose to use amorphous PET and calculated the mass of this material based on the mass and density of the materials used in the original pillbox. For the EoL stage, for all plastic components, we substituted landfilling and incineration practices with recycling for plastic and metal components. However, we assumed that the electronic components are not recycled, due to their small size and specialized composition, which can make them difficult to separate and process efficiently in typical recycling facilities. This results in an estimated impact which is perhaps slightly lower than the original pillbox, but well within uncertainty ranges, because the plastics are a miniscule percentage of total impacts. For the five use cycles scenario of recycle, we calculated the full manufacturing impact for the first use cycle, and impact of manufacturing with recycled plastics for the other four use cycles. The use and transport stages were the same for all five use cycles. EoL was assumed to be recycling in four life cycles, and incineration in the final EoL.

4.6 Combining R-Strategies in One Concept

The final step in our study was aimed at combining different strategies in a single design, to surface any trade-offs among strategies and determine the added value of this combination in terms of improving the sustainability and circularity of the product.

4.6.1 Ease of Combining R-Strategies in One Product

Overall, we believe that most R-strategies can be combined in a single product, while there may arise some drawbacks. Firstly, as refuse has a close alignment with the functional definition, this significantly influences the scope in the design phase (e.g., we cannot reuse or recycle a product after completely abandoning it), making refuse hard to combine. However, all other R-strategies can be combined with varying levels of ease. For rethink, combinations can mostly be made when addressing this strategy from a service and system design perspective. Although this concept so far seems to not necessarily improve sustainability or circularity by itself, it can play a crucial role in enabling other strategies (e.g. by intensifying the use, we can enable strategies such as reuse). Most easy to combine are the strategies of reuse, repair, repurpose, and remanufacture/refurbish. This is because most of them serve overlapping considerations, such as product and material durability, cleanability, and ease of disassembly. Additionally, for reduce, we could adhere to similar considerations but with minimized consumption of materials and resources where possible but aiming to maintain product durability and reliability. However, recycle prioritizes the system operation of the EoL process, which limits the choices in material and connections, possibly jeopardizing some design considerations (e.g. some recyclable materials might be less durable or harder to clean), making recycle less easy to combine to the full extent.

4.6.2 Final Combined Concept

Based on the reflections in section 4.5, we developed a combined concept based on the strategies of rethink, reduce, repair, reuse, repurpose, remanufacture/refurbish, and partially recycle (Figure 22). To create the combined concept, compared to the original design, we make the following design adaptations based on the R-based design concepts:

- Service subscription without product ownership, with a distribution and collection role of the pharmacy (based on rethink and reuse).
- Minimize the size by 50% with just four pillbox compartments, four LEDs, without a charger and with a buzzer instead of a speaker (based on reduce).
- Add four screws and one gasket to benefit durability, disassembly, and daily cleaning (based on reuse, repair, and remanufacture/refurbish)
- Add four screws and one gasket to benefit durability, disassembly, and cleaning (based on reuse, repair, and remanufacture/refurbish)
- Change plastics into recycled, water- and scratch resistant ABS (based on reuse, repair, repurpose, and remanufacture/refurbish), recyclable (based on recycle), and translucent (based on reduce).
- The app provides a medication log (based on reuse) and a self-repair service (based on repair).
- Make sure the battery is a standard rechargeable cell battery (based on repurpose) and that it is easily interchangeable (based on repair).
- Create a modular box with independent electronic bundle and flexible dividers (based on repurpose).
- Add a QR-code to enable a digital product passport (based on remanufacture/refurbish) without adding an NFC (based on recycle).
- Add an embossed sign on the lid for refurbished products (based on remanufacture/refurbish).
- Add a coloured disassembly indicator to simplify battery removal (based on recycle).

Based on these adaptations, we performed another fast-track LCA. The design choices were calculated in the same way as they were calculated for the R-based strategy concepts. While still being within uncertainty ranges, the calculations showed that for only one use cycle this concept may yield an estimated reduction of up to 95% compared to baseline. This improvement percentage for one use cycle is less than that of refuse, but much better than that of all other strategies.

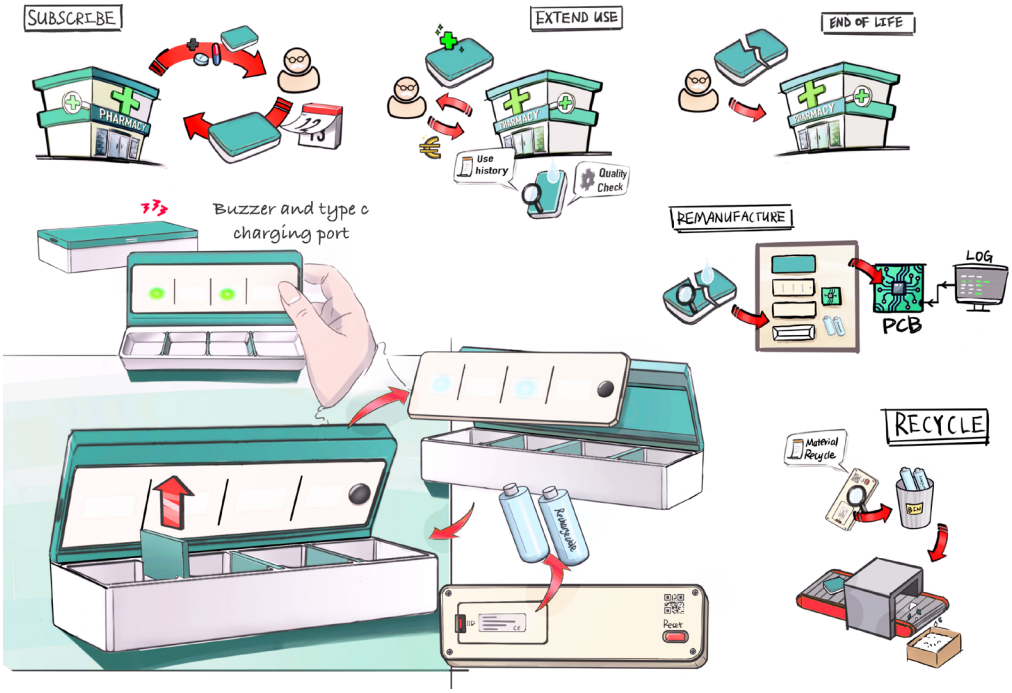


Figure 22: Concept Combining 7 R-Strategy Designs

Although we did not design the circular supply chain, we did try to calculate what would happen if the pillbox were produced from recycled materials and used for one use cycle of three years, after which it is reused twice (for six years in total), repaired once (extending the second reuse cycle by one year), remanufactured once, and then recycled upon EoL (after two years). We calculated this 15 years of use scenario in a similar way as we calculated the five use cycle scenarios for the R-based concepts. As this scenario still entails only one manufacturing and one EoL stage, and since the transport and use stage impacts are negligible, the estimated impacts of the 15 year scenario for the combined concept are similar to those of the 3 year scenario, resulting in an estimated relative impact per use cycle which is 65 – 95% lower than baseline.

4.7 Design Recommendations

The main aim of this paper was to determine to what extent R-strategies can be utilized as a design method. Overall, we do believe that the utilization of R-strategies in a design method has added value. In this section we will explain which aspects should be considered for each R-strategy when designing an electronic health device for circularity/sustainability based on a discussion of our findings. The considerations can be found in Table 14, ordered based on their importance, following the hierarchical order of the R-strategies.

For many reasons, product and system standardization can be beneficial: for example, using the same charging port for many different devices will abandon the need for production and purchase of many different ones. Simultaneously, we would like to recommend resource efficiency; make sure that we are not using unnecessary amounts of materials, resources, and electricity in

the product life cycle (reduce). For the materials and parts that we do use, we need to ensure durability to make the device suitable for reuse, repurpose, or remanufacture/refurbish after the first use cycle. Depending on the level of needed decontamination (e.g. using a simple alcohol wipe versus high temperature steam sterilization), the product needs to be able to withstand necessary chemicals, temperatures, handling, and liquids. When a product is defective, it is preferable to first enable either self-repair or serviced repair to avoid product disposal and elongate repeated cycles of reuse , repurpose and remanufacture/refurbish. In some cases, it is important that the product is easy to disassemble. For example, to test product parts separately or to remove hazardous materials (such as batteries) prior to the recycle process. To enable the testing and assure product quality for any next use, we would also need to ensure that authorized parties are enabled to perform the needed quality assessments. This may include e.g. indicators of contamination and the possibility to test fragile product parts on strength. For this, we also need to provide access to product information about e.g. the number of reuse cycles a product has already been gone through, because of which we will need to ensure product traceability. In case a product is planned for recycling, we also need to ensure material separation to ensure homogenous recyclable waste streams. This goes further than enabling disassembly, e.g. 2K injection moulding, mixed plastics and flame retardants need to be avoided and the use of a standardized PCB colour would allow it to be recognized by the separation equipment of the recycling facilities.

Table 14: Main Considerations for Each Design Concept

R-Strategy	Main consideration	Important requirements that apply										
		Functionality	Utilization	Standardization	Resource efficiency	Durability	Cleanability	Repairability	Disassembly	Quality assessment	Traceability	Material separation
Refuse	Only design, develop, and market products that address unmet needs.	■										
Rethink	Design products that promote full utilisation of functionalities.		■	■								
Reduce	Minimize use materials and resources in production and use stage.				■							
Reuse	Maintain uniform product quality during multiple use cycles.			■		■	■	■			■	
Repair	Ensure authorized parties can access and replace critical product parts.			■		■	■	■			■	
Reman/refurb	Ensure authorized parties can effectively recover the product to as-new state.			■		■	■	■	■	■	■	
Repurpose	Ensure product modularity to enable use for different purposes.			■		■	■	■	■		■	
Recycle	Ensure product materials are easily separable and recyclable.			■					■		■	

4.8 Discussion

Overall, using the R-strategies in our design methodologies has helped generate ideas, and seems to have improved the sustainability and circularity of the smart pillbox concept overall, especially when integrating multiple strategies into a single concept. Only the strategy of rethink seemed to have zero positive impact on product level sustainability, as this strategy mostly focused on developing system level design interventions. However, it is likely that a circular business model could be enabled through this strategy, which would improve the adoptability of most other R-strategies. Reuse and remanufacture/refurbish provided the most sustainability benefit when accounting for multiple use cycles.

Especially the reuse, repair, remanufacture/refurbish, and recycle strategies were easy to implement in the design process. However, it was in some cases hard to get a grip on the definitions of some strategies. This was especially the case for refuse, rethink, and reduce, due to their abstract nature. Based on a trial-and-error design process, we now feel confident to recommend addressing refuse from the perspective of product functionality, rethink from the system and service design perspective, and reduce from the product architecture perspective. The hardest strategy to design for was repurpose, as designing a function to be used after the initial function comes with a lot of uncertainty, as we cannot assure repurposing behavior of the user.

Especially since refuse is on top of the R-strategies hierarchy and is clearly the best option in terms of sustainability, we recommend to always start design processes by asking the following question: do we really need this functionality and if yes, is this specific product really the most effective and most sustainable way of addressing the need? It is, however, also important to consider the drawbacks of this R-strategy. For example, refusing a previously profitable product may lead to serious business trade-offs for any product category; but in the case of health devices, it may also pose serious safety risks. Although in our fast-track LCA we only compared concepts based on kg CO_2-eq, we recommend to also measure the impacts of the product redesigns on the product effectiveness. In the smart pillbox, for example, it would be crucial to determine whether the addition of electronics would improve medication adherence, and if so, whether this increase in adherence would pay back the higher environmental impact, which is a variable we would advise to consider in future assessments of similar products.

We concluded that refuse is hard to combine with other R-strategies, since in its ideal scenario there would not be any product. Thus, for cases where refuse is not favourable or only partially an option, we advise looking into the other R-strategies. In this, we advise brainstorming on all strategies, while putting more effort on R-strategies higher in the hierarchy, starting with optimizing the service systems surrounding the product to enable the other R-strategies (rethink) and minimizing unnecessary use of materials and resources in the manufacturing and use stages (reduce). Overall, we would advise always aiming to combine as many R-strategies as possible.

Therefore, although we now looked at each R-strategy separately, it is important to acknowledge the extensive overlap among them. For example, repair, repurpose, remanufacture/refurbish and recycle could all benefit from easily separable components and materials, and to enable reuse, repair, repurpose, as well as remanufacture/refurbish, part longevity is essential. While combining the different strategies, we would suggest only considering recycling to the extent that it does not unacceptably jeopardize the viability of any other R-strategy, adding it into the process only after designing for others, e.g. reuse.

Lastly, despite not being a sustainable or circular principle, an additional important consideration in the healthcare context is to put safety first. Not doing this can tremendously jeopardize the success rate: e.g., we cannot refuse functionalities that are vital to patient survival or reuse smart devices without first removing sensitive data from the previous patient. To ensure sustainability, it is however important to only design products that answer a user or patient need and will actually be used.

4.8.1 Limitations and Future Work

In the discussion we have already highlighted some specific limitations related to the implementation of the R-strategies in the design process and the assessment thereof. However, it is important to also acknowledge the limitations of our overall study method; most importantly the analysis which is based on a single case study. Despite valuable insights, we highlight the need for further research to validate our findings across diverse contexts in the healthcare domain. Additionally, our sustainability assessment was currently solely based on a mostly product-level fast-track LCA comparison of CO_2 impacts alone. This represents a clear limitation, as sustainability encompasses a broader range of environmental, social, and economic factors that warrant exploration in future investigations. The large uncertainties in LCAs could also be tightened by finding more precise data after further specifying exact designs, though this would cost time and money that may not be worth it for design strategies that do not show obvious potential for significant improvement.

Furthermore, while our study has focused on the R-strategies framework [7], it is essential to recognize that this framework may not encompass all aspects of sustainability, particularly in terms of the bio cycle as defined in the circular economy Butterfly Diagram [13]. Future studies could explore the integration of additional sustainability frameworks to provide a more holistic assessment of product design impacts.

While our study has provided valuable insights into the application of R-strategies in healthcare design, there remains ample room for further exploration and refinement. By addressing the limitations outlined and continuing to advance our understanding of sustainable design principles, we can work towards creating more resilient and environmentally conscious healthcare systems for the future.

4.9 Conclusion

In this paper, we aimed to assess whether the 10R-strategies framework could successfully be implemented in a design method for creating a more environmentally sustainable redesign of an electronic health device. To do so, we performed a design case study on a smart pillbox, including separate design sprints for each R-strategy, and combining those concepts into one redesign suggestion. For each design sprint, we assessed the quality of the integration of the R-strategy and the extent to which the R-strategy-based design concept had improved the sustainability and/or circularity of the product.

Overall, the R-strategies were easy to use as goals in normal design brainstorms. Especially the strategies of reuse, repair, remanufacture/refurbish, and recycle were easy to design for. For refuse, rethink, and reduce, some terminology confusion arose, which was solved by determining

points of focus: we addressed refuse from a product functionality perspective, rethink from a system design perspective, and reduce from a product level perspective. Repurpose was the hardest strategy to design for, as it seemed impossible to assure the repurpose process would actually take place and in which way the product would be repurposed.

To assess the environmental effectiveness of the R-strategies, we performed fast-track LCAs for each design concept. Refuse ensured the most improvement in CO_2-emissions, and reuse is similar if systems are in place for the product to actually be reused several times. Reduce is very likely an improvement, perhaps cutting impacts by half. However, the other R-strategies scored within uncertainty of the original product, so they may or may not provide improvements, depending on implementation specifics. Combining strategies can multiply benefits. We therefore advise designers to always combine rethink with one of the technical strategies (e.g. reuse or remanufacture / refurbish) and to only consider recycling after the other R-strategies have been utilized.

In our discussion on fostering environmentally sustainable electronic health devices using the R-strategies framework, we highlighted key considerations. These include maintaining product functionality in refuse, maximizing product functionalities in rethink, and prioritizing standardization, resource efficiency, durability, and cleanability across R-strategies. We also emphasized the significance of repairability, quality assessment, traceability, and material separation in recycling concepts.

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PART III, Chapter 5

Even when the main barriers to circular design (as identified in Chapter 2) are addressed, there is an improved understanding of circularity within the healthcare context (as discussed in Chapter 3), and appropriate methods and tools are available (as explored in Chapter 4), implementing circular design in practice can still fall short. In many cases, this is not due to flaws in the design itself but results from unforeseen consequences introduced by design interventions.

Chapter 5 investigates these trade-offs through a research-through-design case study on a single-use laparoscopic device. Redesigning the device for sustainability revealed tensions between recyclability, clinical performance, usability, and financial viability. Collaboration with a diverse group of stakeholders uncovered both expected and unexpected consequences, demonstrating that trade-offs are not always negative and providing guidance on how to navigate or mitigate them in future designs.

This chapter extends the narrative of previous chapters by showing that circular strategies, while theoretically sound, must be balanced with practical realities, especially for high-value, high-risk medical devices.

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Chapter 5

Balancing Trade-Offs in Circular Medical Device Design: A Case Study on Laparoscopic Devices

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Abstract— This study explores how circular design principles can be applied to single-use laparoscopic staplers to improve their carbon footprint without compromising critical requirements such as safety, performance, and financial feasibility. Using a research-through-design approach, four alternative concepts were developed: a fully recyclable device, a partially reusable device, a multifunctional device, and a manual device, aiming to reduce the carbon footprint while maintaining clinical performance of the device. Iterative design cycles incorporated feedback from Medtech professionals and from qualitative surveys with additional industry stakeholders. Fast-track life cycle assessments (LCAs) estimated environmental impact compared to the baseline device, while stakeholder feedback assessed trade-offs and synergies related to safety, usability, workflow compatibility, and regulatory compliance. Here, "trade-offs" refer to improvements in circularity coming with losses in other requirements, while "synergies" improve both circularity and other requirements together. Results revealed that each concept delivered potential carbon footprint reductions, particularly the reusable, multifunctional, and manual variants. Trade-offs included increased sterilization burden, altered surgical workflow, and reduced user familiarity; synergies included lower material and logistics costs from reuse and multifunctional design, achieved without compromising safety or usability. The findings highlight that achieving circularity in medical device design involves more than technical considerations; it requires a systems-level approach. Effective implementation depends on aligning design strategies with regulatory requirements, clinical workflows, and supply chain practices. This study provides recommendations to navigate trade-offs and identify synergies, supporting a structured approach to advancing sustainable practices in healthcare.

Keywords: Industrial Ecology, Circular Design, Medical Devices, Life Cycle Assessment, Sustainable Healthcare, Circular Design Trade-Offs

5.1 Introduction

As the healthcare environmental footprint grows [1], [2], the urgency for sustainable solutions intensifies. Among medical waste sources, single-use devices—such as powered laparoscopic instruments—are particularly concerning due to widespread use, short lifecycles, and embedded

electronic components, which add to mounting medical and electronic waste (e-waste) [3], [4], [5]. The environmental impact of medical devices is an increasingly important consideration within healthcare sustainability, particularly in the context of electronic waste, which is one of the fastest-growing global waste streams and remains relatively underexamined in this sector [6].

Laparoscopic surgical instruments—such as long-shafted scissors, clamps, and staplers—are used in minimally invasive surgeries via small 1 to 1.5 cm incisions in the abdomen or pelvis (Figure 23).

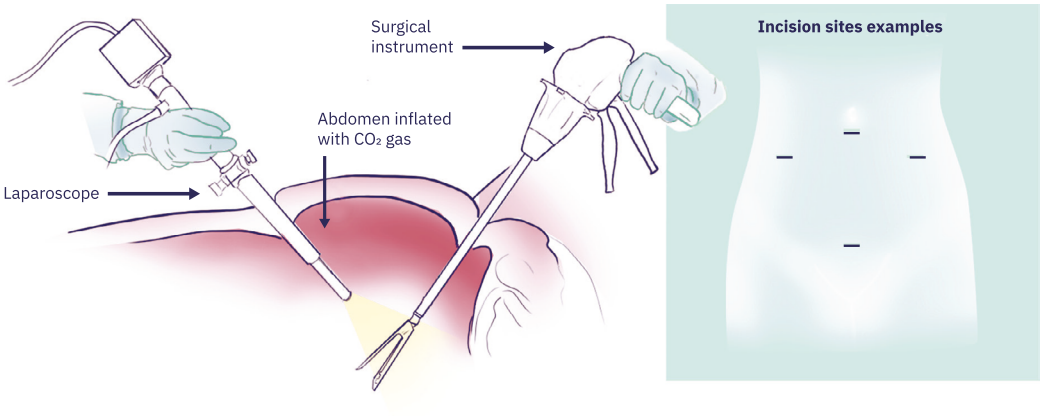


Figure 23: Laparoscopic Surgery

These procedures have improved patient outcomes by reducing blood loss, narcotic use, and hospital stays compared to open surgeries [7], [8], [9]. In this way, the emergence of laparoscopic surgery has already contributed to healthcare sustainability. However, the number of laparoscopic procedures is increasing rapidly—over 13 million were performed globally in 2020 [10]. The growing reliance on single-use and powered laparoscopic devices during those procedures, intended to reduce infection risk, exacerbates environmental challenges, especially through e-waste. Thus, while laparoscopic devices improve health outcomes, their environmental footprint—particularly through increased e-waste, emissions, and resource-intensive production—may contribute to broader public health risks beyond hospital walls.

Fortunately, there are opportunities for improvement. For example, Meissner et al., (2021) demonstrated that switching from single-use to multi-use surgical staplers significantly reduced waste and material requirements—by 40% and 92%, respectively—in laparoscopic sleeve gastrectomy, with similar reductions for other procedures. Similarly, Rizan & Bhutta (2022) reported that hybrid laparoscopic instruments—combining reusable and disposable parts—had a carbon footprint of approximately 1,756 g CO_2 equivalent (CO_2-eq) per operation, versus 7,194 g CO_2-eq for single-use equivalents, a 75% reduction. It is important to note that these instruments are less technically complex than laparoscopic staplers. Nonetheless, these findings highlight powered laparoscopic devices seem viable candidates for circular design, presenting a possible pathway toward reducing surgical waste.

Most laparoscopic instruments—including powered staplers—are however single-use. They are disposed after each procedure, sometimes after each actuation, meaning multiple staplers or their components may be disposed of in a single surgical procedure, leading to substantial waste

of valuable materials and electronic components. This continued reliance on single-use devices is largely due to the challenges involved in adopting a circular model. These challenges include maintaining clinical safety and performance while supporting sterilization and reuse, navigating regulatory frameworks, managing electronic waste, minimizing workflow disruptions, and addressing concerns about reliability and user acceptance [13], [14], [15]. Research exploring these trade-offs, especially for powered laparoscopic devices, remains limited. Although circular economy principles—such as reuse, refurbishment, recycling—offer promising paths to reduce resource use and waste in healthcare [16], their adoption in medical technology is still in early stages.

Existing circular design literature highlights trade-offs among cost, safety, clinical performance, and environmental impact in medical device procurement and use [17], [18], [19]. Yet few studies directly address common design challenges in circular medical devices. Prendeville et al. (2017), for example, examined eco-design dilemmas across industries, identifying tensions and contradictions in balancing sustainability with other requirements. Their framework offers operational, tactical, and strategic responses but does not focus on healthcare's unique demands. Likewise, Samenjo et al., (2023) did focus explicitly on healthcare-setting product design—evaluating circular economy implementation in low resource contexts via the Chloe SED® device—but their insights are confined to developing markets, offering limited guidance for high income, highly regulated environments such as the EU and US.

This study explores single-use powered laparoscopic staplers as a case study to explore how circular design can be applied in practice under the strict safety and regulatory constraints of healthcare systems. It addresses the following research question: How can trade-offs and synergies between circularity, safety, functionality, usability, and regulatory compliance be systematically assessed and managed in the design of complex medical devices? Focusing on this device category allows the study to examine the interactions between environmental goals and the non-negotiable requirements of healthcare. Research-through-design (RtD) methods were used to develop and iteratively refine four concepts—fully recyclable, partially reusable, multifunctional, and manual—while fast-track life cycle assessments (LCAs) quantified environmental impact and stakeholder feedback captured trade-offs and synergies. By integrating RtD, fast-track LCA, and stakeholder input, the study provides practical recommendations for advancing circular medical devices without compromising clinical outcomes or market viability.

5.2 Methods

This study followed a circularity-driven Research-Through-Design (RtD) approach [22] to redesign a medical product for improved circularity and a lower carbon footprint. RtD is a methodology in which design activities themselves are treated as a way of learning: creating prototypes and iterating on concepts generates knowledge about complex systems, user needs, and real-world constraints.

The baseline device—a powered linear laparoscopic stapler commonly used for transecting and sealing tissue—was first analysed to understand material composition, assembly complexity, and opportunities for reuse, recycling, or simplification. Observations of the device in use within the operating room and sterilization department, together with consultations with surgeons and engineers conducted during these observations, helped capture practical handling challenges and workflow considerations. These observations were summarized in a simplified product journey

map (simplified version in Appendix A), which documents the device's lifecycle, handling steps, and system-level opportunities for improvement.

Four design concepts were then developed through iterative cycles, guided by expert input from a Medtech firm and other stakeholders (Figure 24). The design process followed circular design guidelines adapted from [14], alongside additional guidelines addressing regulatory, usability, and safety requirements. Regulatory requirements were integrated through expert consultation (Appendix B). Environmental hotspot analysis (fast-track LCA) was used separately to identify priority areas for improvement in this specific device and to provide a baseline for comparison with the redesigned concepts.

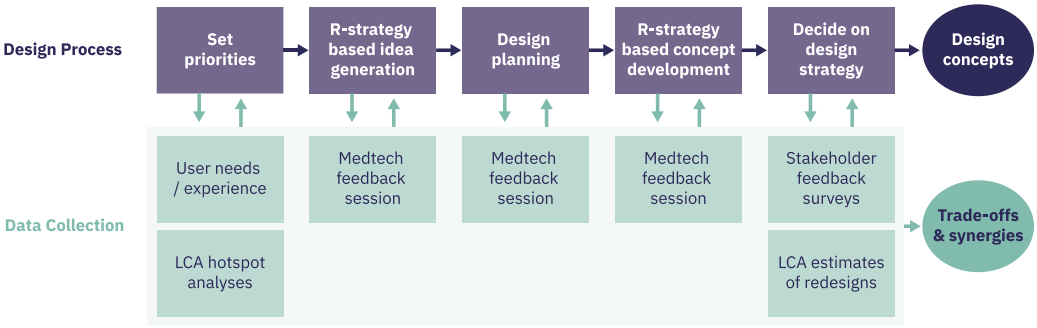


Figure 24: Overview of RtD Methodology

The RtD approach allowed identification of opportunities to improve circularity and lower the carbon footprint, highlighted areas where compromises were needed, and made trade-offs explicit, providing insights beyond this specific stapler. Concepts were developed using a morphological chart, a design tool that breaks a product down into its main subfunctions and explores alternative solutions for each [23]. For this study, the approach was adapted to consider circular strategies—such as refuse, reuse, repair, and recycle—rather than only functional decomposition. This made it possible to systematically identify design opportunities that boost circularity while still meeting clinical and regulatory requirements. Concepts were refined through structured feedback, with updates to the circular design guidelines after each cycle (final version in Appendix C).

Trade-offs between circularity and other key design requirements, such as safety, functionality, and economic feasibility, were evaluated through (1) the level of circularity improvement per concept, (2) expert feedback, (3) stakeholder surveys, and (4) challenges identified during the design process. In this context, trade-offs are defined as the ways improvements in circular design objectives (e.g., durability, reparability, or recyclability) are balanced against drawbacks in one or more performance domains—such as safety, usability, workflow integration, or regulatory compliance. As the devices assessed in the LCA were conceptual, expert feedback and stakeholder survey responses were based on projected performance and assumptions, rather than on validated real-world devices.

5.2.1 Life Cycle Assessment

Fast-track LCAs were conducted to (1) set priorities for redesign from environmental hotspots; (2) decide between design concepts by comparing their estimated LCA performance to the

baseline; and (3) uncover challenges in designing for circularity, highlighting additional trade-offs or synergies.

The fast-track LCAs were performed on the product level; although full-system LCAs provide broader insights into healthcare pathways [24], a product-level approach was chosen for its practicality and focus on redesign-relevant impacts. The study followed a cradle-to-grave system boundary, covering raw material extraction, manufacturing, packaging, transportation, use, and end-of-life (EoL) treatment. Assembly and gamma sterilization prior to distribution were excluded due to their negligible contribution to total impact and lack of reliable data. The assessment was performed using SimaPro version 9.5.0.1, with background data sourced from Ecoinvent v3.9.1. The Environmental Footprint (EF) 3.0 method was used for Life Cycle Impact Assessment (LCIA). The functional unit was defined as the environmental impacts per use cycle. This reflects the clinical service delivered rather than the product itself, thereby enabling a fair comparison between single-use and (partially) reusable device concepts. Finally, both the baseline and circular design concepts were assessed for 50 (re)use cycles, respectively, based on manufacturer guidelines specifying up to 50 uses with proper cleaning and sterilization [25]. For end-of-life modelling, system expansion was applied as the allocation method, crediting the system for energy recovery from incineration and recyclate substitution in the case of recycling, based on a 1:1 substitution assumption. The baseline product and use scenario was a powered linear laparoscopic stapler; a single-use device used for transecting and sealing tissue during minimally invasive surgical procedures, which is incinerated after use. This device served as the starting point for the subsequent redesign within the research-through-design (RtD) process. The baseline product model was constructed using primary data provided by the device manufacturer, including information on materials, production processes, transport, packaging, and end-of-life characteristics. Secondary data from peer-reviewed literature and the ecoinvent database supplemented missing information where necessary. To model the four circular design concepts, the baseline data were updated to reflect key changes such as alternative materials, reuse potential, and sterilization requirements, while maintaining consistent system boundaries and usage context, with larger uncertainties assigned to aspects with less clarity or more variation (e.g., number of reuses). For the purpose of the LCA, the device was assumed to be assembled in the US, and used in a Belgian hospital, and Belgium-specific EoL treatment was applied accordingly. Surgical staples were excluded from the model, as staple type and quantity vary between procedures and could not be standardized across the use cases.

5.2.2 Identifying and Analysing Trade-Offs

Trade-offs between circularity benefits and challenges were identified through an analysis of stakeholder surveys and expert (Medtech) feedback on the product redesigns and were further informed by the design guidelines developed earlier. These guidelines were based on environmental hotspot analysis (fast-track LCA), consultations with surgeons and engineers, and observations in the OR and sterilization department. The insights were examined using both qualitative and quantitative approaches to compare the environmental improvements of the circular designs against challenges related to financial viability, logistics, and technical feasibility. This approach enabled actionable recommendations that balance circularity gains with other key design considerations.

A phased approach (as displayed in Figure 24), starting with Medtech feedback before involving other stakeholders, was adopted for several reasons. First, Medtech professionals bring specialized

expertise in regulatory compliance, medical safety, and technical feasibility, ensuring that designs meet essential industry standards early on. Second, this strategy allows for focused, efficient refinement, preventing premature exposure of underdeveloped ideas to a broader audience. Resolving significant technical and functional challenges early ensures that feedback from other stakeholders can focus on broader considerations such as user experience, sustainability, and market acceptance. Lastly, this phased approach prevents feedback overload, guiding early design decisions with expert input while reserving diverse perspectives for later stages.

5.2.2.1 Medtech Feedback Sessions

At the end of each iterative design cycle, design concepts were evaluated in three online feedback sessions with key stakeholders from a large Medtech firm, representing environmental sustainability, global sustainability oversight, and R&D product leadership in surgical stapling. These sessions aimed to identify potential trade-offs associated with circular design interventions and re-evaluate design decisions to inform subsequent iterations. Feedback sessions were scheduled at critical points to ensure insights could be integrated in the next design cycle. Participants evaluated design ideas from both product-specific and system-wide perspectives:

Product-related aspects:

- Functionality and performance: how design changes affect the device's ability to meet user and patient needs.
- Ease of use and maintenance: implications for usability and long-term maintenance.
- Medical safety: risks related to contamination, perceived safety, and adherence to safety protocols.

System and implementation aspects:

- Financial viability: feasibility from a business and market perspective.
- Regulatory compliance: potential challenges in meeting medical and non-medical standards.
- Technical feasibility: the practicality of implementing the design using current technologies.

A primary focus was on identifying the trade-offs associated with circularity, with participants reflecting on how design decisions could reduce the carbon footprint across the product lifecycle, while potentially jeopardizing design requirements in other areas, such as functionality, safety, financial viability, or regulatory compliance. The Medtech feedback sessions were recorded and summarized. These meetings captured expert observations grouped under the key evaluation perspectives (e.g., environmental sustainability, functionality, financial viability).

The Medtech experts jointly ranked each concept from 1 to 4 per just-mentioned product- and system-related criterion, providing an expert-based evaluation. Heatmaps were generated to visualize those expert rankings. Additionally, the experts were requested to explain the reasoning behind their scores, reflecting on how specific design choices affected the different perspectives. Trade-offs were identified by examining cases where concepts with a higher carbon footprint were ranked higher than those with a lower carbon footprint, and vice versa. When a concept scored low on certain aspects despite offering more circularity interventions, we analysed the underlying reasons for these discrepancies.

5.2.2.2 Stakeholder Surveys

Following the development of four design concepts, a broader group of stakeholders (Table 15) was invited to assess the designs. This qualitative evaluation involved stakeholders rating each concept on a Likert scale ranging from "very poor" to "very good," with "acceptable" as the neutral midpoint, for the same evaluation perspectives as were discussed with the Medtech experts above. Participants also provided written explanations for their ratings, highlighting trade-offs or synergies associated with the circular design in terms of functionality, sustainability, financial viability, and other factors. A full version of the survey is provided in Appendix D.

Table 15: List of Survey Participants

P#	Job title	Expertise	Healthcare experience
1	General Surgeon	Surgery execution and testing new laparoscopic products	Yes
2	Sustainability Business Analyst	Sustainability, industrial design	Yes
3	Assistant Professor	Sustainable design	Yes
4	Technical Advisor	Collection, reverse logistics, recycling, WEEE take-back schemes	No
5	Chief Business Development Officer	Smart collection systems	No
6	Project Management	Circular business models	No
7	Research Associate	Digital Nudging, AI, Sustainability	No
8	Senior Manager in Business Transformation & Innovation	Advanced technologies and innovation	Yes
9	Business Developer	Healthcare industry (pharma & medical devices), business models, behaviour strategies	Yes
10	Assistant Sustainability Project Manager	Project management, sustainability, carbon footprinting	Yes

Although some participants lacked direct healthcare expertise, their inclusion was intentional. As circularity is still emerging in healthcare design, experts from sustainability and circular business fields offered valuable, cross-industry insights. Their broader perspective helped identify design trade-offs that may be overlooked by those within the healthcare sector.

To enable a structured comparison of the design concepts, stakeholder survey data were analysed using the same evaluation criteria as those applied in the Medtech expert ranking. The stakeholder survey (N = 10) used a 1–5 Likert scale across seven criteria: financial viability, logistical feasibility, functionality and performance, ease of use and maintenance, regulatory compliance, medical safety, and technical feasibility. Raw scores (3.0–4.9) were normalized across all 28 values to a 0–1 scale using (raw – 3.0)/1.9 and visualized using quartile-based color coding, ensuring alignment with the expert ranking.

5.3 Results

The summarized results of the baseline fast-track LCA (assessing the single-use linear powered stapler) are presented in Figure 25.

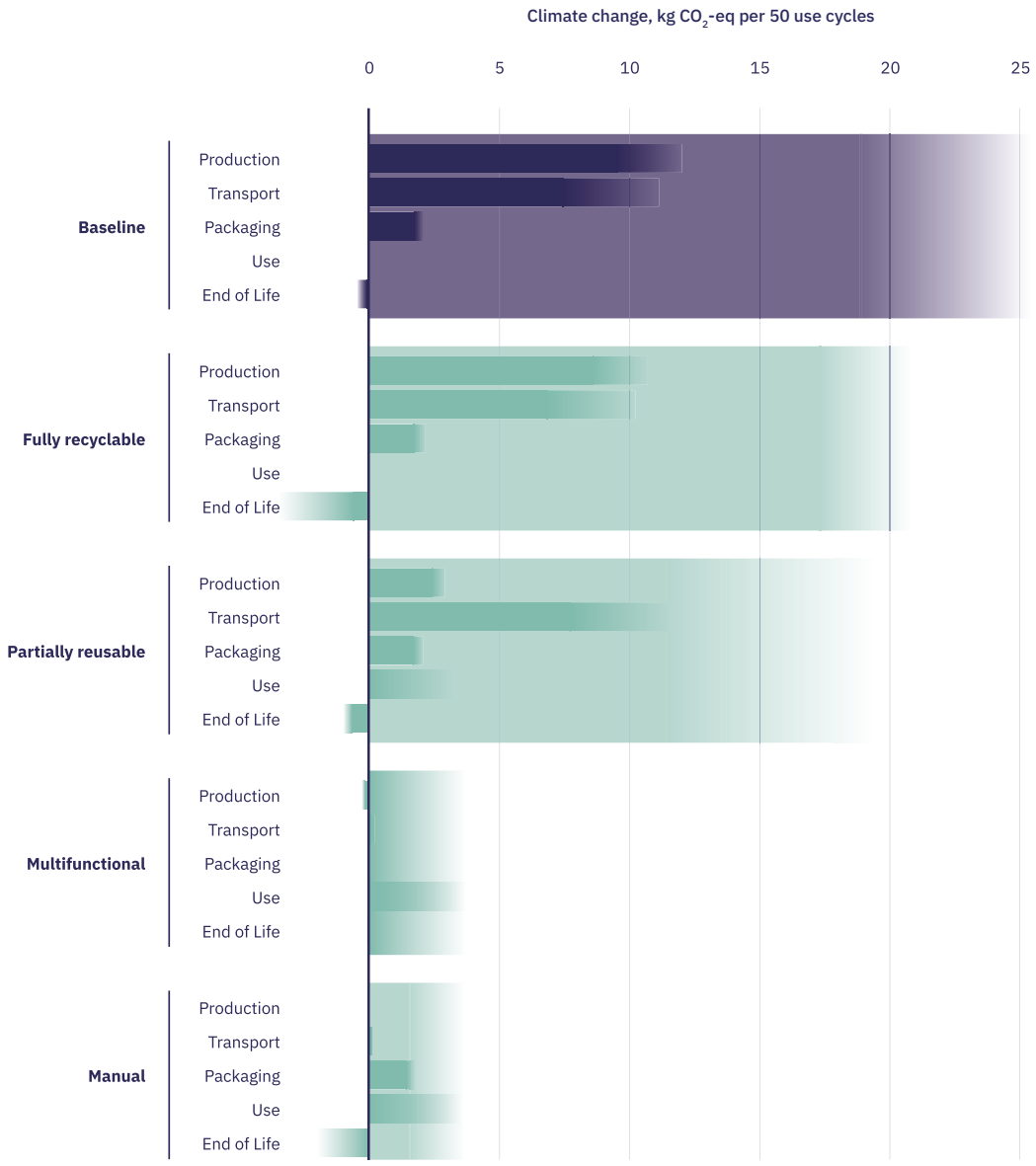
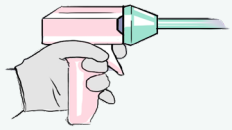
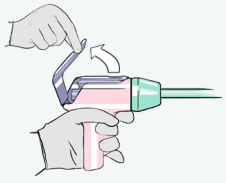
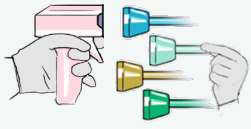
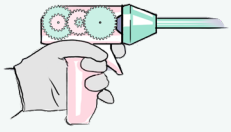


Figure 25: Climate Change in kg CO_2-eq per 50 Use Cycles for Total Impacts of the Baseline Versus New Design Concepts, Including Climate Change per Process. Gradients represent uncertainty.

While the manufacturing impacts seem to dominate overall, they are not significantly different from transport impacts. Transport impacts were high, because different processes (e.g. assembly, sterilization, use, etc.) are based in different regions (or even countries) due to which a lot of transport is needed. This includes for example air transport from the distribution centre in the US to hospitals in Belgium. Based on the LCA, key environmental hotspots were identified, particularly in the production of printed circuit boards and batteries. Usage impacts are zero because the device's battery is already charged in production, no additional charging is performed in the surgery theatre. EoL impacts are net negative because the total treatment burden is fully offset by credit from the energy recovered during the incineration of hazardous waste.

The fast-track LCA hotspots, combined with the established design guidelines (Appendix C), highlighted challenges for improving environmental sustainability at both the product and system levels. System-level considerations—such as material separation, component reuse, and handling—further shaped the design concepts. These insights guided the iterative redesign process. Four conceptual redesigns were developed to enhance circularity while addressing potential trade-offs. Each concept—refined through iterative expert feedback—targets specific hotspots using distinct circular strategies, as summarized in Table 16.

Table 16: Design Concepts and Their Addressed Hotspots

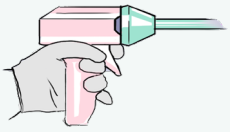
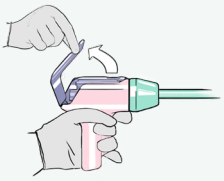
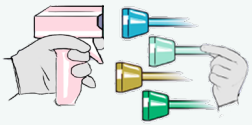
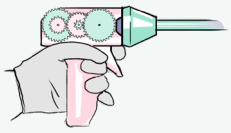
Design Concept	Description	Addressed Hotspots/Challenges
Recyclable Device 	Hospital separates battery, decontaminates components, and sends both battery and device for recycling. Compact design with three click-separable compartments: metal shaft, plastic casing, electronics with single-use battery. Clear icons guide disassembly.	• Material recovery at end-of-life • Battery management simplified through separable electronics unit. • Efficient separation workflow
Partially Reusable Device 	Internal electronics unit is reusable; outer components are single-use and recyclable. Electronics unit is removed, recharged, and reused; plastic casing and other parts are recycled. After ~50 uses, electronics are recycled.	• E-waste reduction through electronics reuse•Battery charging • Risk of battery contamination (in case of battery reuse) minimized. • Workflow integration for disassembly and recharging
Multifunctional Device 	Modular device with reusable main unit and interchangeable click-on shafts. Electronics housed in main unit; shafts and shell are swapped and sterilized after each use. Tracking system monitors usage; electronics refurbished or recycled after lifespan.	• Electronics consolidation (minimizing need to use multiple electronic devices • Material efficiency • Reuse tracking • Operational flexibility across procedures
Manual Device 	Fully manual device with no electronics. Designed for full reuse, cleaned and sterilized after each use. Refurbished at end-of-life, then recycled if necessary. Focus on durability and simplicity.	• Completely eliminates electronics and battery management • Maximizes ease of reuse • Simplified workflow and sterilization

Simplified system maps and concept illustrations can be found in the stakeholder surveys provided in Appendix D.

5.3.1 Life Cycle Assessment (LCA) Comparison

The baseline product and four design concepts were evaluated using LCA to compare their carbon footprint. The environmental impacts of each design concept were derived by modifying the baseline LCA data to reflect specific design changes, as indicated in Table 17.

Table 17: LCA Assumptions per Design Concept

Design Concept	Description
General changes assumed for all concepts	• Metals → 316L stainless steel: preserves strength/biocompatibility • Plastics → medical-grade PP: adequate strength, may slightly alter weight/ balance • Functional equivalence maintained: all concepts meet standard surgical performance (staple line integrity, compression, trigger reliability, laparoscopic workflow compatibility)
Recyclable Device 	• General changes (as above) • Full device sterilized and recycled after each use
Partially Reusable Device 	• General changes (as above) • Reused electronics unit contains battery and PCB • Remaining plastics/metals sterilized and recycled • Split-use sterilization: patient-contact parts single-use; non-sterile components disinfected with IPA wipes • Battery replaced by a rechargeable battery
Multifunctional Device 	• General changes (as above) • Sequential functions only; energy sealing excluded • Test was performed based on functionalities used in common surgeries • Minor learning curve possible; ergonomics acceptable.
Manual Device 	• General changes (as above) • No electronics; fully mechanical • Device fully reusable and sterilizable • All components go to recycling at EoL

As Figure 25 shows, the Multifunctional Device and Manual Device demonstrated the likely lowest impacts in kg CO_2-eq. This was achieved either by eliminating electronic components or by consolidating multiple functions into a single reusable electronics module with separate metal actuator modules—thereby avoiding most of the carbon footprint (kg CO_2-eq) associated with the production, use, and disposal of several separate products. The Partially Reusable Device offered a moderate improvement from baseline by extending the lifespan of electronic components and reducing electronic waste, though it still incurred carbon footprint impacts (kg CO_2-eq) related to electronics. The Recyclable Device offered the least improvement in in life-cycle carbon footprint (kg CO_2-eq). Despite being designed for disassembly and disintegration in shredding for material recovery, its single-use nature meant its impacts were almost the same as baseline, because most of the device's total life cycle carbon footprint impacts are from manufacturing the electronic components. As expected, the reusable design concepts scored higher in terms of reduced life cycle carbon footprint. However, the impact of the use phase increased due to the need for disinfection, sterilization, and battery charging. Notably, this increase did not dominate the overall life cycle results or create a new environmental hotspot.

5.3.2 Assessment of Product- and System-Perspectives

The comparative assessments of the four device concepts, based on stakeholder survey data and Medtech expert rankings, are summarized below. Table 18 presents a heat map of the Medtech collective expert ratings, where 1 indicates lower/poorer ranking, 2 indicates intermediate/less favourable values, 3 represents moderately good performance, and 4 indicates higher/better ranking. Further clarification of how the ranking was performed, can be found in the methods description (section 5.2.2.1).

Table 18: Medtech collective expert ratings (Raw 1-4 scale, coded as: 1; 2; 3; 4)

Average rating of ...	Recyclable design	Reusable design	Multifunction design	Manual design
Financial viability	1	2	3	4
Logistic feasibility	4	2	3	1
Functionality & performance	4	2	1	3
Ease of use & maintenance	4	2	1	3
Regulatory compliance	4	1	2	3
Medical safety	4	2	1	3
Technical feasibility	4	3	2	1

Table 19 presents a similar heat map of the scores derived from the survey ratings for the same criteria. To ensure comparability of the Medtech 1-4 ranking with the 1-5 Likert scale of the surveys, the survey data was normalized into quartiles (more information in section 5.2.2.2).

Table 19: Normalized Survey Ratings (Normalized over all 28 values; quartiles: ≤ 0.3575; > 0.3575–0.525; > 0.525–0.68; > 0.68)

Average rating of …	Recyclable design	Reusable design	Multifunction design	Manual design
Financial viability	0.16	0.26	0.32	0.47
Logistic feasibility	0.37	0.42	0.00	0.63
Functionality & performance	0.68	0.74	0.63	0.11
Ease of use & maintenance	0.63	0.58	0.11	0.42
Regulatory compliance	0.74	0.63	0.37	0.68
Medical safety	1.00	0.74	0.47	0.47
Technical feasibility	0.68	0.68	0.11	0.58

5.3.2.1 Recyclable Device

Table 18 shows that Medtech experts selected the Recyclable Device as their overall favourite despite assigning it a low score on financial viability. This aligns with Table 19, where the concept scores relatively high in regulatory compliance (0.74) and medical safety (1.00), reflecting its perceived reliability and familiarity. They valued its familiar form and minimal perceived disruption to clinical workflows. Stakeholder survey respondents confirmed its ease of integration, noting that it seems "the device does not require maintenance," "the collection of the devices is done as a unit, which is easier to handle," and "most of the infrastructure for the value chain should already be in place." They also highlighted its safety benefits: "less contamination and malfunction risks than reusing or refurbishing," and "safety is guaranteed with no risk of cross contamination." Yet the same respondents rejected it for its environmental shortcomings, warning that "the recycling of plastic is currently limited because of the cost of virgin plastics being much lower". They further cautioned that reliance on virgin feedstocks could incur "significant costs for transportation and use of those virgin materials," underscoring the trade off between immediate feasibility and long term sustainability.

5.3.2.2 Partially Reusable Device

The Partially Reusable Device ranked second worst in LCA impact but was the second most preferred overall, as indicated by its mid-to-high normalized scores in Table 19 (e.g., functionality & performance = 0.74; regulatory compliance = 0.63), with 50 percent of stakeholder survey respondents naming it their favourite. Survey participants praised its ability to reduce e waste while keeping design and logistics largely unchanged: "staff only need to charge the battery as an extra step," and "as the housing is still single use, it would probably comply." In Medtech feedback sessions (Table 18), experts cautioned that the extra steps for charging and reassembly could introduce risks around maintenance, reliability, and aseptic transfer[1], potentially leading to user resistance.

1 **Aseptic transfer** refers to the process of moving materials without contamination, maintaining sterility to ensure safety and prevent infection in medical settings.

Survey respondents echoed operational concerns—"reusing contaminated medical components/devices/parts presents a challenge in terms of compliance with the regulatory framework," and "the re use of 'contaminated' components/products involves decontamination and quality control measures, which in turn increases the contamination risk and device malfunction"—even though, in practice, the electronics module never contacts bodily fluids.

5.3.2.3 Multifunctional Device

The Multifunctional Device, despite its strong low carbon footprint in the LCA, faced significant concerns regarding its practical implementation, as reflected by its low technical-feasibility and ease-of-use scores in Table 19 and its low expert ranking in Table 18. Medtech experts argued the technical infeasibility of integrating multiple functions into a single device due to differences in e.g. circuitry and actuation, while also highlighting challenges in maintenance, usability, and sterilization. Stakeholders also pointed to logistical complexities related to managing the modular components and their sterilization processes, noting that these "may require additional oversight" and that the "many individual components and their processes make it more complex to use and maintain." Inventory control was also emphasized as a critical issue, with difficulties in tracking components leading to procurement inefficiencies and the need for specialized routing between departments. Financially, while some recognized potential long-term cost savings through reuse, others expressed concern over "higher initial costs" driven by the complexity of maintenance, training, and multi-function design. Regulatory compliance was frequently mentioned as a key hurdle, especially around "reusing 'contaminated' medical components" that demand rigorous decontamination and quality control, increasing both contamination risk and operational complexity. Despite these concerns, the device's modular adaptability received praise for "allowing multiple surgical uses" and increasing overall functionality. Interestingly, while many participants questioned the practical usability of this device for the user, the surgeon participant preferred this device precisely for its usability and practicality. This may indicate a trade-off between perceived and real-world operability, emphasizing the need to include clinical end-users in design evaluation.

5.3.2.4 Manual Device

As reflected in the LCA outcomes, both Medtech experts and other stakeholders recognized the manual device as the device with the lowest carbon footprint in theory. However, as Table 18 shows, Medtech experts also described it as the least feasible option. They argued that powered staplers, which exist for ergonomic and performance reasons, have clear benefits over manual staplers. Therefore, reverting to a manual design could compromise usability and surgical outcomes. While reducing electronic components may lower the carbon footprint, experts cautioned that achieving comparable precision and consistency through mechanical means would be highly challenging. If development proceeds in this direction, the focus should be on identifying which electronic functions are essential and exploring smart mechanical alternatives that maintain performance without sacrificing usability.

Other stakeholders echoed these concerns in Table 19, noting that "manual operation may not be ideal for all surgical applications," and that "electronics have simplified procedures by reducing operation times and improving results and patient care." They also highlighted higher risks if the device lacks automated checks to ensure correct procedures, placing greater responsibility on operators. Despite these potential downsides, stakeholders identified several synergies of removing electronics. For example, logistics become "simpler, with no complex waste management

required," and "the reuse of components would align with current and upcoming [sustainability-stimulating] regulations." The device "seems easy to use, with no need for charging batteries or additional steps." Additionally, some stakeholders suggested that a manual device "could be less costly and thus less profitable". This highlights the importance of the business model: hospitals, manufacturers, or both could capture value from new pricing strategies. In particular, "profits can likely be increased if you can charge per surgery or per- use" (although this is harder to implement without electronics to track usage). This pay-per-use approach creates new opportunities for revenue sharing and aligns incentives across stakeholders, but it requires reliable usage tracking to be feasible. However, the Medtech experts pointed out that, due to potentially increasing surgical complications, the whole patient journey could become more expensive and have an increased carbon footprint as the treatment of complications is included in the delivery of care.

5.3.3 Circular Design Trade-Offs

Through the RtD process, we identified a comprehensive list of trade-offs stemming from interventions aimed at improving the circularity and lowering the carbon footprint of single-use laparoscopic staplers. The trade-offs were consolidated over all design concepts. This full list of consequences is presented in Table 20, alongside potential solutions we explored to address these challenges.

Table 20: Overview of Trade-Offs per Sustainability Intervention, With Potential Solutions

Sustainability intervention: use of recycled materials in production	
Trade-off	**Potential ways to manage tension**
Potential decrease in quality and performance for needed functionality.	Develop high-performance recyclable materials and testing to ensure recycled materials meet quality standards for expected number of use cycles.
Increased costs for production, as virgin plastics may be cheaper.	Highlight the long-term added value of reducing the dependence on virgin materials.
Regulatory compliance: use of recycled materials might be restricted.	Use recycled content for non-sterile product parts, and when recycling practices improve, engage with regulators early to update guidelines.

Sustainability intervention: enabling safe reuse (incl. sterilization)	
Trade-off	**Potential ways to manage tension**
Increased hospital costs due to new systems for component maintenance.	Shift focus to long-term savings or introduce alternative models (e.g., pay per use).
Logistic complexity and difficulties; need for changes in infrastructure.	Utilize logistics systems of e.g. sterilization flows and digital tracking systems that are already in place for other instruments used in the same surgical setting. To enable change, plan phased infrastructure upgrades and incentives, by developing a "roapmap".
Regulatory barriers due to strict sterilization and tracking requirements.	Same as above. In addition, collaborate with regulators to create clear protocols.
More effort needed in collection and separation.	Minimize need for separation and develop efficient collection and separation processes. E.g. implement matching coding systems on devices/components and collection bins.
Additional maintenance and quality control.	Use periodic maintenance that is already obligatory. Where possible, automate maintenance checks (e.g. in traceability systems) and enhance quality control processes.
Higher risk of device malfunction.	Implement robust quality assurance and monitoring.

Concerns about contamination risk compared to single-use devices (leading to preference for single-use or recycling over reuse).	Design devices for easier cleanability (e.g. smooth surfaces, limited number of parts, no inaccessible cavities) and communicate safety benefits of decontamination process. Additionally, highlight that processes needed for recycling (e.g. disassembly and decontamination) already enable processes like refurbishment.
Need to change whole system of manufacturers who might resist.	Foster industry collaboration and incentives for system change, or make use of market differentiation business opportunities.

Sustainability intervention: battery charging	
Trade-off	**Potential ways to manage tension**
Requires space that might not be available.	Design standardized solutions for compact charging stations.
Requires additional maintenance.	Develop low-maintenance charging solutions.

Sustainability intervention: using existing recycling systems	
Trade-off	**Potential ways to manage tension**
Regulatory restriction on collecting contaminated electrical devices for recycling.	Ensure full decontamination before collection or explore on-site treatment options to comply with EU waste and infection control regulations.

Sustainability intervention: reality-based decision-making	
Trade-off	**Potential ways to manage tension**
Complexity drives stakeholders to rely on assumptions rather than actual data, while those do not always reflect reality.	Apply system-level thinking and sustainability assessments such as (fast-track) LCA early to guide design decisions and align perception with real impact.

Sustainability intervention: radical and complex innovation	
Trade-off	**Potential ways to manage tension**
Preference for incremental innovation limits adoption of radical solutions.	Use “transfer in perception” to frame radical innovations as approachable.
Assumed infeasibility of complex alternatives without testing.	Prototype early and involve end-users.
Prioritization of less sustainable but simpler strategies.	Promote system-level thinking and evidence-based decision making.

Sustainability intervention: introducing system thinking	
Trade-off	**Potential ways to manage tension**
Assumed trade-offs without verifying with stakeholders.	Engage diverse stakeholders in evaluation, preferably simultaneously.
Financial conflicts among multiple parties.	Facilitate transparent stakeholder collaboration, have all perspectives involved.

Sustainability intervention: multifunctional design	
Trade-off	**Potential ways to manage tension**
High manufacturer costs.	Base the business model and sales prices on system-level cost and savings calculations.

Increased technical complexity, with high uncertainty in feasibility.	Acknowledge how investment in development and standardization of modular design comes with long-term benefits.
Usability concerns due to complexity.	Incorporate user feedback and training (usability concerns are often highlighted by stakeholders who are not the users).
Increased inventory control and management complexity.	Make use of existing logistic systems; e.g. use of instrument packs dedicated for a specific surgery.
More maintenance and quality control needed.	As multifunctional device replaces some other devices, need for maintenance will not necessarily increase over the full system.
Weak points in device connections.	Use the same connectors as used in the single functionality devices, or improve engineering and quality assurance.
Coordination challenges across multiple hospital departments.	Make use of existing logistic systems; e.g. use of instrument packs dedicated for a specific surgery.
Difficulty balancing multifunctionality and performance.	Optimize modular components for specialized tasks.
Need for new storage, logistics, and tracking systems.	Deploy digital tracking (medical devices are already registered for each use) and design standardized storage solutions.
Higher contamination risk due to human error and misuse.	Enhance training and error-proof design.
Increased device cost for hospitals.	Explore cost-sharing and service models or explore pay-per-use models.

Sustainability intervention: enabling device traceability	
Trade-off	**Potential ways to manage tension**
Data privacy and protection concerns.	Use secure, compliant data management systems. Do not store data inside the device.
Technological challenges.	Utilize the digital tracking systems that are already in place in the hospital setting.
Additional regulatory compliance requirements.	Collaborate with regulators early.

Sustainability intervention: providing spare parts	
Trade-off	**Potential ways to manage tension**
Increased complexity and risk in the supply chain.	Strengthen supplier networks, implement robust inventory management, and optimize logistics to ensure timely delivery of spare parts.

Sustainability intervention: reducing electronics in design	
Trade-off	**Potential ways to manage tension**
Risk of limited adoption if perceived as lack of innovation.	Communicate design rationale and benefits. Design for desired device perception.
Less functionality / performance than powered variants.	Aim to engineer for mechanically offering the features that powered devices offer, and if needed, integrate only part of the electronics or aim to use manual variants for low-risk surgeries only.
Lower practicality in high-tech surgical environments.	If certain functions cannot be offered mechanically, aim to design hybrid solutions combining manual and electronic elements.
Reliance on manual input increases risk of misuse or error.	Include training and fail-safes

5.3.4 Sustainable Design Synergies

The design of medical devices for circularity is often met with resistance due to the many drawbacks highlighted previously. However, it is important to note that circular design does not always come at a cost; in some cases, it can even offer clear benefits. For example, reusable devices are not necessarily more expensive, less clinically effective, or associated with higher contamination risks—sometimes they bring savings and advantages that encourage their adoption. Similarly, during our RtD process—especially through stakeholder surveys—we identified many synergies that act as practical enablers for sustainable decision-making. The results of this analysis are summarized in Table 21.

Table 21: Overview of Synergies

Sustainability intervention	Synergies
Use of recycled materials in production	Reduced dependence on virgin materials
Enabling safe reuse (including sterilization)	Reusing valuable components (e.g., electronics) lowers overall costs
	Reduced dependence on virgin materials
	Improved compliance with upcoming sustainability regulations
	Potential for long-term cost savings despite higher initial costs
	If properly sterilized, modular components maintain high safety standards
Multifunctional design	Consolidates instruments, reducing sterilization cycles and energy use, enhancing both circularity and cost-effectiveness
	Reduced cost per procedure
	Increase in functionality—adaptability allows for multiple surgical uses
	Potentially improved usability and user experience
	Interchangeable parts may be a first step toward standardization in the field
Radical and complex sustainable innovation	Enables market differentiation and opens business opportunities through sustainability leadership
	Built-in complexity may support close device monitoring and thus improve safety
Reducing the electronics in the design	Reduces device cost
	Easier regulatory compliance
	Compatible with existing sterilization flows (low contamination risk)
	Easy to use and learn
	Simpler technology, easier maintenance
	Better safety—no electronics in wet operating room environments
	Reduced risk of malfunction
Using existing recycling systems	Dismantling and sterilization processes needed for recycling, already enable transition toward more advanced strategies like reuse or refurbishment
	Familiarity encourages user acceptance
	Familiarity reduces the risk of improper use
Introducing system thinking	Enables development of service-based business models (e.g., product-as-a-service)
Enabling device traceability	Allows devices to be linked to patients to enable traceability in case of error

5.3 Discussion

The results above show that redesigning laparoscopic surgical devices for circularity while improving carbon footprint is inherently challenging, given the strict demands of functionality, performance, usability, medical safety, financial viability, regulatory compliance, and technical feasibility. However, the study also suggests that these challenges are sometimes interpreted as more severe than the evidence indicates, and that considering carbon footprint and circularity can also offer important synergies, benefiting cost, safety, and clinical practice simultaneously. A clear example of this is the multifunctional device. While many stakeholders initially presented its usability as a fundamental trade-off—arguing that surgeons would find such a device impractical—the surgeon participating in the study ultimately selected it as his preferred option, precisely citing its practicality and ease of use, which contrasted with assumptions voiced by others. This discrepancy may illustrate how interpretations of barriers, including compliance requirements and waste definitions, can obscure real opportunities for innovation. Similar patterns have been noted in previous work, where barriers to sustainable medical device design were often more perceptual than factual, particularly regarding safety and regulatory compliance [14].

A similar tension was observed in the difference between stakeholder and expert preferences versus the LCA results. For example, while Medtech experts identified the recyclable device as the least sustainable option due to its reliance on virgin materials, they favoured it overall, because it represented the "most advanced yet acceptable" option—closest to current devices in design and use, and therefore easiest to integrate into existing clinical workflows and regulatory pathways. This made it a pragmatic stepping stone toward circularity, enabling faster adoption and more immediate impact compared to more radical redesigns. In contrast, other stakeholders rejected the recyclable device precisely because they perceived it as environmentally inferior. Instead, they preferred concepts such as the partially reusable and multifunctional devices, which they associated with stronger environmental performance and practical synergies. Overall, only half of the stakeholders selected concepts that were shown by the LCA to offer clear environmental advantages. This mismatch underscores a central challenge of circular medical device design: aligning evidence-based assessments with stakeholder perceptions and preferences.

At the same time, the findings show that circular strategies can yield unexpected synergies rather than trade-offs. Enabling reuse and sterilization not only reduces reliance on virgin materials but can also lower costs by extending the life of high-value components, improve alignment with emerging regulations, and generate long-term savings despite higher upfront investment. Similarly, reducing or eliminating electronic components simplifies production, reduces both upfront cost and long-term cost, enhances sterilization compatibility, minimizes risks in operating room environments, reduces malfunctioning, and can make devices more intuitive for staff. These findings suggest that circular design, when done thoughtfully, does not always involve sacrifice—it may in fact lead to multi-dimensional improvements.

These observations also reinforce that achieving circularity in medical device design is not solely a technical challenge but a systems-level one. Successful implementation requires integrated strategies that align design innovation with regulatory frameworks, clinical practices, and supply chain logistics. This aligns with broader evidence: [26] emphasize the importance of integrating circular strategies with healthcare system dynamics; [27] highlight the necessity of considering hygiene criticality and sterilization processes in device design; and [14] identify systemic barriers such as regulatory constraints and stakeholder dynamics that hinder circular implementation.

Taken together, these insights underscore the need for design processes that integrate both quantitative assessments (e.g., LCA) and qualitative stakeholder perspectives. Focusing solely on technical solutions or environmental metrics, as much previous research has done, is insufficient. Instead, structured design approaches—such as the one demonstrated in this study—can surface synergies, distinguish factual from perceptual trade-offs, and generate actionable recommendations that advance sustainability while respecting clinical and regulatory realities.

5.3.5 Limitations

This study examined a single case of one laparoscopic device. While this enabled an in-depth analysis of trade-offs, the narrow scope limits the generalizability of findings to the broader medical device sector. Additional studies across diverse device types and clinical contexts are needed to validate and extend these insights. Moreover, the assessed products and systems were conceptual designs, meaning the results depend on assumptions and interpretations that may differ in real-world implementation. Despite efforts to include a wide range of stakeholders, not all perspectives could be represented, and a large, fully representative sample was not feasible. Consequently, the qualitative recommendations may not fully capture the priorities or constraints of all stakeholder groups and may not be directly transferable to other devices. Furthermore, MedTech experts evaluated the concepts using a 1–4 ranking system, while survey participants used a 1–5 Likert scale. This difference was necessary to enable direct comparison between concepts for experts, but it also posed a limitation because experts could not assign equal ratings to multiple concepts, whereas survey participants could. The central contribution is to demonstrate how integrating quantitative assessments (e.g., LCA) with stakeholder input can reveal opportunities for circular innovation and uncover synergies between sustainability and operational requirements. Even a single-case analysis, as shown here, can highlight key trade-offs, potential synergies, and considerations relevant to advancing circularity in medical devices.

5.3.6 Future Research

Future research should build on these findings by developing a circular design guide tailored to medical devices. This guide should provide a structured, step-by-step overview of the product development process with an embedded mapping of common trade-offs at each phase, prompting decisions based on evidence (e.g., LCA and user tests) rather than assumptions. It should also identify strategies to positively address or mitigate those trade-offs. Furthermore, research should explore how these strategies differ by device type, clinical use case, and geographical/regulatory context, and examine how early-stage collaboration between stakeholders can lead to more holistic and effective outcomes.

5.4 Conclusion

This study explored how trade-offs and synergies between circularity and carbon footprint and safety, functionality, usability, and regulatory compliance can be assessed and managed in medical device design. Our findings uncovered several important trade-offs, such as additional sterilization steps, increased technical complexity, or workflow adjustments. However, even under strict clinical and regulatory constraints, those trade-offs can be managed or mitigated, despite there not being many examples of this in practice. Simultaneously, leverageable synergies

were identified, where circular strategies improve both environmental and operational outcomes. Comparing a baseline single-use laparoscopic stapler with redesigned concepts, multifunctional and manual designs could theoretically reduce environmental impacts by 80–90% but realizing these gains in practice remains challenging. Partially reusable devices offer moderate, feasible improvements, and fully recyclable single-use designs provide limited benefits., though it might be easier to implement. Stakeholder feedback highlighted that usability and workflow constraints—such as workflow disruption—often influence design decisions more than technical or environmental limitations. While these constraints may not be regulatory, failing to address them can lead to complicated device use and subsequent issues. Regulatory compliance therefore represents the minimum requirement; building beyond it improves device performance and outcomes. Integrating environmental assessment with stakeholder insights proved essential to distinguish factual trade-offs from assumptions and to identify opportunities where circular strategies can enhance safety, usability, or cost-efficiency. While some high-impact strategies remain difficult to implement under current conditions, circular design in healthcare does not need to come at the expense of performance or safety. When approached thoughtfully, it can deliver multidimensional benefits, supporting patients, clinicians, industry, and the environment alike.

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PART IV

from insights to action

Chapter Reading Guide

This chapter is structured differently from a conventional scientific article. Instead of following a strictly academic format, it translates the research into practical guidance and design-oriented reflections intended for real-world application in medical device development. The chapter is organised as follows:

1. Why a Guide — and for Whom?

Introduces the need for practical circular design support within the regulatory, safety, and organisational constraints of healthcare.

2. How the Guide Came to Life

Explains how research findings, case studies, stakeholder input, and iterative design explorations informed the guide.

3. Strategic Highlights

Summarises the key barriers, opportunities, and conditions necessary for implementation in practice.Outlines how the guide can be further developed and evaluated in practice.

4. Iterative Design Ideations

Describes the exploration of different formats (e.g., decision trees, checklists, taxonomy, workbook) and the lessons learned from testing them.

5. Inside the Guide: Structure and Core Components

Presents the framework:
A – Define | B – Question | C – Circulate | D – Embody | E – Evaluate

6. Assessment Against Design Guide Criteria

Outlines how the guide can be further developed and evaluated in practice.

7. From Concept to Practice: Future Testing Plan

Describes how the guide could be further developed and tested

Chapter 6

Where Research Meets Reality: Development of a Circular Design Guide for Medical Devices

Transitioning the healthcare sector to a circular economy—and even implementing circular design in practice—extends far beyond what the scientific community alone can achieve. For this reason, although this chapter is grounded in the research presented elsewhere in the dissertation, it is not written as a scientific article. Instead, it translates the findings into practical guidance for designers, healthcare professionals, policymakers, and industry leaders.

While this dissertation has provided valuable insights, the key question remains: are these insights adoptable? This chapter responds to that question by exploring how the findings can be leveraged to support the development of a practical Circular Design Guide for Medical Devices (of which the final version will be presented alongside this thesis). It illustrates how research, case studies, and stakeholder input can be synthesised to help practitioners navigate the realities of healthcare while applying circular principles. Rather than presenting a finished guide, the chapter offers the Design Guide 1.0 as a prospective, actionable starting point. It provides practical frameworks, case insights, and design considerations that practitioners can immediately apply or adapt while the guide itself continues to be refined.

6.1 Why a Design Guide — and for Whom?

Professionals in this field are tasked with designing responsibly, yet they operate within a highly constrained system governed by safety requirements, regulations, and linear supply chains.

A Circular Design Guide aims to bridge this gap by translating the extensive body of scientific knowledge into a practical resource for the healthcare sector. It is aimed primarily at Medtech designers, engineers, and product managers—those who shape the medical devices of the future. The guide shows how circular principles can be integrated into everyday design practice and provides practical frameworks and considerations for navigating constraints while applying circular strategies.

6.2 How the Guide Came to Life

The development of the Design Guide was informed by four complementary activities: (1) synthesizing scientific findings from the DiCE project, including those presented in this dissertation, into content relevant to circular medical device design; (2) gathering insights on industry and user needs through collaborative sessions and workshops with stakeholders; (3) synthesizing a generalized medical device development process to ensure that the guide complements existing practices; and (4) conducting iterative design ideation to explore and evaluate multiple guide configurations. After completing these activities, results were compiled in a single document, with findings categorized by topic. The following sections describe the methods used to generate these insights.

6.2.1 Integrating Insights from Research

Research insights were collected to understand what designers, engineers, and project managers need to support circular device design. This was done through three approaches: background research to identify system barriers, analysis of circular healthcare case studies, and review of relevant expert knowledge from non-design fields within the DiCE project.

6.2.1.1 Background Research on Understanding Circular Healthcare

To ground the design guide in the realities of healthcare practice, background research was conducted as presented in Chapters 2 and 3 of Part II of this dissertation. This research mapped the current healthcare system, identified key barriers and opportunities for circular practices, and established initial design considerations.

Chapter 3 then explored the healthcare ecosystem in greater depth, examining how circular strategies can be embedded within existing structures. The taxonomy developed through this work clarifies the steps, guiding questions, key considerations, and shared terminology needed to support circularisation in healthcare, and directly informed the development of the design guide.

6.2.1.2 Insights from Real-World Design Case Studies

Four design case studies were carried out within the DiCE project to explore how circular strategies translate into medical device design practice. By working through real design processes, the case studies were used to surface practical challenges, trade-offs, and decision-making moments that arise when designing for circularity in healthcare.

The first case study focused on the circular redesign of a smart pillbox, partly presented in Chapter 4 of Part III of this dissertation. This study explored the use of circular strategies like reuse, refurbish, and repurpose as a design tool, including their strengths and limitations. The second case study examined the circular redesign of a laparoscopic device, partly presented in Chapter 5 of Part III, and investigated the trade-offs involved in applying circular strategies to a complex, high risk medical device. The third case study addressed the circular redesign of an electronic label used in clinical trials, adopting a system level perspective with particular attention to regulatory requirements, strategy selection, and data security considerations. The fourth case study focused on the circular redesign of an innovative wearable sensor device and followed the proposed design guide workflow to assess its applicability, while also exploring the development of a sustainability roadmap and a sustainability versus actionability matrix.

In addition, several TU Delft master's graduation students working on circular medical device redesign projects were asked to apply predefined circular strategies derived from the background research and to reflect on their usefulness throughout the design process [1], [2], [3], [4], [5], [6]. Their individual reflections offered valuable insights into how circular design guidance is interpreted and applied in practice.

6.2.1.3 Insights from the Field

In the DiCE project, extensive research was conducted not only on circular design, but also on other fields relevant to the circular transition of medical devices [7]. These insights were analysed to identify those most useful for inclusion in the circular design guide, covering areas

such as business models, procurement constraints, regulatory compliance, behavioural research related to take-back logistics, sustainability assessment, and dissemination and communication strategies.

6.2.2 Collaborating with Stakeholders

To ensure the design guide was grounded in medical device development practice, stakeholder input was gathered through three types of sessions. Three one-hour online sessions with ~10 participants each (experts in medical device development, circular economy, or both) discussed guide content and presentation format, using slides and post-its to collect ideas. Two one-hour in-person workshops with 10–30 participants focused on initial setup suggestions and guide format, including structured discussions and partial walkthroughs. Finally, a three-hour collaborative session with three MedTech experts used a whiteboard to co-create the step-by-step content of the first version of the guide.

6.2.3 Mapping to the Standard Design Process

Based on comments made by several stakeholders, it was determined that rather than presenting a full stand-alone circular design guide, to improve adoptability, the guidance provided should align with the standard design process currently used by Medtech industry to develop a medical device. However, since there is some variety in how different companies perform this development a generalized workflow typical for medical device development was synthesised. The generalized workflow was based on a consolidation of the typical design engineering workflow currently equipped at two large medical device companies, and aligned with the V-model as expected by regulatory bodies [8]. The V-model is a structured development framework in which system requirements are progressively translated into detailed design specifications on the left side of the "V", while corresponding verification and validation activities on the right side ensure that each design stage is systematically tested against its initial requirements. It was later also reshared and confirmed by the same companies to ensure they could work with it. This workflow serves as the baseline, with circular guidance added on top.

6.2.4 Design Through Iterative Ideation

Based on insights from background research, case studies, and stakeholder input, multiple potential configurations of the Design Guide were explored to evaluate adoptability and guide the overall design approach. The following list presents the key configurations that emerged through this process and the ways in which each was evaluated:

- **Decision tree:** A stepwise tool to guide designers through circular strategy choices. Its usability and practical value were discussed with two circular design experts and one circular supply chain expert, providing targeted feedback on real-world applicability.
- **Reflective questions chart:** A chart prompting designers to reflect on design choices and circular considerations. This format was initially explored through self-testing and reflection, and key aspects—such as the questioning framework—were later incorporated into the taxonomy and checklist components.
- **Design guidelines / checklist:** A consolidated list of actionable circular design

recommendations. Several DiCE partners, including industry and design experts, reviewed the list, focusing on clarity, coverage, and ease of use for medical device designers.
- **Overview / taxonomy:** A structured map of strategies, considerations, and categories for circular medical device design. This component was evaluated throughout development (see Chapter 3) to ensure it accurately represented circular design principles and practical constraints.
- **Workbook:** An interactive guide to lead designers through exercises and reflection on circular design steps. Recommended by multiple partners, its usability was explored through stakeholder discussions, with flexibility in content and structure to accommodate different design contexts.

6.3 Strategic Highlights

Outcomes of all research findings were analysed and compared by grouping them into those relevant to the content and scoping of the guide, and those relevant the adoptability in practice. In sections 6.4.1 and 6.4.2, the outcomes of this analysis are summarised, and in section 6.4.3, they are translated into main criteria relevant to the development of the guide.

6.3.1 Content-Specific Findings

As discussed in Chapter 2, Part II of this dissertation, and further elaborated in [9], the transition of the healthcare sector towards a circular economy is impeded by a set of persistent barriers. These barriers are not limited to technical or regulatory constraints, but also include perceived risks, responsibilities, and feasibility concerns held by stakeholders. Based on this work, the five most influential barriers identified are:

- Regulatory and safety constraints, including strict validation requirements, risk aversion, and uncertainty regarding compliance of reuse, refurbishment, and novel material strategies.
- Perceived and actual patient safety risks, where concerns about hygiene, sterilisation, data protection, and reliability often outweigh perceived sustainability benefits.
- Fragmented responsibilities and unclear ownership, particularly across product life cycles, circular business models, and end-of-life phases.
- Linear supply chain structures and procurement practices, which limit incentives for circular solutions and favour single-use devices.
- Knowledge gaps and misaligned perceptions, including limited understanding of circular strategies, inconsistent interpretation of terminology, and lack of shared metrics to assess circular value.

These barriers, together with others identified in the background research (Chapter 2 and [9]), increase the complexity of designing medical devices for circularity and point to the need for targeted, context-aware guidance. A Circular Design Guide can add value by explicitly addressing both structural constraints and stakeholder perceptions, thereby supporting informed and realistic decision-making throughout the development process.

In addition to barriers, Chapter 2 also identified several opportunities and design guidelines relevant to circular medical device development. The most relevant findings include the importance of early

integration of circular thinking during concept definition and system design, design for modularity and material compatibility to enable reuse and refurbishment, explicit consideration of trade-offs between sustainability, safety, usability, cost, and regulatory feasibility, and the adoption of system-level perspectives that extend beyond the product to include logistics, business models, data infrastructure, and user behaviour. Together, these insights suggest that the design guide should function as a structured ideations and decision-support tool rather than a prescriptive checklist of optimal solutions.

Across Chapter 3, Part II, and Chapter 4, Part II of this dissertation, and as published in [10], [11], the R-strategies were shown to be valuable resources for informing circular design decisions. For this reason, the visual taxonomy presented in Chapter 3 forms a foundational element of the design guide. However, while the R-strategies hierarchical structure offers an initial indication of potential environmental value, findings from case studies, stakeholder discussions, and student projects demonstrate that this hierarchy cannot be applied uncritically in the medical device context. This is partly because the actual environmental impacts of different R-strategies are not necessarily monotonic, so the relative benefit of a given strategy can only be assessed through careful evaluation of each new design idea. This indicates that the use of those strategies is more useful as an ideation tool, rather than in decision support. Regulatory requirements, medical risk classifications, user acceptance, and system boundaries often necessitate deviations from the idealised order of strategies. Moreover, inconsistent interpretation of R-strategy terminology across stakeholders reinforces the need for a shared reference framework.

Additional insights from background research, stakeholder engagement, case studies, and partner-provided analyses further refine the guide's content requirements. Across these sources, the importance of early identification of hotspots, trade-offs, and knowledge gaps in decision support emerged consistently, as circular ambitions were frequently constrained by late discovery of regulatory, logistical, or technical limitations. Stakeholders and case studies further highlighted the need to integrate user- and patient-centred considerations, including behavioural insights related to trust, hygiene, and data protection, as acceptance proved decisive for circular solutions. A broadened system perspective was also repeatedly emphasised as useful for both ideation and decision support, requiring engagement with actors beyond the design team, such as procurement, logistics, reprocessing, and regulators. Finally, stakeholders mentioned that sustainability considerations should ideally be addressed iteratively across the full development process, with transparent handling of uncertainties and explicit attention to service-life extension strategies and their enabling business models.

6.3.2 Adoptability in Practice

The ways in which adoptability in practice can be enabled, was mostly explored through the stakeholder discussions and expert recommendations.

Experts highlighted a current lack of circular expertise and training in the Medtech industry, while insights from the background research, as also presented in the earlier chapters of this dissertation, pointed at a lack of practical circular design tools in this field. The circular design guide for medical devices is meant to fill this gap. For this reason, in the stakeholder discussions, it was agreed that the guide must be practical rather than theoretical and focus on implementation and adoption. To enable this, as should be the case for any Medtech development process, also the circular design guide should start with the unmet needs of the medical professionals and patients.

Another important point noted in the stakeholder discussions, is that the guide must fit into the existing design process, building on the standard medical device development rather than reinventing it or presenting another method to execute in parallel. To enable this, a generalized version of the current medical device development process was mapped (as explained in section 6.3.2). The outcomes of this are presented in Figure 26.

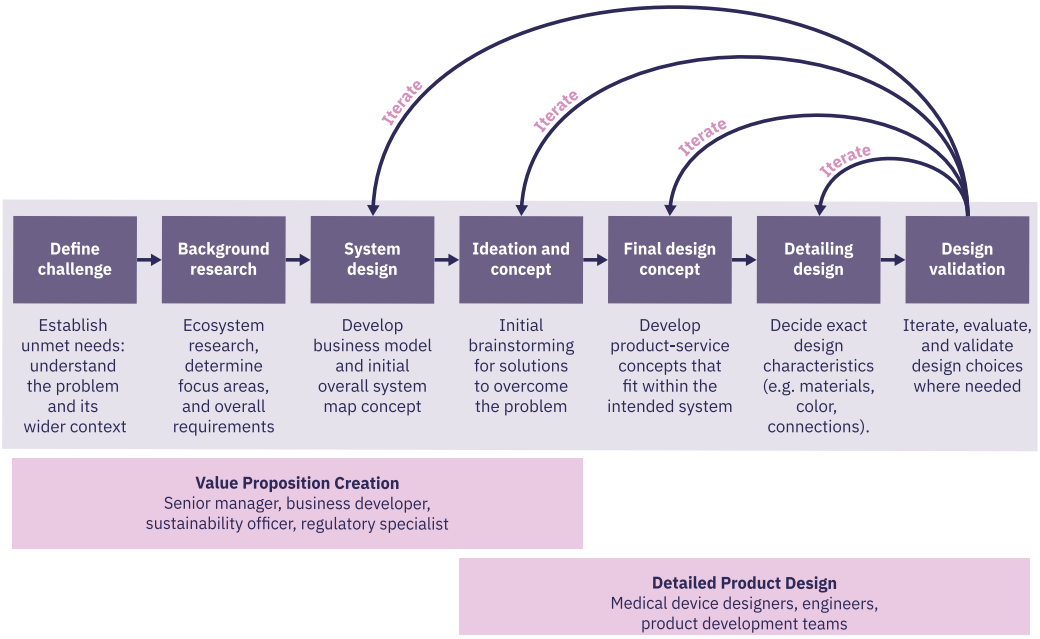


Figure 26: Generalised Medical Device Development Process

It is important to note that while this process is presented in a linear manner, it was confirmed during the stakeholder discussions that this figures represents the main steps taken in an iterative process. The first three steps (define challenge, background research, and system design) belong to the usual value proposition creation (VPC) process. In larger Medtech companies, these steps are usually not performed by designers or engineers, but by senior management, business development, sustainability officers, and regulatory specialists, who define the starting point for the actual design process. This means that many of the decisions made that determine the suitability of a design for circularity are made in those initial phases. Stakeholders highlighted that the VPC feeds the earlier stages, after which the actual product design follows, which includes ideations, detailed design and validation. This is important information because this means that the design guide should cover all steps in this process, while serving several different target groups.

With regard to the different target groups (and large number of stakeholders involved), it is important to keep in mind that there is a current lack of clarity in responsibilities; not only was this barrier found in the background research [9], as also presented in chapter 2, part II of this dissertation, the need to clarify responsibilities and collaboration needs came forward in the stakeholder discussions, the expert input, and was recognized during the execution of the case studies and student projects. Therefore, during the stakeholder discussions it was specifically discussed that the design guide should include guidance on setting out clear responsibilities, for

example including tools for planning and reflection. This is especially true for responsibilities in relation to the circular business models and circular product design. Stakeholders highlighted those two activities to be interdependent and iterative.

To support easy adoption of the design guide, stakeholders emphasized the importance of phased adoption. While bold and ambitious solutions should still be encouraged when feasible, so that smaller steps do not preclude more innovative approaches, stakeholders argued that aiming for the most environmentally sustainable product from the outset is often infeasible. Overly ambitious sustainability goals can lead to the unintended neglect of circular design strategies altogether. To mitigate this risk, the guide should support designers, engineers, and product managers by identifying circular design interventions that can serve as practical stepping stones in earlier development phases. Additionally, stakeholders stressed that the guide should be adaptable to a wide range of medical devices and design processes, accommodating both incremental and radical innovation pathways.

Lastly, stakeholders and experts agreed that to fit into existing design practices, the design guide should be concise, modular and engaging rather than lengthy or static, by e.g. including exercises, examples, templates and visuals. They stated the need to ensure online accessibility.

6.3.3 Key Research Insights

Based on research, case studies, and stakeholder input, the Circular Design Guide for medical devices, must ideally:

- ... be needs-driven and adoption-focused, prioritizing practical relevance over ideal circularity.
- ... align with existing medical device workflows (Figure 26).
- ... cover both Value Proposition Creation (VPC) and product design, linking business case to design decisions and system-level enablers.
- ... consider trust, privacy, and user interaction as explicit design criteria.
- ... support user stories, storyboards, and visualizations to illustrate impacts and trade-offs.
- ... include stakeholder ecosystem mapping and role allocation tools early.
- ... provide templates to identify circular actors across the product lifecycle.
- ... offer material selection guidance, modularity principles, and design for reuse/ refurbishment.
- ... reference relevant standards and regulations (e.g., ISO, CE).
- ... include checklists for recyclability, cleanability, and circular compliance.
- ... define circular checkpoints and set priorities per phase (e.g., early LCA, feasibility, reuse).
- ... include a knowledge mapping step with links to resources, standards, examples, and circular databases.
- ... be delivered as a modular online tool, including templates, and examples.

6.4 Iterative Design Ideations

Based on the initial findings and discussions, as well as in-between the gathering of such findings, several different design guide and design tool configurations were explored and evaluated, as introduced in section 6.4.1.

6.4.1 Decision Tree

One insight that emerged repeatedly was the need to integrate circularity early in the design process and to consider all R-strategies—including refuse, rethink, and reduce—rather than focusing on a single option. To support this, a decision tree was developed to help determine which R-strategies are suitable for a specific device, or how a device could be adapted to make certain strategies viable. Users are guided step by step through the tree, examining each option until they reach one of the red "end points." Each choice leads to recommendations tailored to that strategy, such as disassembly considerations for recycling. A version of the decision tree is shown in Figure 27.

The decision tree was evaluated with two circular design experts and a circular supply chain expert in healthcare. On the positive side, it provided clear stepwise guidance and was considered concise and complete at a high level. However, several limitations became apparent. Some steps were overly generalized, and the tool relied heavily on the R-strategy hierarchy, whose effectiveness was later shown to vary depending on the context and type of medical device (see [11] and Chapter 4, Part III).

During one discussion, the supply chain expert noted that user intentions could influence outcomes. Even with clear end points and directional arrows, a user could potentially reach a conclusion without fully reflecting on their assumptions, effectively "bailing" on responsibility. This highlighted the need to complement the decision tree with critical reflection prompts and context-aware guidance.

6.4.2 List of Design Guidelines / Checklist

In [9] (see also Chapter 2, Part II), a set of circular design guidelines for medical devices was proposed and subsequently refined through several case studies. The top 10 of the resulting guidelines are listed below.

- ☐ Maintain (or improve) quality, function & usability of the original device when introducing circular strategies.
- ☐ When integrating circular strategies, make sure to mitigate safety risks for intended use of the device/material/system.
- ☐ Aim to combine different circular strategies as much as possible (while prioritizing the strategy higher in the hierarchy).
- ☐ Consider the device EoL from the start of the design process.
- ☐ Enable easy disassembly (for cleaning, removing hazardous materials, and sorting materials).
- ☐ Enable traceability of devices and materials during their circular life cycles, for example through a digital device passport.

- ☐ Minimize material use in both device and packaging while maintaining device quality, longevity, and functionality.
- ☐ Provide clear and easy-to-understand instructions on the execution of the steps in the different circular strategies.
- ☐ Ensure reliable performance of functional components across different use scenarios, including interchangeable parts or cartridges.
- ☐ Ensure data security and patient privacy when devices store or transmit information, including during reuse or refurbishment cycles, in compliance with applicable regulations (e.g., GDPR, HIPAA).

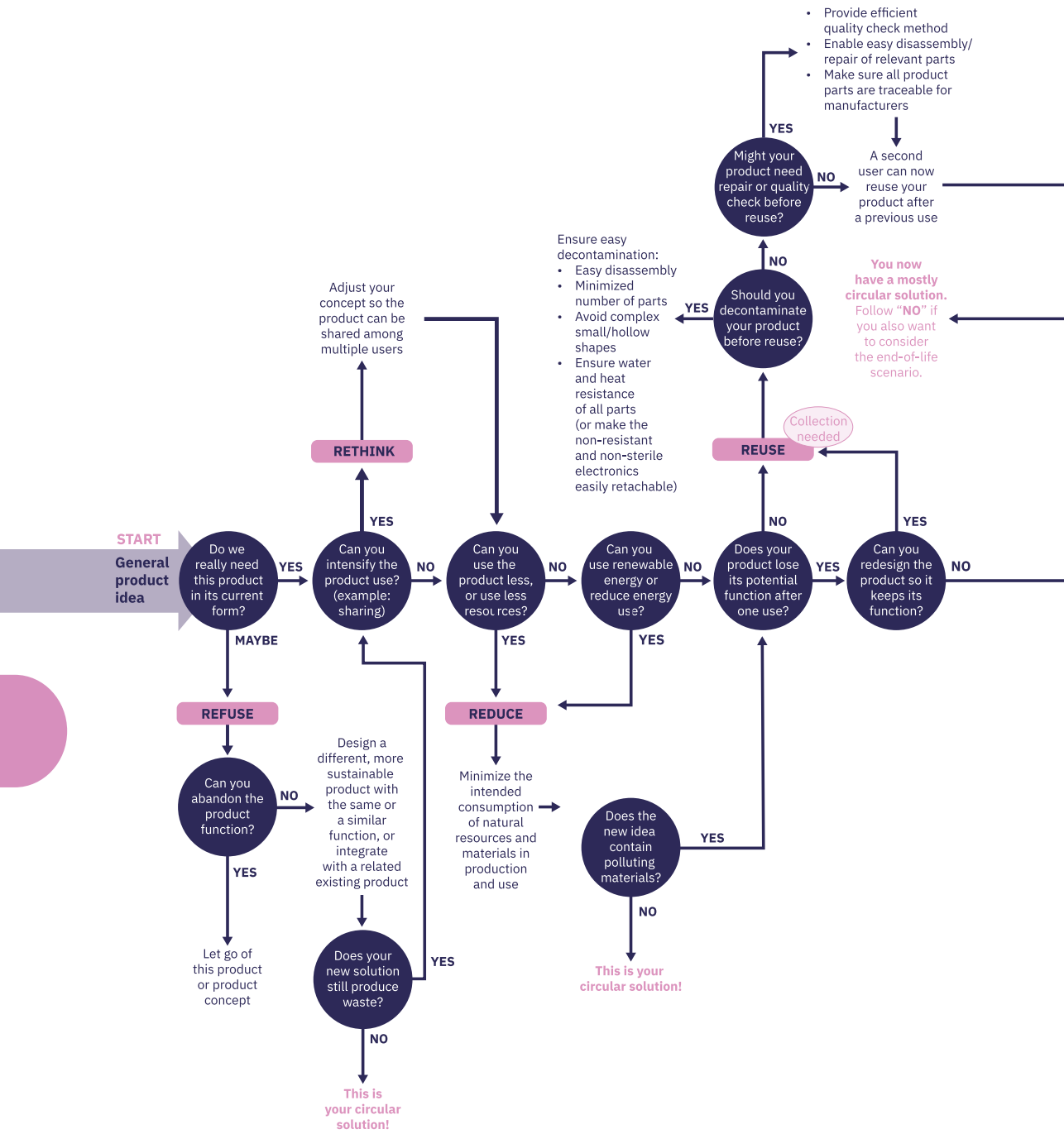
This list of design guidelines was iteratively developed and discussed in collaboration with DiCE partners. While it is valued as a good starting point and clear overview of considerations, it was also determined that it does not really provide real design guidance and is too generic to be directly applied to any medical device type. There is no way included to help the user tailor it to their specific device, and there is a risk that requirements which are attached to a knowledge gap of the medical device developer are ignored

These limitations indicate that the guide must go beyond a static checklist. It should provide context-sensitive support, helping users adapt guidelines to the specific device type, development phase, and stakeholder ecosystem. The guide should include decision aids, reflection prompts, and practical examples to ensure that all relevant requirements are considered, even where developers have limited prior knowledge. In this way, the guide can move from a high-level overview to a usable, actionable tool for circular medical device design.

6.4.3 Visual Taxonomy of Circular Healthcare Flows (CHFs)

Another, more detailed tool developed is the Visual Taxonomy of Circular Healthcare Flows, as presented in Chapter 3, Part II of this dissertation and published in [10]. A full evaluation of this tool is discussed in Chapter 3. A miniature version of the taxonomy is shown in Figure 28.

Overall, the feedback was overwhelmingly positive. The tool was even described as “groundbreaking work that provides a clear and actionable framework for understanding how materials flow through the healthcare system.” However, despite this praise, questions about practical actionability remained. The taxonomy provides a clear framework, but it does not indicate where or how to fill knowledge gaps, nor is it specifically tailored to the medical device development process, as it is largely mapped onto the linear supply chain. Like the decision tree, it relies heavily on the hierarchy of R-strategies and does not include steps for sustainability assessment or opportunities to test assumptions in context.


START
General product idea
Do we really need this product in its current form?
YES
MAYBE
NO
Can you intensify the product use? (example: sharing)
YES
RETHINK
Adjust your concept so the product can be shared among multiple users
NO
Can you use the product less, or use less resources?
YES
REDUCE
Minimize the intended consumption of natural resources and materials in production and use
NO
Can you use renewable energy or reduce energy use?
YES
NO
Does your product lose its potential function after one use?
YES
NO
Can you redesign the product so it keeps its function?
YES
NO
REUSE
Collection needed
Should you decontaminate your product before reuse?
YES
Ensure easy decontamination:
• Easy disassembly
• Minimized number of parts
• Avoid complex small/hollow shapes
• Ensure water and heat resistance of all parts (or make the non-resistant and non-sterile electronics easily retachable)
NO
Might your product need repair or quality check before reuse?
YES
• Provide efficient quality check method
• Enable easy disassembly/ repair of relevant parts
• Make sure all product parts are traceable for manufacturers
NO
A second user can now reuse your product after a previous use
You now have a mostly circular solution. Follow "NO" if you also want to consider the end-of-life scenario.
Does the new idea contain polluting materials?
YES
NO
This is your circular solution!
REFUSE
Can you abandon the product function?
NO
YES
Let go of this product or product concept
Design a different, more sustainable product with the same or a similar function, or integrate with a related existing product
Does your new solution still produce waste?
YES
NO
This is your circular solution!

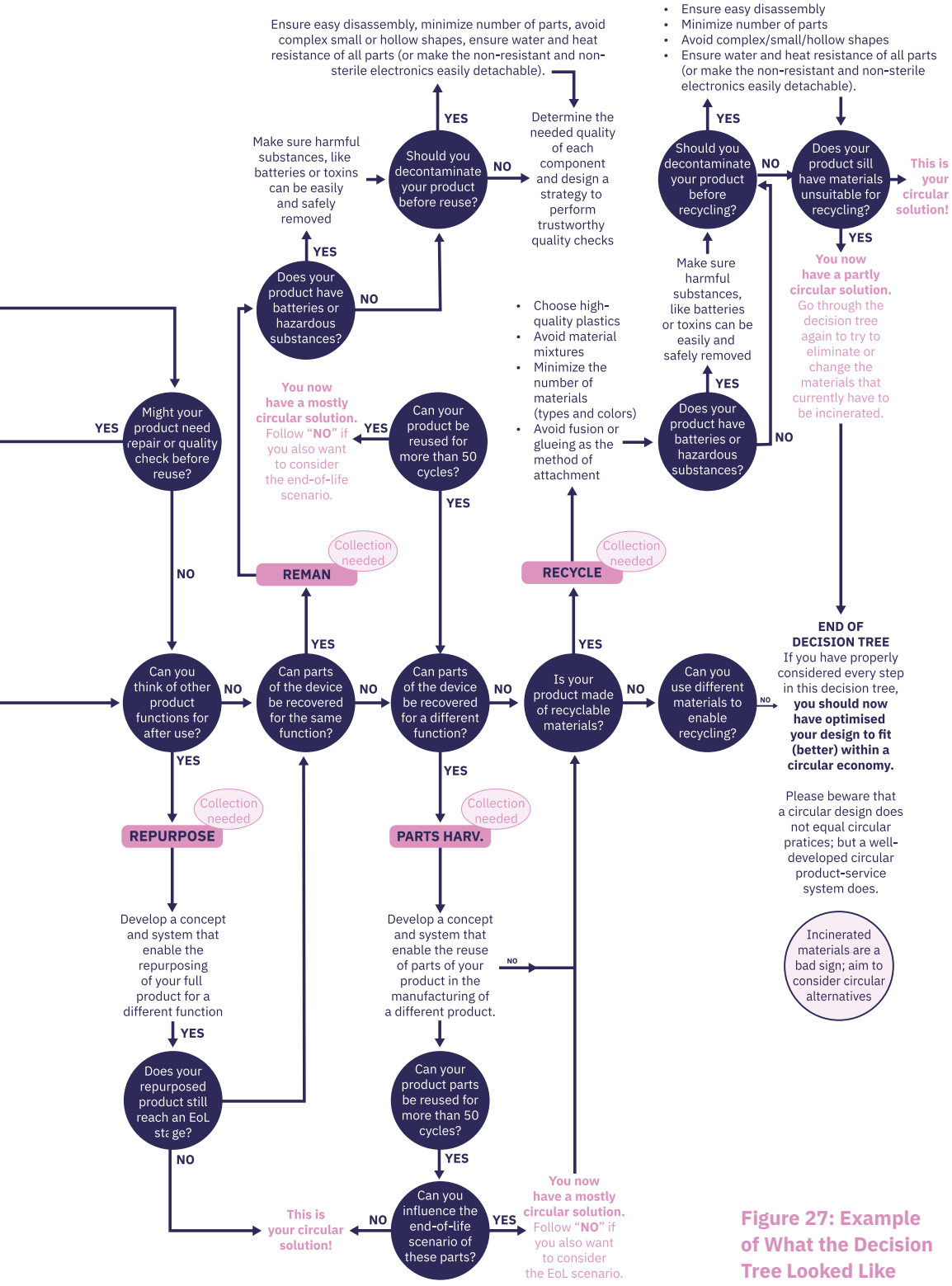


Figure 27: Example of What the Decision Tree Looked Like

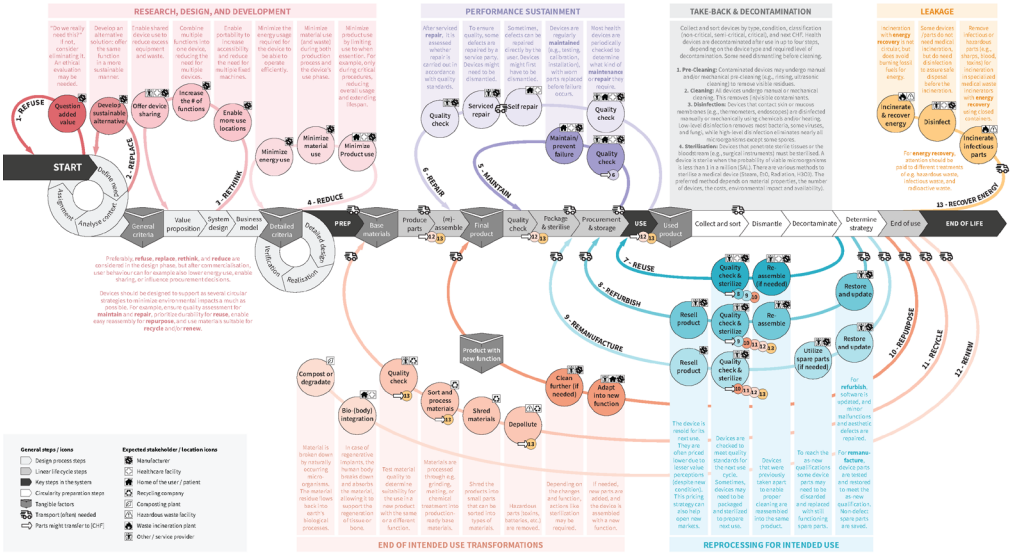


Figure 28: Miniature Version of Visual Taxonomy of Circular Healthcare Flows

Based on this feedback, the final circular design guide should build on the taxonomy's strengths while addressing these limitations. It should provide practical, context-aware guidance to help designers identify and address knowledge gaps, integrate sustainability assessment, and validate assumptions. Additionally, it should be aligned with the medical device development process, support decision-making throughout the lifecycle rather than presenting a purely theoretical or supply-chain-focused framework.

6.4.4 Reflective Questions Chart

Findings showed that many non-circular decisions are driven by perceptions of safety, regulatory constraints, or feasibility rather than actual real-world considerations. To address this, a "reflective questions chart" was developed. In this chart, users are posed targeted questions that help them identify applicable circular strategies, determine relevant considerations for each stage of the medical device development process (based on the generalized workflow previously presented in section 6.4.2, Figure 26), and connect these considerations to specific design requirements for each strategy. Figure 29 shows an example of this configuration.

The tool was perceived as clear and useful, particularly because it is closely tied to the design and development process and provides a personalisable overview of considerations. It can be seen as a more flexible, context-aware version of the earlier list of design requirements. However, it is better suited as a component within the design guide rather than a stand-alone tool, and it retains some of the limitations of the earlier guidance, such as relying on generalized assumptions rather than providing fully tailored solutions.

6.4.5 Practical Workbook

An often-discussed topic in the stakeholder sessions was the separation between Value Proposition Creation (VPC) and detailed product design, which are often handled by different teams. At the same time, there were multiple discussions about creating a practical workbook with integrated steps and exercises. A draft configuration combined these ideas into a two-part workbook: one for the VPC and one for detailed product design, structured like a toolbox. The VPC workbook included:

- Introduction to sustainable healthcare
- Overview of the visual taxonomy
- Defining the challenge (e.g., identifying user needs and environmental or social sustainability hotspots)
- Stakeholder mapping
- Identifying barriers
- Ideation guidance based on circular strategies, structured like a morphological chart (using R-strategies as "functions")
- Examples of ideation
- Business model selection
- Sustainability vs. ease-of-implementation matrix, leading to an implementation roadmap
- Development of the final value proposition, including supply chain, business model, and a tangible user story
- Guidance on briefing designers for circularity

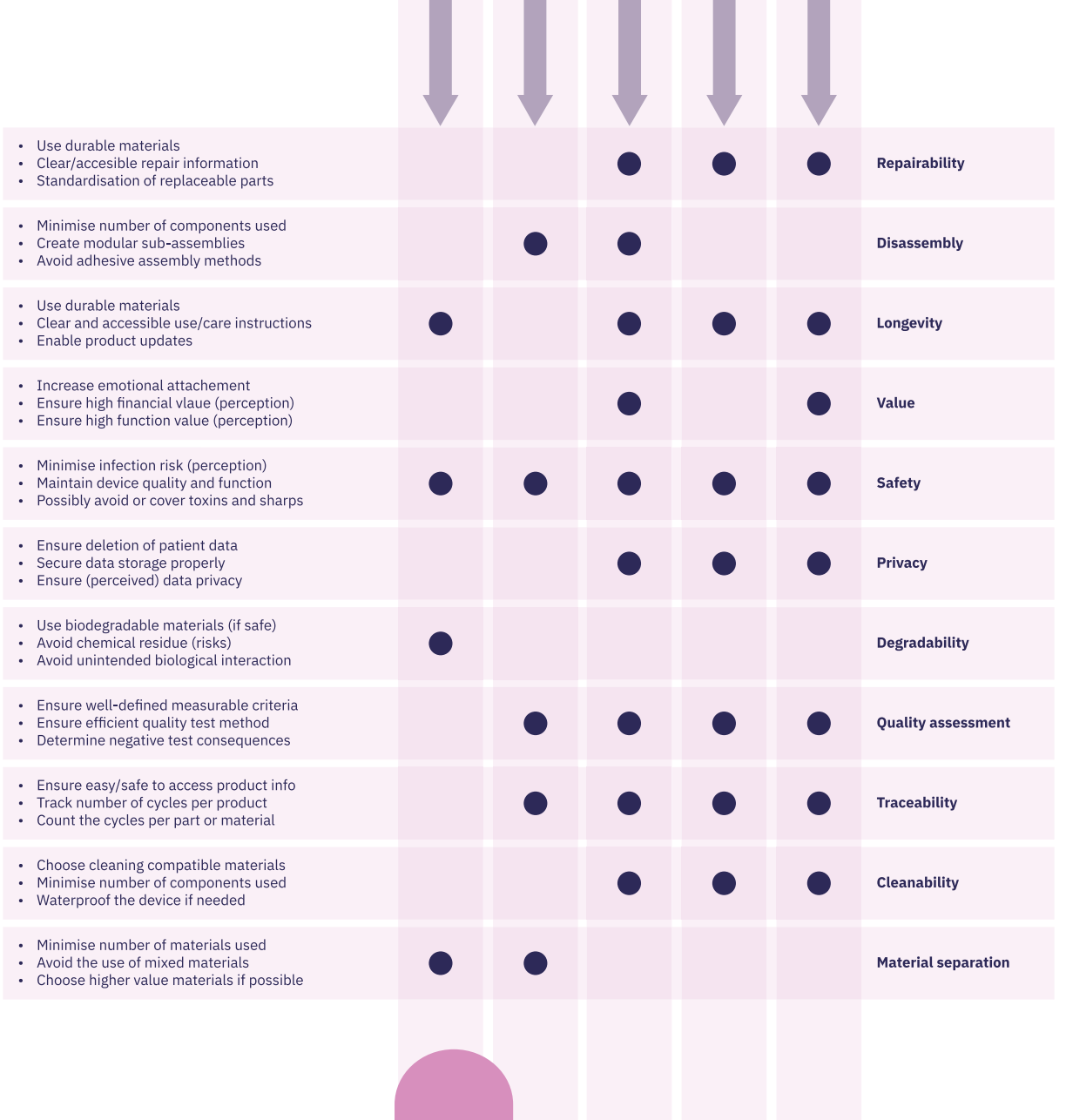
Figure 30 shows two example pages from the VPC workbook. The Circular Product Design Toolbox, which had similar-looking pages, included:

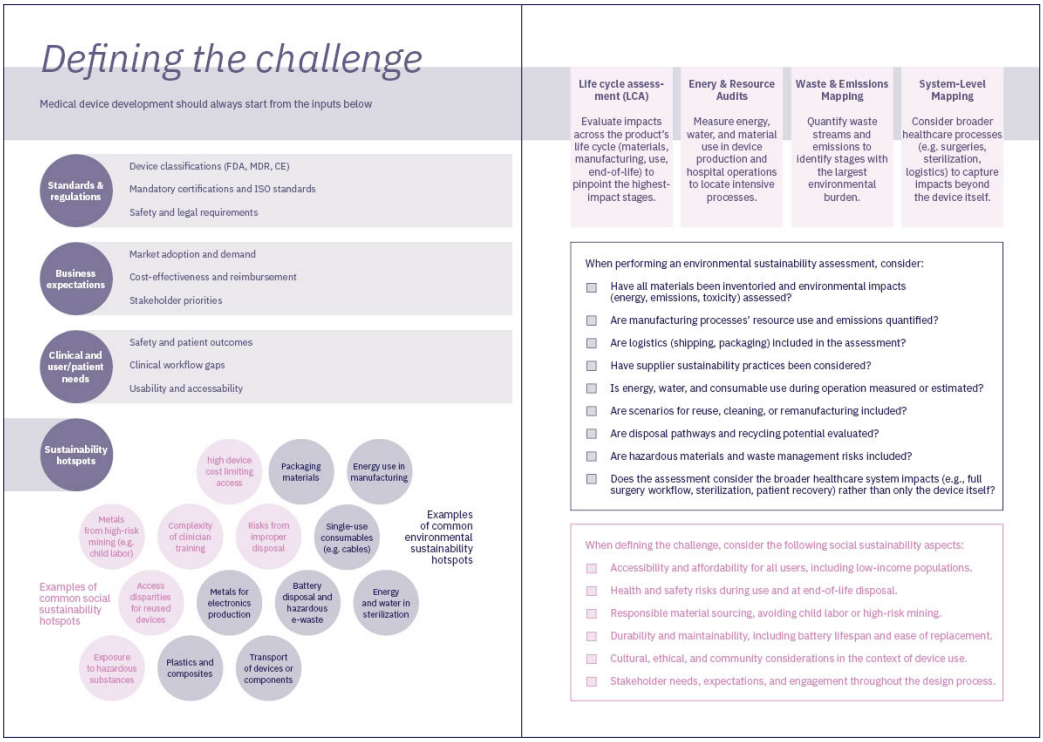
- Introduction to sustainable healthcare from a design perspective
- Overview of the visual taxonomy
- "Challenge the Design Challenge" – helping designers check that all relevant circular strategies are considered
- Full overview of general circular design criteria
- Guidance on tailoring criteria to a specific device type
- Guidance on identifying "knowledge gaps," such as recycling processes, regulatory conflicts, or how decontamination affects sustainability
- Pages with information to address those gaps
- Examples of design ideation
- Evaluation and validation guidance for design criteria, environmental and social impact, business models, etc.
- Final design development guidance with implementation recommendations
- List of relevant resources

When evaluating the set-up of these workbooks in stakeholder discussions, the step-by-step structure and focus on knowledge gaps were appreciated. Many of the previous insights—like sustainability assessment, examples, and device-specific tailoring—were successfully integrated. The split between VPC and product design was generally welcomed, as it clarified the different phases. At the same time, caution was noted: in smaller companies, one team often handles both, so keeping the bigger picture in mind is important.

Sustainability perspective / Business perspective / Clincial perspective	Project aim		High-level criteria	System design		product-level criteria	Product design		Deliver to market
	Value proposition creation (VPC)	Background exploration (if needed)		Product journey	Architecture design (incl. standardisation		Detailed design (with iteration)	Realisation verification validation	
Refuse	Do we really need to solve this problem? if yes, do we need a separate device to do so?			Can we come-up with more sustainable alternatives that address the same need?			Are there more sustainable solutions or functions that address the same need?		
Rethink	Can we possibly overcome more than one challenge in one device, by increasing the number of functions?			Can we introduce device sharing and/or enable use in multiple different locations?					
Reduce	Do we need to solve this problem in all possible situations? E.g. limit it to high-risk situations.			Can we minimise the number of situations in which the use of this device is needed?			What choices can we make to minimise material and energy use?		
Reuse	Can/may we develop a device that can be used for more than one use cycle for the purpose?			Can we introduce reusability in the product journal / system?			How can we consider all relevant circularity enablers?		
Repurpose	Can/may we possibly overcome another challenge in a different context in the same device?			Can/may we possibly include repurposing by design (after reuse) in the system?			How can we consider all relevant circularity enablers?		
Remanufacture	Can/may we develop a device that is suitable for more than one life cycle after full restauration?			Can/may we possibly include remanufacturing (after reuse) in the system?			How can we consider all relevant circularity enablers?		
Recycle				Can/may we possibly recycle the materials at EoL?			How can we consider all relevant circularity enablers?		
Renew				Can/may we possibly introduce regenerative medicine or biodegradable materials?			How can we consider all relevant circularity enablers?		

Figure 29: Version of Reflective Questions Chart


• Use durable materials
• Clear/accesible repair information
• Standardisation of replaceable parts
Repairability
• Minimise number of components used
• Create modular sub-assemblies
• Avoid adhesive assembly methods
Disassembly
• Use durable materials
• Clear and accessible use/care instructions
• Enable product updates
Longevity
• Increase emotional attachement
• Ensure high financial vlaue (perception)
• Ensure high function value (perception)
Value
• Minimise infection risk (perception)
• Maintain device quality and function
• Possibly avoid or cover toxins and sharps
Safety
• Ensure deletion of patient data
• Secure data storage properly
• Ensure (perceived) data privacy
Privacy
• Use biodegradable materials (if safe)
• Avoid chemical residue (risks)
• Avoid unintended biological interaction
Degradability
• Ensure well-defined measurable criteria
• Ensure efficient quality test method
• Determine negative test consequences
Quality assessment
• Ensure easy/safe to access product info
• Track number of cycles per product
• Count the cycles per part or material
Traceability
• Choose cleaning compatible materials
• Minimise number of components used
• Waterproof the device if needed
Cleanability
• Minimise number of materials used
• Avoid the use of mixed materials
• Choose higher value materials if possible
Material separation
Circularity enablers per circular strategy



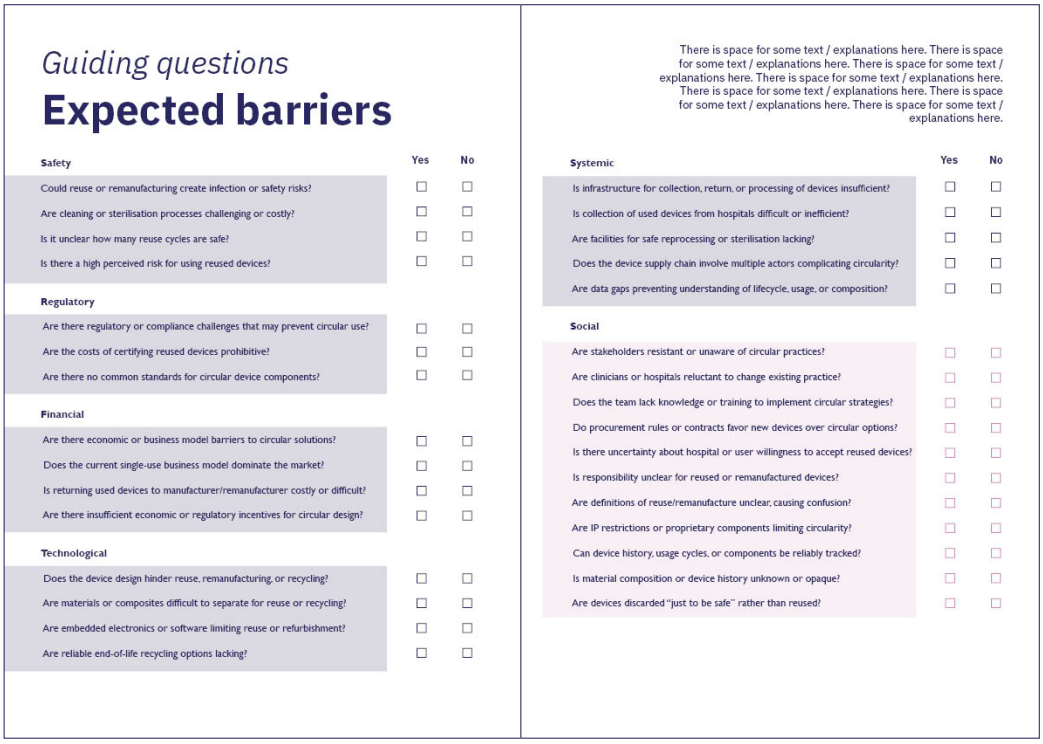


Figure 30: Miniature Example Pages of Practical Workbook Prototype

Some additional recommendations also emerged. Without a clear introduction, and with some sections being more informative than actionable, the workbook could feel overwhelming. It tried to cover basic design principles, general medical device knowledge, and circular design insights all at once, which in practice was unnecessary—users already know the design process and can access standard circularity information. Similarly, framing sections as "knowledge gaps" could feel demotivating, implying that users did not know what they were doing. Experts suggested reframing these as reflective questions, so users build on their existing knowledge rather than being told what they "don't know."

Ultimately, the final circular design guide should focus on the specific overlap between healthcare and circularity—for example, how contamination affects recyclability or which medical-grade materials are suitable for reuse. It should provide practical, context-aware support, include reflection prompts and actionable examples, and remain modular (VPC vs. product design) while keeping the overall process visible, so users can navigate circular considerations without feeling overwhelmed or patronized.

6.4.6 Key Ideation Insights

The iterative ideation process made it clear that a Circular Design Guide for medical devices can't just be a static list or a textbook. Designers, engineers, and product managers need a guide that supports real decision-making, helps navigate trade-offs, and makes the complexity of circularity manageable without overwhelming the user. Early reflection, practical examples, and a clear connection to the device development process are crucial.

From the different tools explored—decision trees, checklists, taxonomies, reflective charts, and workbooks—a few overarching insights emerged about what the guide should provide:

- **Self-reflective questioning:** Prompts that challenge assumptions, trade-offs, and device-specific choices, helping users build on their own knowledge.
- **Clear overview of steps:** Follows a clear guided process that fits into the full design journey from Value Proposition Creation to detailed product design, with optional deeper layers for those who want them.
- **Capture complexity simply:** Make circularity visible and understandable without oversimplifying critical decisions.
- **Practical, context-aware guidance:** Cover materials, modularity, reuse/refurbishment, safety, regulations, data, stakeholder engagement, and supply chains.
- **Concise and visual:** Minimal text, with diagrams, tables, and examples to convey information quickly and clearly.
- **R-strategies explained, not prescriptive:** Ensure all strategies are considered, while acknowledging variability in prioritization depending on device type and persistent terminology ambiguities.
- **Real-world examples:** Illustrate circular decisions in medical device cases.
- **Modular structure:** Users can access the level of detail they need, according to role, device type, or stage in the process.

6.5 Inside the Guide: Structure and Core Components

Based on extensive background research and further explorations, recommendations were developed for the creation of the Circular Design Guide for Medical Devices. Building on—but not simply replicating—the existing medical device development stages, including VPC and detailed product design, a 5-step approach is proposed, as illustrated in Figure 31: A – Define, B – Question, C – Circulate, D – Embody, and E – Evaluate.



Figure 31: Steps Included in Circular Design Guide for Medical Devices V1.0

In the included steps, the VPC and product design processes are not treated separately because many decisions that affect circularity are made early in the VPC phase—often by senior management, business development, sustainability, and regulatory experts—and continue to shape the subsequent product design. Keeping both phases together ensures the guide mirrors actual MedTech workflows, reflects the iterative nature of design decisions, and provides coherent guidance across all stages. The guide is designed to be flexible for different target groups, recognizing that in smaller MedTech companies, these roles may overlap or be performed by the same individual, requiring adaptable guidance that still captures all relevant considerations.

The following sections outline the rationale behind each step and provide illustrative examples. A – Define and B – Question are exclusively related to the VPC process, they are primarily aimed at establishing the foundational value proposition before product development begins. C – Circulate also contributes to the value proposition; however, it overlaps with the detailed product design phase, which continues in D – Embody, and requires coordination, especially when different teams are involved. The general outline of the steps is listed below.

- **A – Define:** This step clarifies system-level priorities, assesses whether interventions are truly needed, and identifies key environmental hotspots.
- **B – Question:** Challenge the assumptions that drive design decisions to explore circular alternatives, supporting strategies such as refuse, replace, rethink, and reduce.
- **C – Circulate:** Ideate where and how the device might be used, collected, or returned, ensuring alignment with safety and decontamination requirements.
- **D – Embody:** Focus on specific design requirements, addressing barriers and trade-offs within the product and system design.
- **E – Evaluate:** Assess the environmental and social sustainability of design options and iterate as necessary to ensure meaningful impact.

Throughout all steps, it is recommended to reference relevant resources and provide brief examples, with more detailed elaboration included in an appendix to make the exercises tangible and actionable.

6.5.1 Step A – DEFINE

The first step in any circular design process is to ensure that the underlying problem or need truly warrants intervention—and that intervention is actually wanted or needed by the people affected. This means looking beyond whether a device could be developed, to consider whether existing solutions are sufficient, and if not, what the real needs are and under what conditions a new solution would be accepted. Only once this is clarified should potential solutions—devices, procedures, or service innovations—be considered, and those that are unnecessary should be refused or rethought. Exercises in Figure 32 illustrate how this can be approached.

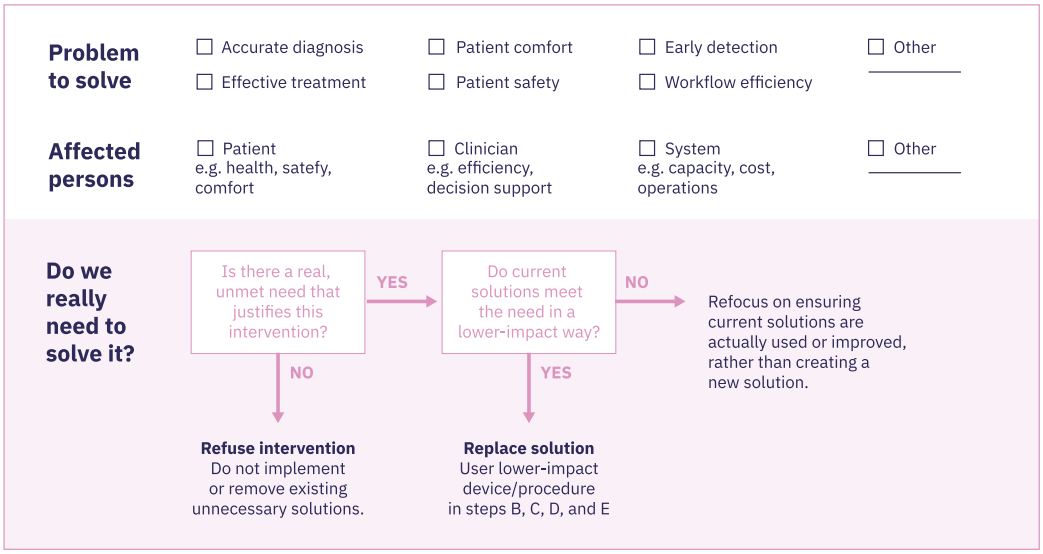


Figure 32: Exercises that Determine the Added Value of Development in the Design Guide

Developers naturally believe in the value of their own solutions—otherwise, they would not have created them. In the healthcare sector, this presents an even greater challenge, as asking, "Do we really need this?" can quickly shift from a neutral evaluation to an ethically charged question. Framing refusal at the problem and user-need level—rather than targeting a specific device—makes the evaluation more strategic and neutral, allowing circular thinking to be applied without personal conflict. Examples can show that even well-intentioned solutions may be unnecessary or could be replaced with more sustainable alternatives. Figure 33 presents illustrative cases which clarify these principles and provide practical guidance. Additional details are available in the appendices of the design guide for deeper exploration.

Once it has been established that the need is valid and relevant, it becomes important to identify which aspects of potential solutions should be the focus of circular improvements. In practice, many developers do not perform comprehensive environmental impact assessments for each potential solution, often due to resource constraints, incomplete e data, and time limitations. The guide addresses this by providing a method for rough estimation of potential environmental hotspots (as shown in Figure 34), while also referencing resources for more detailed assessments and encouraging deeper analyses whenever feasible. The results of the environmental impact assessment should guide the focus and priorities for all subsequent steps in the design process.

Refuse examples



Refuse UV-light oral hygiene interventions, as they reduce microbes without proven impact on oral health outcomes.



Refuse bloodletting procedures in cupping therapy, as there's insufficient evidence of therapeutic benefit.



Refuse the use of personal protective equipment in situations with proven lack of safety benefits.

Detailed examples in appendix

Replace examples

Replace electronic blood pressure monitoring with manual measurement when reliability is comparable.



Replace complex wearable rings with pulse oximetry for assessing oxygen saturation.



Replace laparoscopic surgery with endoscopy when appropriate, reducing unnecessary invasiveness.



Figure 33: Refuse and Replace examples in Design Guide

Identify Environmental Hotspots

Define the focus-points of the circular (re)design. Impacts should be determined from full system rather than product perspective, including multiple uses and downstream effects.

Tick each box where the answer is 'yes'	
Does the device contain metals or electronics?	☐ Production
Does the device contain critical or rare materials (e.g. cobalt, rare earth metals)?	☐ Production
Is air transport used for shipping?	☐ Transport
Is continuous or high-power operation required?	☐ Use
Does the device consume significant electricity during use?	☐ Use
Is the device difficult to recycle or disassemble?	☐ End of life
Does the device contain hazardous materials (e.g. batteries, chemicals)?	☐ End of life
Is the device single-use or (partially) disposable?	☐ **Production & end-of-life hotspots are amplified**

Guidance

Fast-track LCA first!
Generally quicker than anticipated and provides most robust insights.

Checklist alternative
If full LCA is not feasible, use this checklist to identify hotspots

Resources for environmental assessment

Fast-track LCA for healthcare *(VentureWell guide)*

Hotspots, materials, energy, process mapping *(Sustainable Design: From Vision to Action, Ch. 7-9)*

Carbon footprint estimation *(GHG Protocol)*

Figure 34: Worksheet for Identifying Environmental Hotspots

6.5.2 Step B – QUESTION

Based on the observation that many non-circular decisions stem from habitual reliance on linear processes, strict adherence to protocols, or unquestioned assumptions—such as perceived versus actual safety—Step B – Question is designed to help users critically examine and, where necessary, correct their assumptions to enable circular interventions. One practical approach is the use of decision trees, a format that has been positively received as a methodological tool, as illustrated in Figure 35.

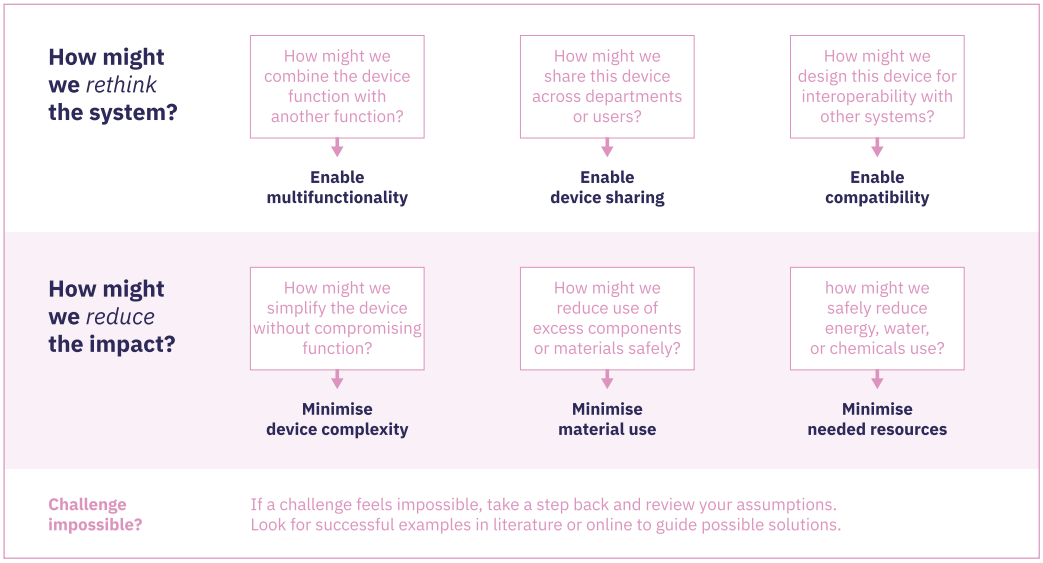


Figure 35: Design Guide Decision trees for rethinking the System and Reducing the Impact

Content-wise, these example decision trees guide users to rethink how the current system is structured and identify potential interventions to improve circularity. They also help determine ways to reduce environmental impact, such as by minimizing device complexity, material consumption, or resource use. These concepts can be further clarified through concrete examples, such as those presented in Figure 36.

Because this step involves critically examining one's own habits and assumptions, a double-check point should be incorporated. As illustrated in Figure 37, this could take the form of a checklist, allowing users to ensure they have considered all alternative solutions and potential improvements before proceeding. As an additional checklist item (on the bottom), Design Guide users are also encouraged to ensure that they prioritise their ideas for interventions according to the environmental hotspots identified in the previous step.

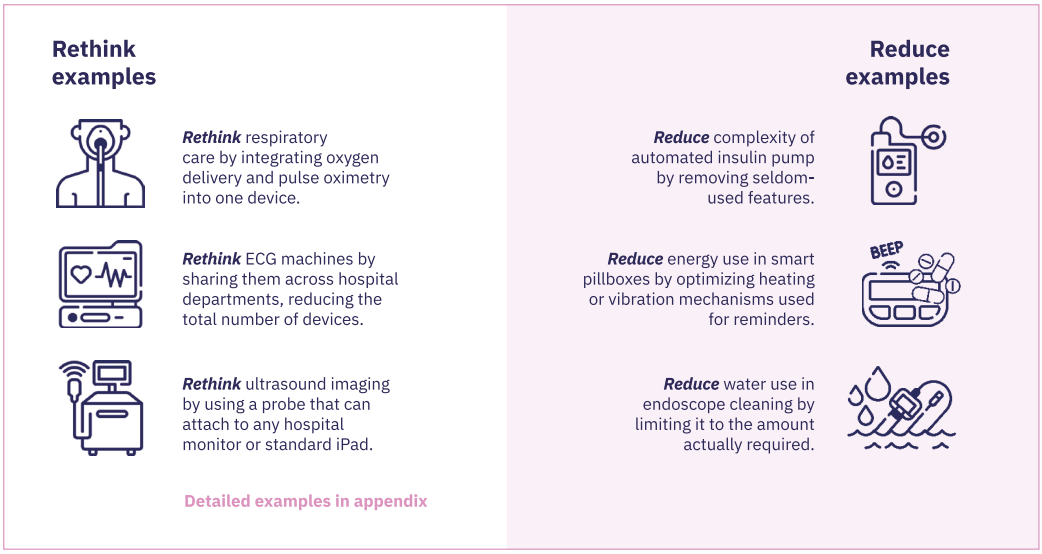


Figure 36: Examples of Rethink and Reduce in Design Guide

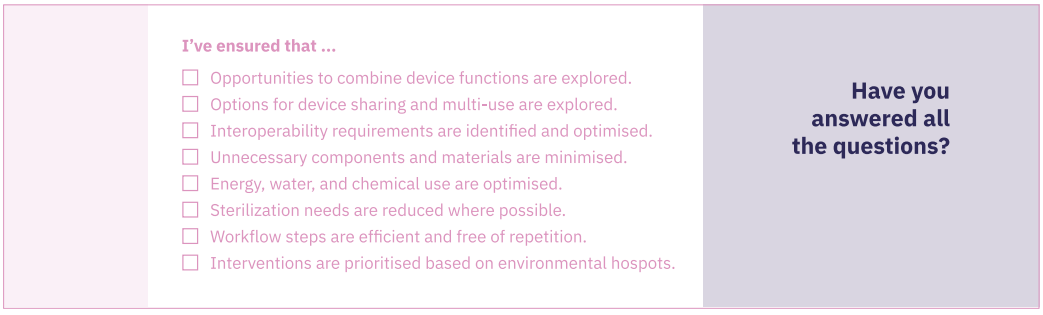


Figure 37: Checking Assumptions Checklist for the Design Guide

In some cases, however, self-assessment may require an additional layer. Even with the best intentions, practices intended to increase safety can sometimes have the opposite effect. For example, while protective gloves are commonly used to prevent contamination, research has shown that properly sanitized bare hands can, in certain situations, be safer than using gloves. Despite this, gloves are often still used and disposed of after each use, generating significantly more waste. To address such scenarios, a step like this could be implemented as an accountability checklist (Figure 38), providing guidance with concrete examples to prevent confusion and help users make better-informed, circular decisions.



Figure 38: Second Assumptions Checking Checklist and Examples for the Design Guide

6.5.3 Step C – CIRCULATE

Once the foundational principles for circular design interventions are established in Steps A and B, the value proposition can be fully realized by ensuring that devices remain in circulation. Step C – Circulate focuses on the collection (take-back or bring-back) of medical devices from patients' homes or healthcare facilities, as well as the processes that follow collection, including how these align with business models.

Figure 39 provides an example of guidance on the collection of devices that must be returned by the user—typically a patient or caregiver (the part for devices that are used in hospitals and other healthcare facilities will be shown later). The recommendations include strategies for behavioural change and motivation, emphasizing that highlighting the continued value of the device can improve return rates—for example, devices that look, feel, or function as valuable are more likely to be returned. Above all, however, the return process should be clear, simple, and effortless.

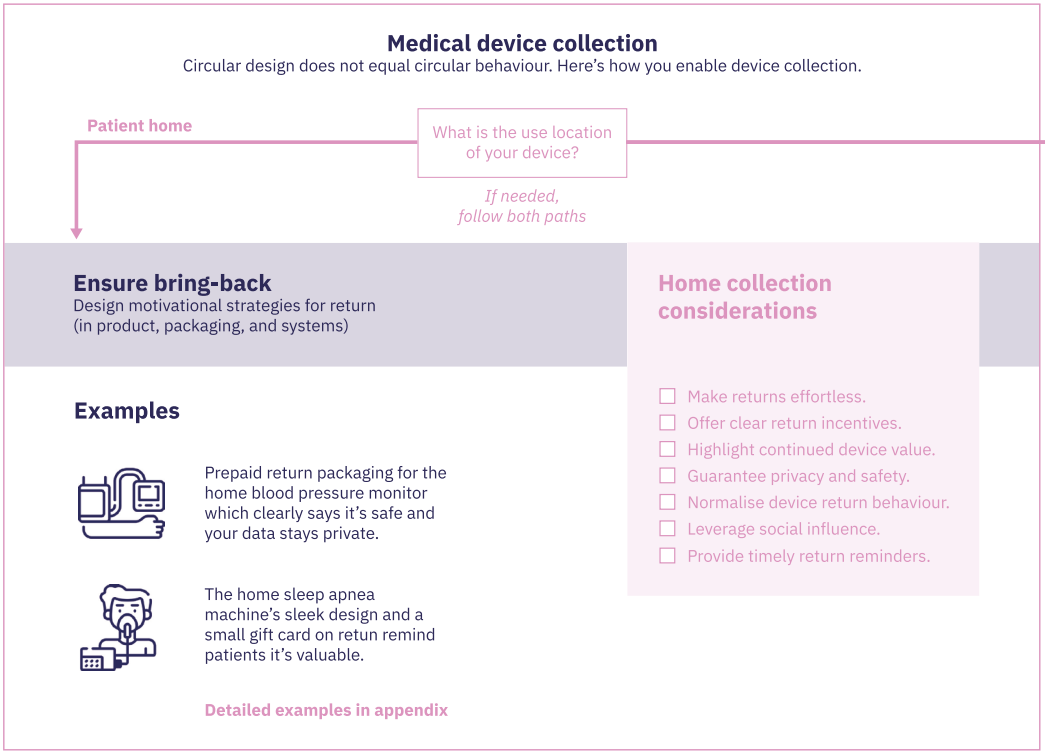


Figure 39: Collection Guidance and Bring-Back Examples for Design Guide

A similar situation applies when devices are collected within healthcare facilities, although the system operates differently. The design guide should inform users that devices reaching the end of their use in a hospital—or other clinical setting—and intended for reuse do not always need to be sent off-site. In many cases, they can be reprocessed on-site, and only sent back to the manufacturer when more than standard decontamination is required. Responsibilities for collection and processing should be clearly indicated to avoid confusion. These options can be illustrated with examples, as shown in Figure 40, providing users with a general understanding of the possibilities and their implications for circular design. However, the real detailed set-up of systematic interventions like this one is complex and too detailed explanation in the design guide could overwhelm the user. Instead, some general circulation considerations could be shared in a checklist, while referring to more detailed resources that can be accessed when needed. An example of such a list is shown in Figure 41. While those links to detailed resources are not added in this example yet, the resources will be provided by partners working on these topics as part of the DiCE project.

Finally, in addition to the previously discussed options—and beyond referencing the earlier Visual Taxonomy of Circular Healthcare Flows—providing general guidance on what should happen to devices after collection can add significant value. Drawing on the expertise of DiCE partners in circular business model development, a matrix could be created that considers both medical criticality (e.g., Class I, IIa, IIb, III) and expected length of use. This tool would help determine which circular strategies are most appropriate for each type of device. An example of such a matrix is shown in Figure 42.

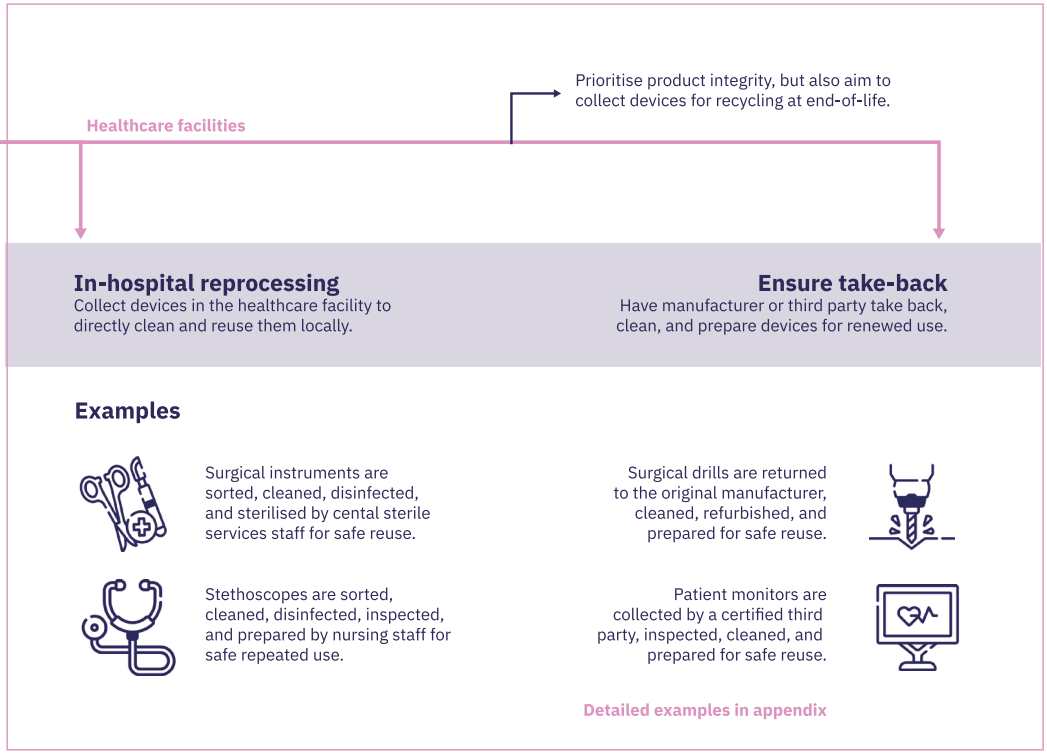


Figure 40: Collection Guidance and Take-Back Examples for Design Guide



Figure 41: General Circulation Considerations for Design Guide

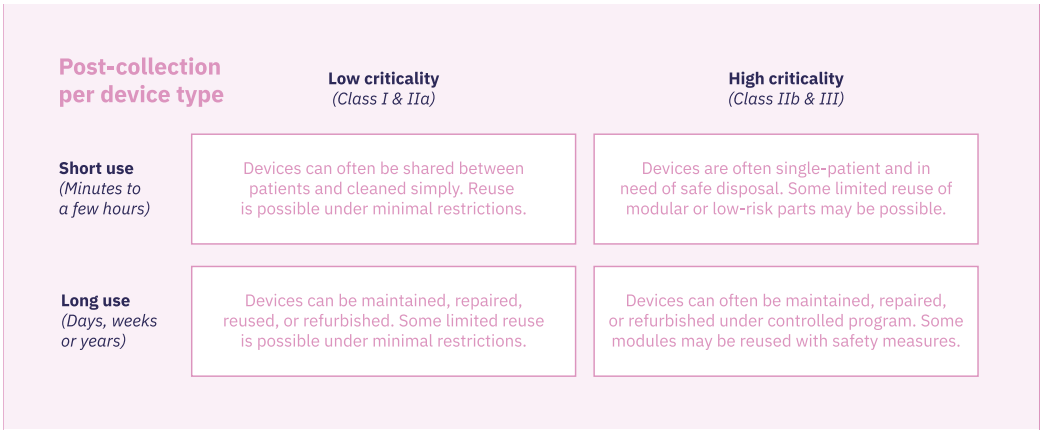


Figure 42: Post Collection Paths for Design Guide

6.5.4 Step D – EMBODY

After Step C – Circulate, the value proposition is considered complete, and the design engineer can begin developing a circular (re)design of the medical device. It is important to note that circular design—and design in general—extends beyond the physical product itself. The goal is not only to design the form, materials, and ergonomics, but also to define the specific interactions throughout the device's lifecycle, including before, during, and after use. In the design guide, product and service design should be treated separately and prioritized according to the environmental hotspots identified earlier (see example in Figure 43). This ensures that design efforts focus on the areas with the greatest potential for reducing environmental impact.

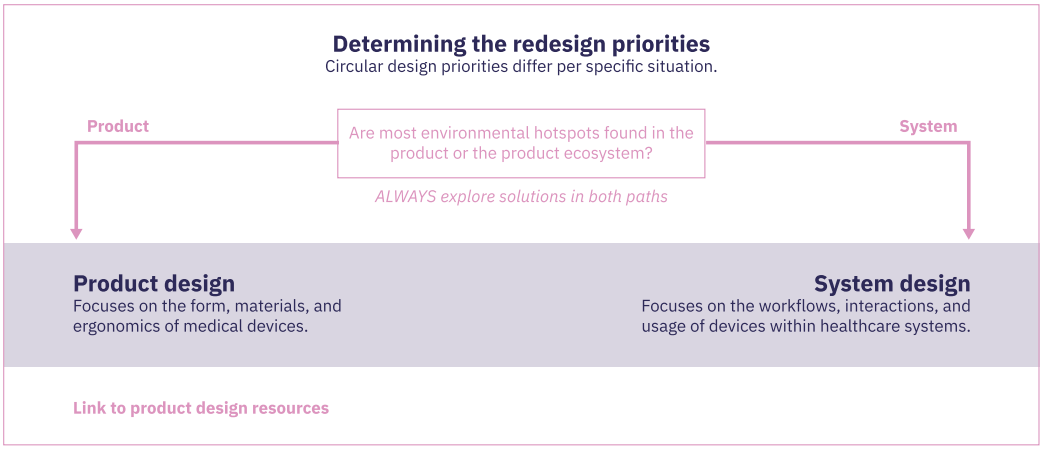


Figure 43: Determining Redesign Priorities in Design Guide

Furthermore, when addressing design considerations, two topics are particularly important to provide guidance on: requirements and barriers. First, the main design recommendations and guidelines for circularly designing medical devices—based on our research—should be clearly presented without overwhelming the user. This could be achieved, as shown in Figure 44, by highlighting the top 10 requirements, emphasizing those of highest priority, while also referencing a more comprehensive list for users who wish to explore further.

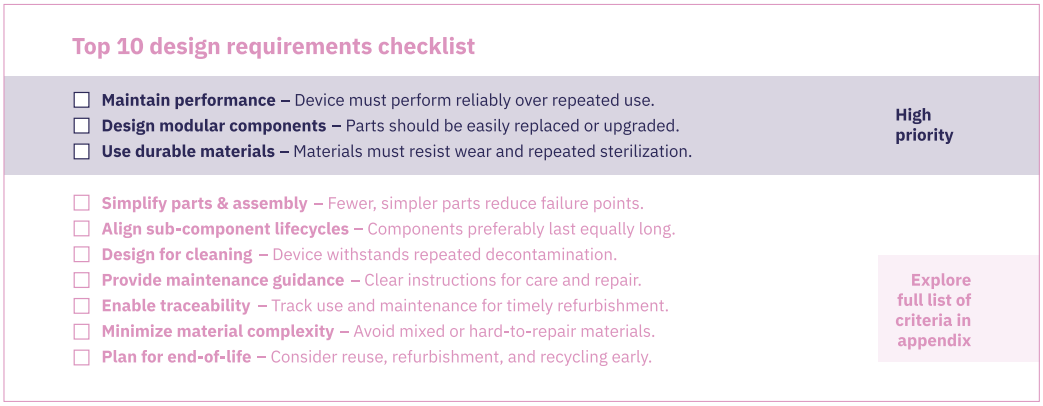


Figure 44: Design Requirements Top 10 in Design Guide

While these requirements are already healthcare-specific, stakeholders emphasized the need for even more targeted guidance. For example, insights on which medically approved materials are suitable for recycling can be highly valuable, as illustrated in Figure 45.



Figure 45: List of Medically Approved Recyclable Materials for Design Guide

In addition, the most significant healthcare-specific barriers identified through [9] could be presented along with recommendations on how to overcome them, also shown in Figure 46. The figure further provides examples of guidance for critical cases, such as when a device cannot be properly cleaned even after redesign interventions. Solutions commonly encountered in healthcare—such as hybrid designs, refillable components, or sleeve-based approaches—illustrate practical ways to address such challenges.

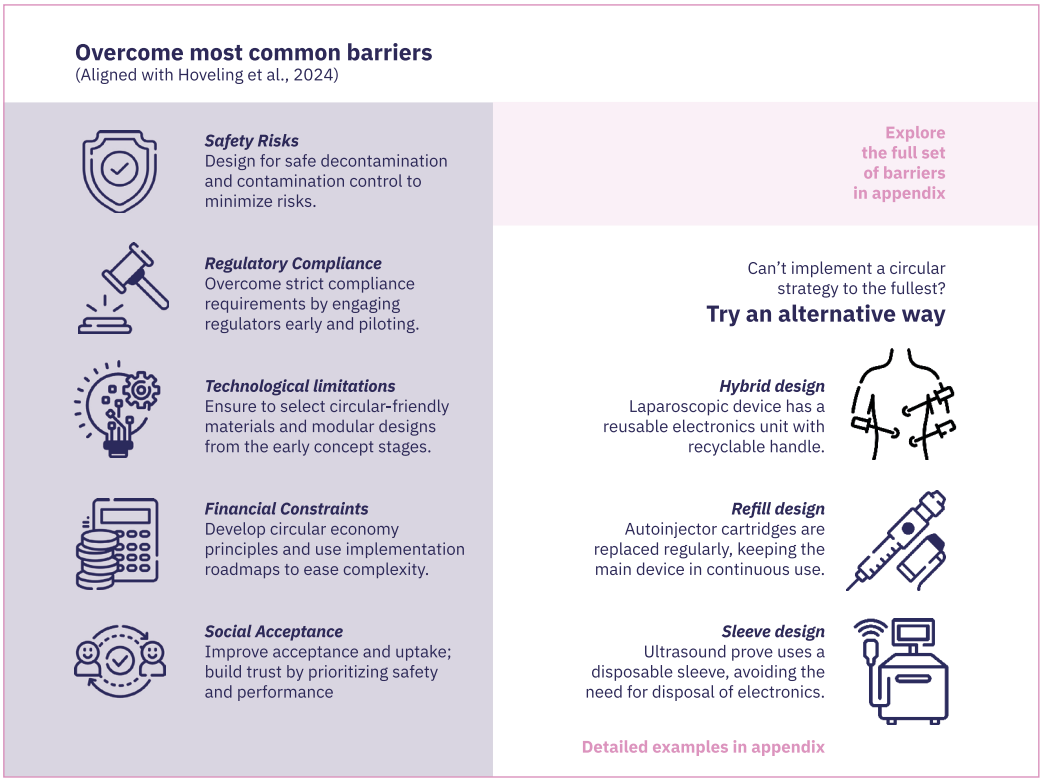


Figure 46: Most Important Barriers and Example Recommendations for the Circular Design Guide

6.5.5 Step E – EVALUATE

Step E helps teams evaluate design ideas to ensure circular redesign interventions achieve the intended outcomes and determine which design ideas should be moved forward with. For this, assessments should be conducted to verify that:

- The device meets the defined design requirements (this is assumed to be common practice),
- The environmental impact is actually minimized in practice, and
- Social sustainability is not compromised, which is critical to ensure safe, ethical, and equitable use of medical devices throughout their lifecycle.

This step specifically focuses on the latter two points—environmental impact and social sustainability—since meeting design requirements is generally already part of standard practice.

However, it is important to fully define certain design aspects before initiating the evaluation process. To guide users in determining readiness, a double-check decision tree could be included, helping them decide whether the device is prepared for environmental and sustainability assessment (see example in Figure 47).

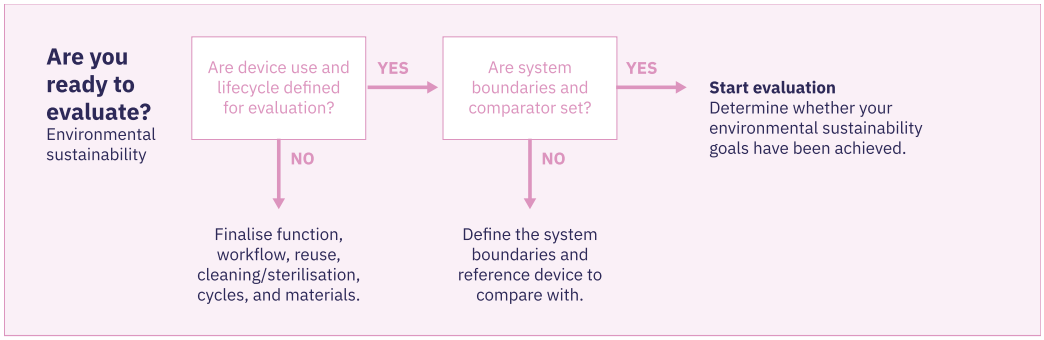


Figure 47: Decision Tree Before Environmental Assessment in Design Guide

Design guide users should be encouraged to carry out environmental sustainability assessments, without being instructed in detail on how to perform them. Instead, the guide can offer key considerations to help ensure the quality and relevance of such assessments, alongside references to external resources covering different assessment methods.

Figure 48 presents an example of such a checklist, complemented by examples of healthcare-specific adverse effects that should always be taken into account. These examples illustrate how certain circular design interventions may unintentionally increase environmental impact—for instance by adding complexity, affecting patient recovery, or altering clinical workflows—thereby counteracting their intended sustainability benefits.



Figure 48: Environmental Sustainability Evaluation in Design Guide

Following the environmental sustainability assessment, a social sustainability assessment is conducted. Social Life Cycle Assessment is relevant for the Circular Design Guide because it helps identify how design decisions affect stakeholder well-being throughout a product's life cycle, enabling interventions that are both environmentally sustainable and socially responsible. The assessment begins with a decision tree (Figure 49) to identify potentially affected stakeholders and determine who is responsible for these impacts and able to mitigate them.

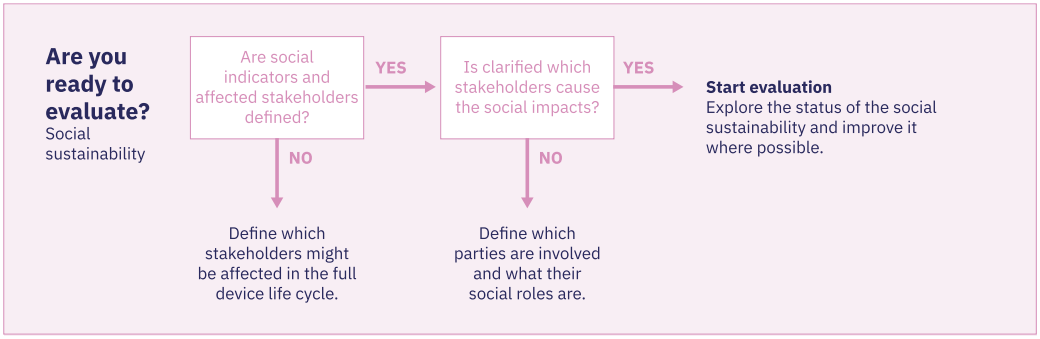


Figure 49: Decision Tree Prior to Social Sustainability in Design Guide

Figure 50 presents the social sustainability checklist and examples of potential social issues. Users are also advised to perform a full social LCA.



Figure 50: Guidance on Social Assessment in Design Guide

6.6 Assessment Against Design Guide Criteria

To understand how well the current version of the Circular Design Guide meets the needs of medical device developers, it was evaluated against the key criteria derived from research, case studies, and stakeholder input described earlier in this chapter. The assessment focuses on three main dimensions: content coverage, adoptability in practice, and support for reflective, iterative design. Table 22 summarises the evaluation, highlighting where the guide performs strongly and where further development could enhance its usefulness.

Table 22: Assessment of Design Guide 1.0 against Design Guide Criteria

Criterion	Current Status	Opportunities for Improvement
Integration of circular strategies (R-strategies)	Included via decision trees, checklists, and reflective prompts	Tailor guidance to specific device types; clarify when hierarchy of strategies applies
Environmental & social hotspot identification	Early-stage identification tools included	Better link to detailed sustainability assessment outcomes and responsible stakeholders
System-level perspective	Visual Taxonomy and workbook exercises support broader thinking	Expand guidance on supply chains, business models, and cross-team collaboration
Healthcare-specific constraints	Regulatory, safety, and patient-centered considerations included	Add concrete examples across device types and risk classes
Alignment with existing workflows	Follows generalized V-model and VPC process	Adapt guidance for smaller teams or iterative, overlapping development stages
Usability & engagement	Workbooks, visuals, templates, and checklists included	Improve modularity, online accessibility, and interactivity
Reflective & iterative design support	Prompts, matrices, and checklists included	Introduce tracking of decisions, lessons learned, and stakeholder responsibilities
Phased adoption & prioritization	Early concept introduced through workbook	Provide structured guidance on prioritizing circular strategies per development stage

The current guide provides a solid, research-informed foundation. It integrates circular strategies with system-level thinking, aligns with existing development workflows, and actively supports reflection and iteration. Practitioners can immediately use it to identify hotspots, explore trade-offs, and connect circular strategies to real design decisions. At the same time, opportunities remain to increase its practical relevance and adoptability. Future iterations should focus on device-specific guidance, interactive and online functionality, structured prioritization of strategies, and clearer integration of environmental and social assessments. Addressing these areas will ensure the guide is not just informative but actionable, helping designers, engineers, and project managers navigate the complexities of circular medical device development without feeling overwhelmed.

6.7 From Concept to Practice: Future Testing Plan

The recommendations for the Circular Design Guide presented in this chapter are research-informed explorations rather than a fully validated tool. Their development is therefore based on a set of explicit, testable assumptions derived from literature, stakeholder input, and exploratory evaluations, which require further validation in practice. These assumptions are that:

- Early-stage reflection on device necessity, clinical value, and environmental hotspots reduces the risk of non-circular decisions becoming fixed later in development.
- The use of structured reflection tools (e.g., decision trees and checklists) helps designers challenge habitual safety-, usability-, and regulation-driven assumptions without compromising clinical performance.
- Explicit consideration of collection, return, and reprocessing pathways increases the likelihood that devices remain in circulation rather than becoming waste.
- Separating value proposition creation from detailed product and system design improves clarity across roles and supports more targeted circular redesign decisions.
- Providing prioritised, healthcare-specific guidance supported by evidence, rather than prescriptive assessment methods, enables user engagement without causing cognitive overload.

Given the scope and timeframe of this dissertation, extensive multi-cycle user testing was not feasible. Instead, this section outlines a realistic and scalable evaluation approach for future work.

6.7.1 Evaluation Framework

Future evaluation of the Circular Design Guide can be structured using the framework proposed by Cash, Daalhuizen, and Hekkert (2023), which distinguishes between effectiveness and adoptability. This framework is well suited to the early maturity of the guide and supports formative, qualitative evaluation.

Effectiveness relates to whether the guide meaningfully supports circular design decision-making in medical device development and can be assessed through the following criteria:

- **Applicability:** To what extent is the guide applicable across different types of medical devices?
- **Scope:** Does the guide address both product design and relevant system or supply-chain aspects?
- **Adherence:** Is it clear when the guide has been sufficiently or fully applied?
- **Circularity Impact:** To what extent does using the guide support improved circular design outcomes?

Adoptability concerns whether the guide can be realistically used within existing development contexts and includes the following criteria:

- **Ease of Use:** How easy is the guide to apply in practice?
- **Ease of Learning:** How much time and effort are required to understand the guide?
- **Efficiency:** Can the guide be applied with limited resources, time, or effort?
- **Self-Assessment:** Does the guide support users in reflecting on and evaluating their circular design efforts?

Beyond effectiveness and adoptability, the guide's adaptability to future changes is also crucial. Taken together, these dimensions provide a structured foundation for evaluating both its practical usability and its potential impact.

6.7.2 Feasible Testing Approach

In practice, evaluation would likely consist of one or two focused testing rounds involving a small group of medical device designers, engineers, or sustainability specialists. Rather than full project-based validation, testing could include:

- Guided walkthroughs of the guide using hypothetical or retrospective design cases;
- Semi-structured interviews to capture perceived usefulness, clarity, and feasibility.

6.7.3 Positioning for Future Development

To summarize, the first version of the Circular Design Guide presented in this chapter should be understood as a starting point for advancing circular design practices in medical device development. Its primary contribution lies in prompting ideation and evidence-based decision-making, structuring reflection, making implicit assumptions explicit, and consolidating fragmented knowledge into a coherent design support framework. Future work should focus on iterative refinement through practice-based application, collaboration with industry partners, and gradual integration into real development projects to further test, adapt, and validate the guide over time.

References Chapter 6

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PART V

discussion and future outlook

Chapter 7
Discussion, Implications, and the Road Ahead

This chapter reflects on the insights brought together in Chapter 6, relates them back to the original research questions, and situates the findings within broader theoretical, practical, and societal contexts. It also explores limitations and avenues for future research and practice.

7.1 Connecting the Dots: Interpreting the Findings

The research presented in this dissertation was motivated by the urgent need for practical approaches to circular design in healthcare devices, particularly electronic ones, where safety, hygiene, and regulatory constraints have so far limited the adoption of existing strategies. The central research question guiding this work was:

How can medical devices containing electronic components be redesigned to support a circular economy, while ensuring clinical and regulatory compliance?

To answer this overarching question, a series of sub-questions (RQ1–RQ5) were addressed across Chapters 2–6, and structured through three phases: understanding, experimenting, and synthesizing. In the following section, each research question is briefly revisited, after which the key insights are synthesized.

7.1.1 Recap Phase I – Understanding Circular Healthcare (RQ1a–c, RQ2)

Phase I laid the empirical and conceptual groundwork for circular design in active medical devices by addressing the following four research questions:

- **RQ1a:** What circular medical devices are already on the market, and what can we learn from their strategies to drive future circularity?
- **RQ1b:** What barriers to the circular transition can be found, how likely do they occur, and what are potential opportunities to overcome them?
- **RQ1c:** What circular design guidelines can we identify based on the outcomes of RQ1a and RQ1b?
- **RQ2:** How can circular healthcare flows be systematically mapped and visualized to provide conceptual clarity and support stakeholders in applying circular strategies within healthcare constraints?

These questions sought to understand how circular strategies operate, and fail to operate, within healthcare's realities.

RQ1a: In Chapter 2, research into over 1,400 active medical device revealed that the application of circular strategies in medical device design remains limited and unevenly distributed. Only 25% of the devices implemented circular strategies, and even fewer combined multiple strategies.

Circular practices were concentrated primarily in reusable, medium-criticality devices used in controlled clinical environments, while high- and low-criticality devices – especially those used in home care – demonstrated considerably lower levels of circular integration.

RQ1b: Also in chapter 2, an analysis was performed into the barriers to the circularization of healthcare. The research uncovered a constellation of six barrier categories: safety, systemic, regulatory, financial, technological, and social. While safety concerns were most frequently cited, interviews revealed that these concerns are often amplified in practice through precautionary overinterpretation. Similarly, regulatory frameworks were frequently interpreted more conservatively than legally required, driven by liability avoidance and risk aversion. These findings suggest that while technological limitations can pose challenges, the central impediments to circularity often arise from a complex interplay of governance structures, risk perception, and institutional inertia. Focusing on device design provides a practical way to explore how circular strategies can be applied within these systemic constraints.

RQ1c: Building on RQ1a and RQ1b, finally Chapter 2 translated findings into 29 circular design guidelines for active medical devices. These guidelines emphasize integrating circularity from the earliest design stages while maintaining safety, clinical performance, and usability. They encourage moving beyond reuse to include higher-priority strategies such as refuse, rethink, reduce, remanufacture, and repurpose, and combining multiple strategies where possible. Operationally, they promote modularity, ease of disassembly, traceability, simplified materials, and alignment with device lifetimes and cleaning processes.

RQ2: Chapter 3 further highlighted that limited implementation is reinforced by conceptual ambiguity. Inconsistent terminology around especially reuse, reprocess, repair, refurbish, and remanufacture creates confusion across design, procurement, regulation, and clinical practice. Existing circular economy models lack the sector-specific precision required for healthcare. To address this, the Circular Healthcare Flows visual taxonomy was developed, which harmonizes terminology and maps physical product flows within clinical, regulatory, and operational contexts. Unlike hierarchical models, the taxonomy emphasizes context-sensitive decision-making, recognizing that environmental, clinical, and regulatory outcomes cannot be inferred solely from hierarchy position. The taxonomy serves both a conceptual and practical function, providing a shared language for designers, clinicians, and policymakers to coordinate circular strategies effectively.

Taken together, Phase I established four overarching insights:

1. Circularity in active medical devices remains limited and dominated by reuse, but a range of circular strategies is feasible.
2. Barriers stem as much from systemic norms, institutional practices, and risk perception as from technological constraints.
3. Conceptual ambiguity and inconsistent terminology across stakeholders hinder coordinated circular transition efforts.
4. Generic circular economy frameworks require adaptation to healthcare's regulatory, clinical, and operational realities.

Phase I reframed the central research challenge: the question is not simply how to apply circular strategies to medical devices, but how to embed them within a highly regulated, safety-critical system where language, governance, and infrastructure define what is possible.

7.1.2 Recap Phase II – Designing in Practice (RQ3a–b, RQ4)

Phase II built on the systemic and conceptual understanding developed in Phase I to investigate how circular strategies perform in real-world medical device design contexts. It addressed the following three research questions:

- **RQ3a:** To what extent can the 10R-strategies be applied in the redesign of electronic health devices to generate feasible and viable circular concepts?
- **RQ3b:** How can circular strategies, applied through the 10R-framework, contribute to environmentally sustainable solutions in healthcare devices?
- **RQ4:** How can trade-offs and synergies between circularity, safety, functionality, usability, and regulatory compliance be systematically assessed and managed in the design of complex medical devices?

Rather than assuming established circular frameworks could be directly transferred into healthcare, Phase II tested them in practice through two iterative design case studies: smart pillboxes (Chapter 4) and powered laparoscopic staplers (Chapter 5), combining structured application of the 10R framework with iterative concept development and design prototyping to explore feasibility in context.

RQ3a: Chapter 4 demonstrated that the 10R strategies—refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover—can guide design practice, though their applicability varies across device types, workflows, and system constraints. Higher-priority strategies such as refuse and reduce offer the greatest potential impact but often require substantial changes to device design or functionality. Mid-order strategies like reuse, repair, and refurbish were generally easier to adopt, requiring more incremental adjustments and fewer modifications to existing design processes. Lower-order strategies, including recycle and recover, could usually be implemented with minimal effort but offered limited additional value and sometimes conflicted with higher-priority approaches. Rethink played a distinctive role, enabling mid-order strategies by restructuring device functions and facilitating adoption. For example, as noted in Chapter 4, redesigning the product–service system to fully utilize product functionalities encouraged pillbox returns, thereby enabling other return-dependent strategies. These strategies were not only analysed conceptually but translated into tangible design concepts and prototypes, allowing practical constraints and opportunities to surface during development. Overall, while higher-priority strategies often involve greater effort, the 10R hierarchy is best understood as a flexible guideline: the feasibility and applicability of each strategy depend on device type, design constraints, and system-level context.

RQ3b: By iteratively refining and assessing design concepts through LCA and prototype-based evaluation, environmental consequences could be compared early in the design process. Environmental evaluation of the smart pillbox concepts showed that applying circular strategies through the 10R framework can reduce material use, e-waste, and carbon footprint, although realized benefits were highly context dependent. Mid-order strategies such as reuse, repair, and refurbish provided meaningful environmental gains while remaining operationally feasible, whereas recycle and recover contributed relatively little on their own. Higher-priority strategies such as refuse and reduce offered potential impact, but in this case their effect was limited by system conditions, illustrating that even strategies with high potential impact depend on lifecycle and operational context. These findings underscore that, while implementing circular economy principles in the design of a medical device is intended to support sustainability, the realized environmental benefits depend on lifecycle stage, system conditions, and operational context.

RQ4: Chapter 5 highlighted the trade-offs and synergies between circularity and other key design priorities, including safety, functionality, usability, and regulatory compliance. Trade-offs included increased sterilization and maintenance effort, logistical complexity, higher upfront costs, and potential operational disruption. Yet many interventions also produced synergies, such as lower long-term costs, improved alignment with emerging sustainability regulations, simplified logistics, and enhanced usability when designed thoughtfully. Notably, stakeholder preferences sometimes diverged from favourability based on LCA outcomes; for example, the multifunctional device showed one of the lowest carbon footprints, but received low expert ratings for technical feasibility and ease of use. Beyond the discrepancy between expert preferences and LCA results, perceptions also differed across stakeholder groups. For example, while several respondents emphasized contamination risks and regulatory barriers associated with reuse, others viewed the same concepts as compatible with existing sterilization practices and safety standards. This variation illustrates how feasibility and safety were interpreted differently depending on stakeholder perspective, underscoring the importance of integrating environmental assessment with diverse stakeholder evaluations.

Taken together, Phase II established three overarching insights:

- Circular strategies can be applied in design practice, but require careful inclusion of safety, usability, regulatory, and workflow constraints.
- The practical application of the 10R hierarchy generally supports its prioritization: higher-order strategies (refuse, reduce, rethink) tend to offer greater environmental leverage, while mid-order strategies (reuse, repair, refurbish) balance impact with feasibility. However, environmental gains are context- and product-dependent, so the hierarchy should be treated as a flexible starting point to guide ideation and small iterative design loops rather than a strict rule.'
- Trade-offs between circularity, clinical performance, and regulatory compliance can be managed—and sometimes leveraged into synergies—through iterative design, stakeholder engagement, and system-level thinking.

Phase II demonstrates that circular design in healthcare must be approached as a systems-level endeavour. Embedding circular strategies is feasible, but only when environmental ambitions are continuously negotiated with clinical performance, regulatory compliance, operational workflows, and stakeholder perception. The hierarchy of R-strategies provides strategic direction, yet real-world implementation depends on contextual adaptation and evaluation. By integrating LCA, stakeholder assessment, and design prototyping, this phase shows not only that circularity can be implemented in complex medical devices, but how it can be operationalized without compromising safety or functionality.

7.1.3 Recap Phase III – From Insights to Action (RQ5)

Phase III synthesized the systemic insights from Phase I and the applied design experiments of Phase II into a Circular Design Guide, aimed at supporting designers, engineers, and other stakeholders in implementing circular principles across medical devices. It addressed the following research question:

- RQ5: How can the insights from this research be synthesized into a practical, adoptable Circular Design Guide for medical devices, supporting designers, engineers, and other

stakeholders in systematically implementing circular principles across product and system levels?

Phase III translated the insights from Phases I and II into actionable guidance, focusing on how circularity can be embedded within standard medical device development processes. The design guide outlines a modular, stepwise approach—A – Define, B – Question, C – Circulate, D – Embody, E – Evaluate—that guides practitioners from evaluating device necessity and environmental hotspots, through planning circulation and design interventions, to assessing environmental and social impacts. Key lessons for healthcare circular design include:

- Circular decision-making must be integrated into the existing medical device development workflow, ensuring that sustainability interventions are feasible within standard design, engineering, and regulatory processes.
- Early-stage decisions— including defining the core clinical function, exploring system-level configurations, and framing the business model—have the greatest leverage for enabling circularity while maintaining patient safety and regulatory compliance.
- Guidance must be practical and adoptable, providing modular, layered recommendations: users can follow core steps while referring to additional resources, examples, and reflective prompts to tailor strategies to device type, workflow, and regulatory requirements.
- Circular guidance benefits from context-awareness, supporting reflection on assumptions, trade-offs, and local system conditions, rather than prescribing one-size-fits-all solutions.

Phase III thus completes the dissertation's trajectory: from diagnosing structural barriers (Phase I), to testing circular strategies in practice (Phase II), to translating insights into actionable, healthcare-specific recommendations that are feasible, adaptable, and directly applicable in medical device development.

7.1.4 Key Lessons and Comparison with Literature

The preceding chapters highlight the key lessons emerging from this dissertation: circular design in active medical devices is feasible but constrained by systemic, regulatory, and contextual factors; mid-order strategies such as reuse, repair, and refurbish are often the most implementable; and guidance is most effective when modular, layered, and integrated into existing design workflows. To understand how these insights fit into the broader academic discourse, it is helpful to compare them with recent literature. This comparison reveals both alignment with and challenges to previous assumptions and highlights the gaps this dissertation addresses.

Several recent studies confirm that safety and regulatory requirements strongly limit circular opportunities, especially for high-criticality medical devices [1], [2], [3]. Specifically, [4] found that sterilization standards and clinical safety requirements significantly restrict reuse, refurbishment, and recovery pathways. However, much of the literature treats regulations as static constraints, while this dissertation shows that decision-making is shaped not only by the rules themselves but also by the ways in which they are interpreted, operationalized, and enacted by designers and organizations.

A related but distinct challenge concerns perceived financial barriers. Even [5], who examined perceived barriers to circular economy adoption and differences between academic and industry perspectives, did not empirically examine whether increased costs constituted a material

barrier or reflected participants' expectations that circular strategies would be more expensive. Importantly, circular economy interventions do not inherently result in higher financial costs, particularly when full lifecycle costs are considered [6]. More broadly, [7] argues that circular economy approaches, such as extending product lifetimes and preserving value across multiple use cycles, can reduce resource expenditure while generating economic value.

Together, these findings suggest that perceived economic barriers may in some cases reflect assumptions rather than inherent economic constraints. This subtle but important distinction highlights the role of social and institutional practices in enabling or hindering circularity. The relevance of perceptions has been acknowledged previously by [2], who note that "barriers to circularity include perceptions regarding infection prevention, behaviours of device consumers and manufacturers, and regulatory structures that encourage the proliferation of disposable medical devices."

Much of the circular economy literature emphasizes R strategy hierarchies as a guiding principle, from the classic 3Rs—reduce, reuse, recycle [7], [8] to more elaborate frameworks that include refuse, rethink, repair, refurbish, remanufacture, repurpose, recycle, and recover [9], [10]. These hierarchies provide strategic guidance, as is also acknowledge and elaborated on in Chapter 3, but they often oversimplify complex, sector specific contexts. In healthcare, operational dependencies, clinical workflows, and regulatory requirements mean that the hierarchy alone cannot determine feasibility. Rather than assuming higher-order strategies should always take precedence, this dissertation highlights that mid-order strategies—reuse, repair, and refurbishment—often provide meaningful environmental impact while remaining operationally viable. This illustrates how the hierarchy can be applied flexibly as a practical guide for ideation and iterative design loops, rather than as a strict prioritization rule.

Finally, previous research has identified barriers to circular economy adoption, including limited awareness, infrastructure constraints, and a lack of practical guidance [2], [11], [12], [13], [14], [15], [16]. This dissertation confirms these challenges and provides insights from a design perspective, highlighting how considering circular strategies within everyday design practices, aligning them with existing workflows, and explicitly reflecting on trade-offs and assumptions can inform more effective design exploration. In doing so, the dissertation moves beyond simply identifying barriers, offering tools and processes that facilitate the iterative evaluation and operationalization of circular design concepts in practice.

Taken together, the literature largely supports the core insights of this dissertation: circularity in healthcare is constrained by systemic and regulatory factors, context shapes strategy effectiveness, and practical guidance for designers is scarce. At the same time, this work extends the field by translating high-level circular principles into actionable, workflow-integrated, and context-sensitive recommendations that designers can apply in real-world medical device development.

7.2 Contributions to Circular Design Theory in Healthcare

This dissertation advances circular design theory for active medical devices by integrating conceptual frameworks with empirical insights to show how circular strategies can be understood, evaluated, and operationalized within complex healthcare contexts. Circularity in healthcare systems is understood as the systemic circulation of materials, components, and devices within healthcare systems, aiming to maintain value, minimize waste, and support multiple product lifecycles while safeguarding patient safety and ensuring regulatory compliance. Circularity is framed as a pathway to environmental sustainability, where recirculating materials and components reduces environmental impact across the device lifecycle—including material extraction, manufacturing, use, and end-of-life—without compromising clinical performance or operational feasibility. The main contributions of this dissertation are:

- A conceptual framework and visual taxonomy of circular healthcare flows, which provides conceptual clarity in a growing field and clarifies how materials, components, and devices can circulate safely and effectively within complex clinical contexts. This taxonomy is the primary theoretical contribution of the dissertation.
- Empirical insights from research-through-design that highlight the barriers, trade-offs, and opportunities that arise when applying circular strategies in active medical devices.
- Demonstration of research-through-design as a methodology showing how iterative design, evaluation, and stakeholder engagement can address sustainability challenges in highly regulated, safety-critical systems.
- Advancement of circular design theory through the integration of actionable, context-sensitive guidance: this dissertation links high-level circular principles to practical decision-making in medical device workflows, iterative design, and stakeholder engagement, addressing a gap in sector-specific theoretical guidance.

These contributions extend circular design theory by showing that circularity and sustainability in healthcare are not abstract ideals but practical, context-sensitive approaches that can be embedded in medical device development. By combining conceptual clarity with operational pathways, this work bridges the gap between high-level circular economy principles and real-world adoption in healthcare settings.

7.3 Recommendations for Practice

Building on the insights from Phases I–III, this dissertation offers targeted recommendations for implementing circular design in healthcare, organized by key stakeholder groups. Figure 51 highlights the most important recommendations for both developers of medical devices and the users and buyers of those devices, including clinical professionals and hospital procurement teams. While all recommendations are based on a mix of findings from all chapters, the main source is also listed in Figure 51.



Medtech design & industry leadership

		Main source
1	Integrate circularity early in the development process	CH 2 & 3 interviews
2	Manage trade-offs between circularity, usability, safety, and regulatory compliance.	CH 5 trade-offs
3	Use iterative testing and lifecycle assessment.	CH 4 &5 design
4	Set organisational incentives for circular initiatives.	CH 5 trade-offs
5	Promote cross-functional collaboration across design, production, and end-of-life.	CH 2 barriers



Clinical & procurement stakeholders

		Main source
1	Involve clinician perspectives early to align on workflow, sterilisation, and usability.	CH 4 & 5 design
2	Collaborate to identify context-specific constraints and circular opportunities.	CH 2 barriers
3	Assess supplier practices; favour devices designed for longevity and modularity.	CH 2 best practices
4	Consider total lifecycle costs, not just upfront costs, in procurement decision.	CH 5 trade-offs
5	Support safe practices through collection, traceability, and reprocessing protocols.	CH 3 taxonomy

Figure 51: Main Recommendations for MedTech Design & Industry Leadership (left), and for Clinical & Procurement Stakeholders (right).

While developers and users are the primary stakeholders in driving the circular transition of healthcare, their ability to effect change is heavily influenced by [TH1.1]other actors—particularly policymakers. For this reason, Figure 52 also provides clear recommendations (and main sources) aimed at policymakers, designed to enable and support developers and users in advancing circular practices effectively.



Policymakers

		Main source
1	Provide clear standards for safe reprocessing of medical devices.	CH 2 & 3 interviews
2	Align regulations with circular goals to reduce perceived risk and encourage adoption.	CH 5 trade-offs
3	Create incentives to reward manufacturers and healthcare providers for circularity.	CH 2 opportunity
4	Support frameworks that enable innovation and experimentation within regulatory limits.	CH 2 barriers

Figure 52: Main Recommendations for Policymakers

7.4 Limitations and Critical Reflections

As with any research, this dissertation comes with a set of limitations that deserve careful consideration. Methodologically, the scope of the study was necessarily focused. The case studies, while providing rich, context-specific insights, were limited to a small number of device types and clinical settings. This means that while the findings illuminate key dynamics of circular design in active medical devices, they may not capture all variations present across the full spectrum of healthcare technologies. Similarly, the sampling of participants and stakeholders—though diverse—reflects specific professional and institutional contexts. For example, most MedTech professionals had experience primarily with larger medical device companies rather than smaller firms, their expertise was centred on hospital settings rather than private clinics, and they were based predominantly in high-income, Western countries. These contextual factors may have influenced perceptions, priorities, and responses.

The generalizability of the findings is therefore constrained. Insights drawn from smart pillboxes and powered laparoscopic staplers, for instance, may not fully translate to high-volume disposable devices, implantables, or home-care technologies. While the principles and frameworks developed here provide a starting point, adaptation will be needed to suit other device types, clinical workflows, or regulatory environments.

The design guide itself, while co-created with stakeholders and grounded in empirical evidence, carries its own limitations. Recommendations were shaped by the experiences, expertise, and perspectives of the participating clinicians, engineers, and designers, as well as the interpretive lens of the researcher, which may introduce additional subjective bias. Certain strategies may reflect context-specific feasibility rather than universal applicability. Moreover, the iterative design approach, while central to the research-through-design methodology, cannot fully anticipate every operational or regulatory nuance in real-world deployment.

Finally, ethical and practical considerations arise when contemplating the scaling of circular approaches. Interventions that work in one institution may encounter unexpected regulatory, cultural, or infrastructural barriers elsewhere. Decisions around reuse, refurbishment, or device lifecycle extension carry responsibilities for patient safety, clinical effectiveness, and legal compliance, highlighting that circular innovation in healthcare must always be carefully balanced against ethical imperatives.

Taken together, these reflections underscore that the findings and recommendations of this dissertation are both context-sensitive and provisional, providing a foundation for future work rather than a definitive blueprint.

7.5 Looking Forward: Future Research and Opportunities

While this dissertation has shown that circular design in healthcare is both possible and necessary, there remains a rich landscape of research questions and opportunities to explore. The journey ahead begins with collaboration: How can designers, engineers, clinicians, environmental scientists, and policymakers work together across traditional boundaries to enable system-level circularity? For example, collaboration between competing MedTech companies could lay the foundations for shared standards, harmonized terminology, and joint experimentation—but what mechanisms or incentives can make such cooperation feasible?

At the product level, technology offers untapped potential: How can digital twins, digital product passports, and AI-driven lifecycle assessment tools be used to track devices, monitor environmental and operational impacts, and link design interventions with measurable outcomes? These tools could make environmental and operational impacts visible in real time, providing the insight necessary for better decision-making across the device lifecycle.

Scaling circular design interventions and strategies beyond pilot projects presents another key question: Which strategies and systemic incentives allow circular approaches to be transferred across hospitals, regions, or countries, and what business models make them financially and environmentally sustainable?

Long-term thinking raises further avenues for inquiry: How do circular interventions reshape clinical routines, professional practices, and organizational norms over time, and what are the broader social and environmental consequences? A more efficient or reusable device, or a redesigned clinical procedure, may have effects far beyond its immediate lifecycle, contributing to both better patient outcomes and reduced environmental impact. At the same time, these interventions could produce unintended side effects or rebound effects, such as increased workload, changes in behaviour, or shifts in resource use, which need to be monitored and managed alongside intended benefits.

Finally, none of these efforts will succeed without education: What training, resources, and structured guidance are most effective in equipping designers, clinicians, and procurement teams to integrate circular thinking into everyday practice? Sector-specific standards, checklists, or certification schemes could support this work, translating principles into concrete, actionable steps that embed circularity into healthcare.

References Chapter 7

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Closing Remarks

This dissertation has explored how circular design can be meaningfully applied to active medical devices, bridging conceptual frameworks, empirical research, and practical guidance. It demonstrates that circularity in healthcare is achievable, but always within the constraints of safety, regulation, and clinical practice. By integrating systemic insights with iterative design experiments, the work provides both a deeper understanding of the barriers and trade-offs and a pathway for embedding circular principles into everyday device development. Beyond its immediate contributions, this research highlights the importance of collaboration, technological innovation, and education in enabling systemic change. Ultimately, the findings underscore that environmental sustainability and circularity are not abstract ideals but practical, context-sensitive approaches that can coexist with high-quality healthcare. The hope is that these insights inspire continued exploration, dialogue, and action, shaping the future of circular healthcare practice and research.

back matter

Afterword

When I first joined the DiCE project, I was immediately confronted with the scale of healthcare pollution — way beyond what I had ever imagined. Seeing fully functional but unused medical devices, from electric toothbrushes to high-tech surgical tools, being thrown away sometimes even brought me close to tears. It was shocking, frustrating, and somehow motivating all at once. Those moments reminded me why I started this journey: to do something meaningful in a field that really needed it.

A big part of this work has been looking at circular design for medical devices, especially those with electronics. Thinking about healthcare from a design perspective showed me that small changes can make a real difference — extending product life, cutting e-waste, improving sustainability, and even making devices easier to use at the same time. Healthcare is complicated, yes, but that complexity is also what makes it exciting. There are so many small things you can do as a designer that actually matter. Little choices, little changes, that make products last longer, generate less waste, or just work better for the people using them.

The PhD journey has not always been easy, but it reinforced something I already believed from the start: curiosity, persistence, and collaboration matter more than anything. Beyond all the findings and analyses, this research has shown me the real potential for solutions that actually improve practices, reduce waste, and create better systems. Looking back, it feels like a natural continuation of what I wrote in my foreword: as designers, we have a chance — maybe even a responsibility — to work with complex systems and leave the world a little better than we found it.

Acknowledgements

Doing a PhD is often described as an individual journey, but in reality, it is anything but solitary. Looking back, I now fully understand why supervisory teams are sometimes jokingly referred to as “academic parents”. In many ways, that is exactly what they have been.

First and foremost, I would like to thank my promotor Prof. Dr. ir. C.A. Bakker. Conny, I deeply appreciate your eye for detail, your directness, and your kindness. Thank you for creating an environment where I felt comfortable showing vulnerability and for reminding me that vulnerability can be a strength rather than a weakness. Your guidance has shaped both my research and the way I approach challenges more broadly.

I would also like to thank my second promotor, Dr. Faludi. Jeremy, from the very first day we met, your enthusiasm was infectious and a constant source of inspiration to make research actionable in real-world settings. You taught me the tricks of fast-track LCA, meticulously scrutinised my figures until they were just right, and shared many memorable experiences along the way. I am especially grateful for the opportunities we had abroad — from visiting the Vienna City Hall to the memorable road trip with Jason on the way to the consortium meeting in Maribor.

Speaking of which, the DiCE consortium was a wonderful place to begin an academic journey. From the moment I joined, it felt like a warm welcome. While the journey was certainly not without its challenges, I have had the pleasure of collaborating with so many amazing people — far too many to name individually, but you know who you are. Thank you all for your generosity, advice, and collaboration.

I would also like to thank my co-authors. Coming from such diverse backgrounds, working together was always both stimulating and enjoyable. Remarkably, we never once had a setback in our collaborations, which is a rare and wonderful thing.

From the TU Delft side, I would like to give special thanks to Prof. Dr. ir. J.C. Diehl. Although you were not formally part of my supervisory team, you played a significant role in shaping this research by thinking along with me and helping connect my work to the healthcare world. In many ways, you have been a mentor, and I have thoroughly enjoyed working with you.

Research like this would not have been possible without the many students who helped test ideas about circular medical device design in practice. Thank you especially to Evy, Dorien, Matthijs, Yifeng, Jamil, and Jasper for your enthusiasm and hard work. I am equally grateful to my earlier research assistants Anne, Marlou, Jelle, and Yichen. Without your efforts, several chapters would simply not exist in their current form. Thank you for your patience with the large data searches and endless Excel sheets, and a special thanks to Yichen for the beautiful sketches of the pillbox redesigns.

Beyond the research itself, there are also people who made the PhD experience far more enjoyable and far less lonely. My colleagues Maaike, Elisabeth, and especially Paula, and later also Yichen, thank you for the countless conversations — whether about research struggles, small victories, or simply life in general. Your presence made the journey much more pleasant.

During the PhD I also had the good fortune of meeting Ariadna Izcara Gual, who was brave enough to take on the challenge of redesigning the vaginal speculum with me. What began as a passion project eventually grew into establishing a company to continue this important work. I feel incredibly lucky to have shared this journey with you — the challenges, the learning moments, and the exciting developments around Lilium. Starting this venture left us both overwhelmed at times, but it has also felt like living a dream. I cannot wait to see where our collaboration takes us next.

Finally, I would like to thank the people who supported me beyond academia: my family, my soon-to-be family-in-law, and my close friends. Your encouragement has meant more than I can put into words, especially during the moments when I struggled to see the light at the end of the tunnel. Thank you all for your patience during the times when I was less present than I would have liked to be. I would also like to give special thanks to my father, for his invaluable strategic advice, and to my mother, for her guidance on the visual presentation of this work whenever I hit a creative block.

Finally, and most importantly, I want to thank my partner, José Luis Avila Cuenca, my soon-to-be husband. The past four years have been quite the adventure, and somehow it feels like this is only the beginning. Thank you for supporting me through every step of this journey and for patiently putting up with my complete obsession with this research. Your encouragement, calmness, and humour kept me grounded when things became overwhelming. I am incredibly lucky to have you by my side. And who knows — perhaps one day, out of curiosity or love, you might even open one of my research articles (I promise there will be no quiz afterwards).

personal sections

List of Publications

Below, the full list of publications of Tamara Hoveling is presented. Publications that were included in this dissertation are highlighted.

Journal Articles Under Review

Hoveling, T., Muindi, N., Faludi, J., & Bakker, C. (2026). Balancing trade-offs in circular medical device design: A case study on laparoscopic devices. Journal of Industrial Ecology (under review).

Peer-Reviewed Journal Articles

Hoveling, T., Ijzenbrandt, J., Hinrichs Krapels, S., Ritzen, L., Bramer, W. M., van Raaij, E., Faludi, J., Bakker, C., & Diehl, J. C. (2026). Mapping circular economy product and material flows in healthcare: A visual taxonomy. Journal of Cleaner Production, 538, 147258. https://doi.org/10.1016/j.jclepro.2025.147258

Hoveling, T., Nijdam, A. S., Monincx, M., Faludi, J., & Bakker, C. (2024). Circular economy for medical devices: Barriers, opportunities and best practices from a design perspective. Resources, Conservation & Recycling, 208, 107719. https://doi.org/10.1016/j.resconrec.2024.107719

Scholten, H. J., Hoever, Y., van Loon, F. H. J., Kanters, E., Hoveling, T., de Wild, M., Bouwman, R. A., & Korsten, E. H. M. (2022). Acoustic lens improves superficial in-plane ultrasound guided procedures – The significance of the beam width artefact. Journal of Clinical Anesthesia, 78, 110666. https://doi.org/10.1016/j.jclinane.2022.110666

Scholten, H. J., Hoever, Y., Kanters, E., Hoveling, T., de Wild, M., Korsten, E. H. M., & Bouwman, R. A. (2022). Ultrasound transducer with dynamic visual aid improves out-of-plane vascular access: A feasibility study. British Journal of Anaesthesia, 129(3), e69–e71. https://doi.org/10.1016/j.bja.2022.05.037

Conference Proceedings

Hoveling, T., Jin, Y., Faludi, J., & Bakker, C. (2024). Redesigning health devices for the circular economy: A case study on smart pillboxes. In Electronics Goes Green 2024+ (IEEE).

Hoveling, T., Faludi, J., & Bakker, C. A. (2023). A circular economy for medical devices: Barriers and opportunities for laparoscopic instruments. In Going Green Care Innovation 2023.

Hoveling, T., van Haren, J., & Delbressine, F. L. M. (2021). Simulating the first breath: Design of the respiratory reflex in a fetal manikin. In Proceedings of the ICBBE 2021 (pp. 163–169).

Liu, L., Hoveling, T., & Markopoulos, P. (2021). Design students' challenges in individual brainstorming using a design fiction method. In INTERACT 2021.

About the Author



Tamara Hoveling is an interdisciplinary researcher and designer passionate about sustainable healthcare. She combines environmental impact assessment, design-driven innovation, and policy-relevant methods to improve care pathways, enhance patient outcomes, and reduce environmental impact. Her work focuses on translating research into real-world solutions, including women's health innovations such as Lilium.

Education

PhD Candidate – Industrial Design (2022–present), TU Delft
Research on circular design of (active) medical devices for sustainable healthcare.

MSc Industrial Design (Research Track) (2019–2022), TU Eindhoven
GPA: 8.2/10 | MSc Thesis grade: 8.5/10
Thesis: Liquid-based neonatal incubation device ("artificial womb").

BSc Engineering: Product Design (2016–2019), Hogeschool van Amsterdam
Graduated cum laude | BSc Thesis grade: 10/10
Thesis: Sustainable ultrasound-guided vascular access solution.

Professional Experience

Project Coordinator (2024–present), NovaLilium
Co-development of patient-friendly gynaecology device

Freelance Designer & Writer (2018–2022), Pistache Creation Office
Translation of complex topics into accessible language

Scientific Researcher (2019), Catharina Hospital
Ultrasound transducer prototype development and user validation

BSc Internship (2019), Philips Research
Redesign of ultrasound-guided IV solution (usability & circularity)

Earlier roles: Design Intern – Mazda Motor Europe (2017–2018);
Teaching Assistant – Hogeschool van Amsterdam (2016–2017)

Research Interests

Circular economy in healthcare · Sustainable medical device design · Life-cycle assessment · Regulatory innovation · Women's health technologies · Design for safety and compliance

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Chapter 2 – Appendix A
Example Interview Questions

A.1 General Questions

- Question 1: Could you first explain a bit about what you / your company works on exactly?
- Question 1.1: What are the sustainability goals of your company and how do you make sure to reach those goals (and by what time)?
- Question 2: What types of devices / materials does your company focus on more specifically?
- Question 3: Do you also have specific expertise in the area of sustainability of health devices / medical devices? Can you explain?
- Question 3.1: How do you believe circularity to be different for medical devices, compared to non-medical devices?
- Question 4: How do you define the terms [insert relevant R-strategies and other relevant terms such as reprocessing]? Do you believe we have used the terms correctly?
- Question 5: Is there any recovery flow that you think is best for the environment, in the context of medical devices, and why?
- Question 6: Are there specific things you do differently when working with devices that are intend to go through multiple loops?

A.2 Barriers, Risks, and Opportunities

We would like to know what the advantages, risks/barriers and opportunities are for each circular strategy [for each mentioned barrier, we asked participants to also come up with possible solutions].

- Question 7: What do you think are the most important reasons to choose or not choose for your each of these circular strategies?
- Question 7.1: Can you mention any specific advantages, barriers, and risks? [if participants could not come up with many answers, we mentioned for following possible categories as examples: financial, regulatory, social, safety, and practicality]
- Question 7.2: Why do you think many circular strategies are currently not (yet) implemented within the healthcare sector?
- Question 7.2: Of all barriers that you have previously mentioned, which one do you think is the most important one?

[The questions below are examples of questions that could be asked to get more information about the barriers that are mentioned by the participants]

- Question 8: How do you think should be dealt with the dangers of electronics? And of medical waste that is potentially contaminated?
- Question 9: How do devices or components reach the right facilities?
- Question 10: Are there any logistic issues that often occur in these processes?

- Question 11: Do you believe circular flows are generally ‘accepted’ in Europe (and beyond)? How is this for medical devices?
- Question 12: We assume you also know quite a lot about the [fill-in depending on the participant] barriers to circularity in this context. Can you tell us a bit more about these barriers and potential opportunities of overcome them?

A.3 Design Recommendations

- Question 13: If we were to design a new medical device or redesign an existing medical device that contains electronic components, and we want it to be suitable for [circular strategies of their expertise], what requirements should this device ideally have, for as far as you know?
- Question 13.1: Are there particular design requirements you think are already adhered to for this purpose?

[The questions below are examples of questions that could be asked to get more information about the recommendations that are mentioned by the participants]

- Question 14: What specific recommendations are most important to help overcome the barriers that we have discussed earlier?
- Question 15: What specific design aspects are to be considered to make a device [e.g. easy to clean, easy to disassemble, suitable for recycling, etc., based on what the participants have mentioned].
- Question 16: Are there certain materials that are considered a ‘no-go’ for most flows?

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Chapter 3 – Appendix A

Initial Visual – Research Probe for Interviews

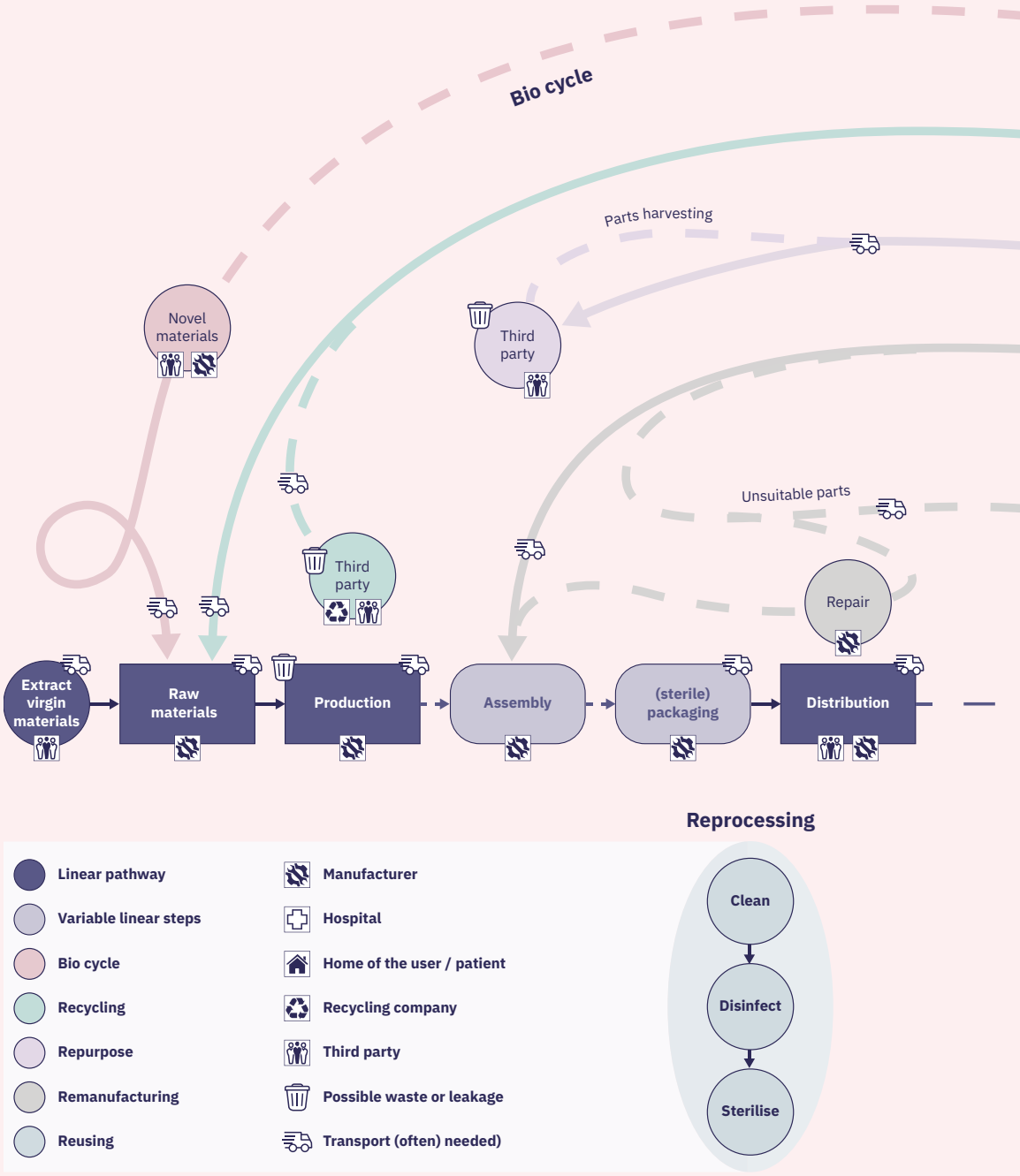
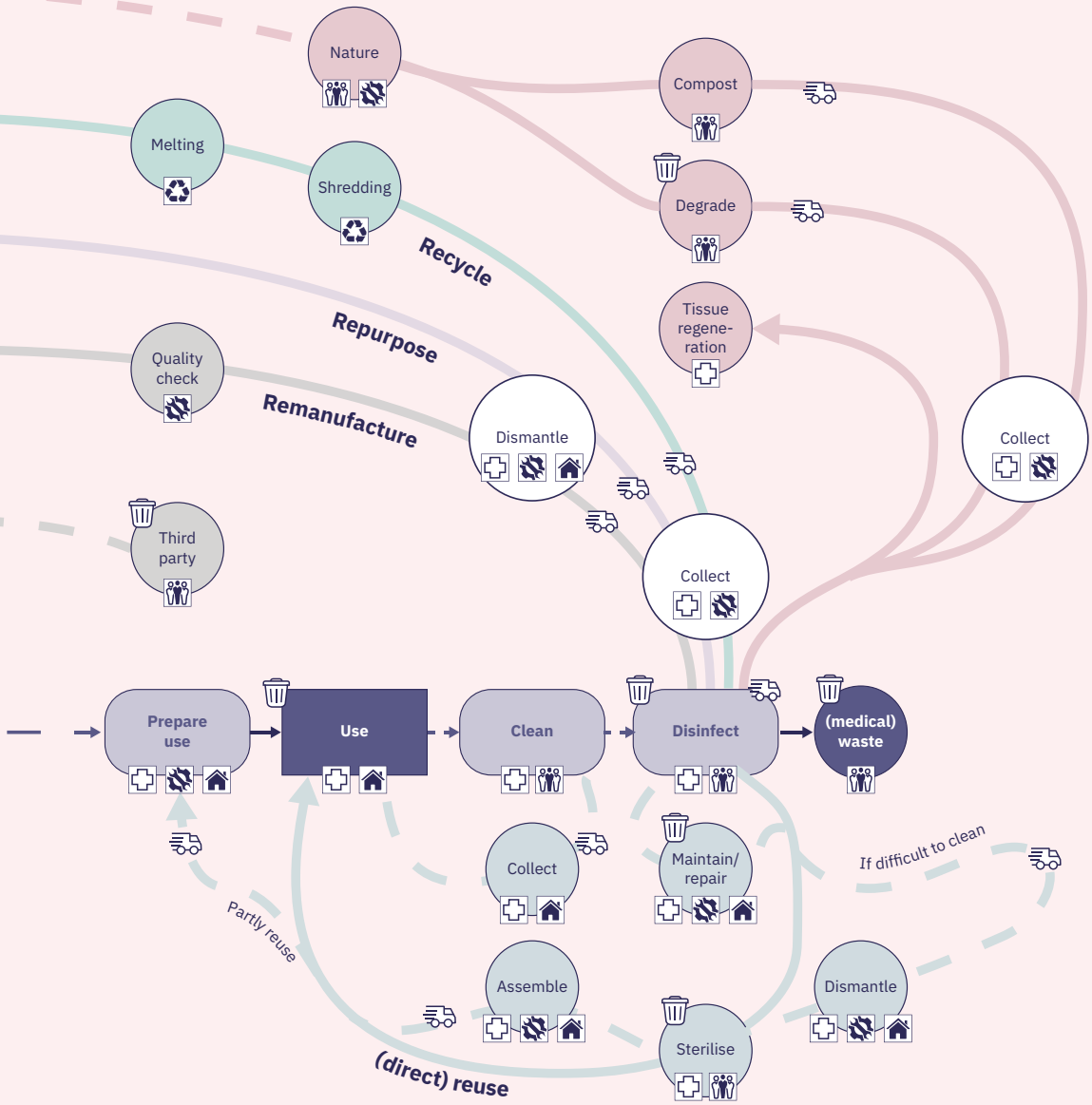


Figure 53: Interview Research Probe


Nature
Compost
Melting
Shredding
Degrade
Recycle
Tissue regene-ration
Repurpose
Quality check
Remanufacture
Dismantle
Collect
Third party
Collect
Prepare use
Use
Clean
Disinfect
(medical) waste
Collect
Maintain/ repair
If difficult to clean
Partly reuse
Assemble
Dismantle
Sterilise
(direct) reuse

Chapter 3 – Appendix B

Expert Interviews Protocol

Below, the interview protocol used during all expert interviews of the second interview cycle is displayed. Note that the protocol below does only include the content-specific questions, and not the introduction.

First, explain to the participant: we are developing a visual that displays the different processes that (medical) product can go through after use to make then circular. We are assuming that you have some experience in [specific process(es) of their expected expertise], because [...]. If you also have other knowledge that might be relevant to answer our research questions, please let us know. We will show you the visual with all the steps.

[show the visual to the participant while explaining it in detail]

- **Question 1:** How would you define the terms displayed in this visual (e.g. recycling, remanufacturing, reprocessing, reuse, repurpose)? Do you believe we have used the terms correctly in our visual? We will use the by-you preferred terms in the continuation of this interview.

- **Question 2:** The image displays that health devices will be collected after disinfection and will then be processed in different kinds of ways to loop back into a production process or into nature. We want to know what is correct or incorrect about this overview, so we can adjust it until it is accurate.

[Go through the visual in detail again, asking for feedback on each detail of their expertise. Let the participant specify what they like about the current visual and what they think should be improved. In case participants are struggling to provide points of improvement, follow-up questions below are example questions that can be used to ask for further clarification where needed.]

- **Question 2.1:** What do you think are the most important differences between [flow] and [flow]?

- **Question 2.2:** Collection and sorting were already proven to be a huge barrier to circularity in healthcare. Do you agree?

- **Question 2.3:** Do you think that we should elaborate more on the exact collection processes in our visual? If yes, can you provide us with detailed steps?

- **Question 2.4:** How do you think should be dealt with the dangers of electronics?

- **Question 2.5:** How do you think should be dealt deal with the dangers of medical waste?

- **Question 2.6:** How do you know which materials you are dealing with and how to handle them?
- **Question 2.7:** How do devices or components reach the right facilities?
- **Question 2.8:** What are the procedures in place for devices that need to be disassembled or sorted with a specific waste stream, such as highly infected devices?
- **Question 2.9:** Can you provide us with some examples of [flow of expertise] systems in healthcare that were successful? Why do you think those work well?

Chapter 3 – Appendix C

Updated Visual After Expert Interviews

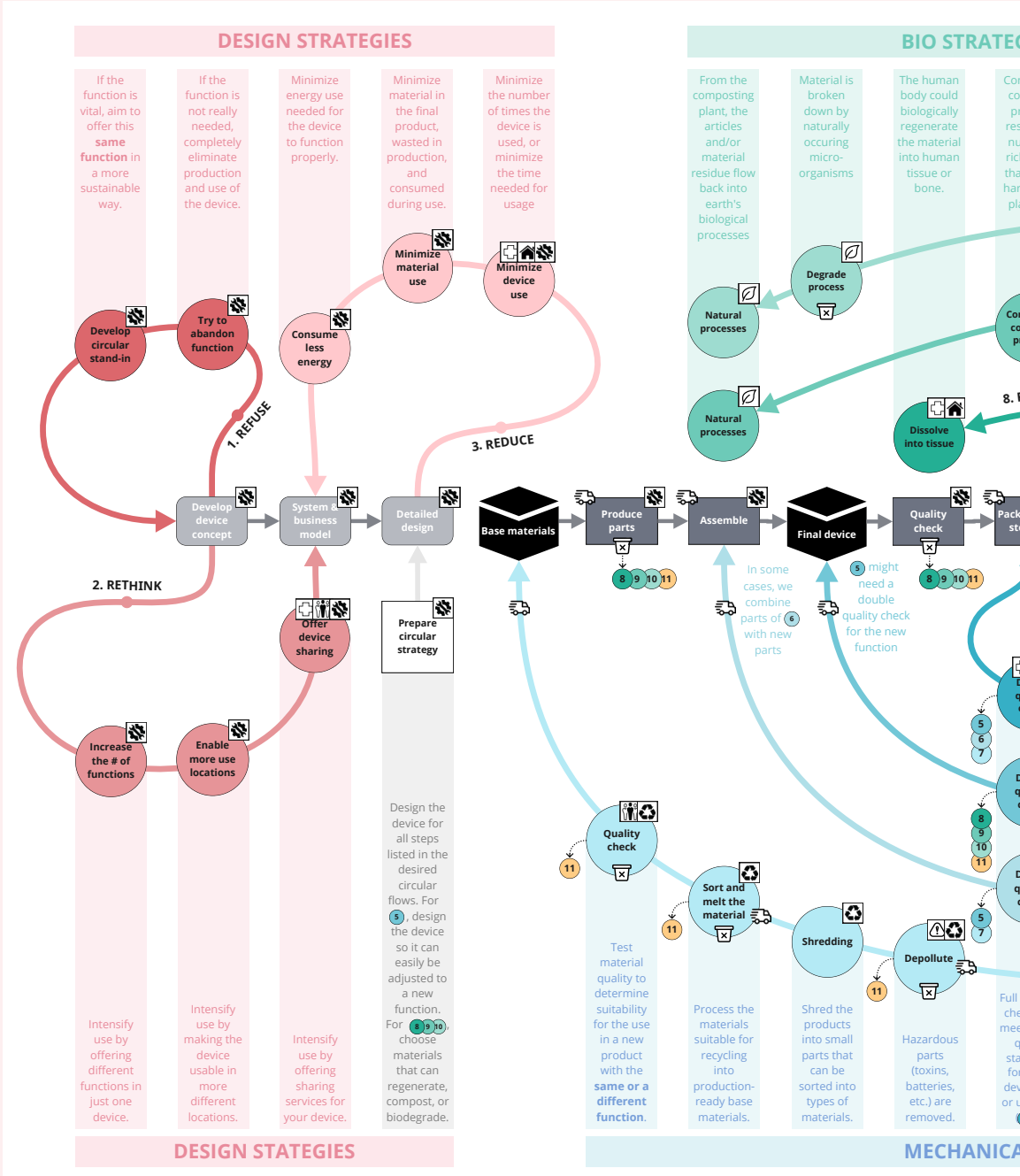
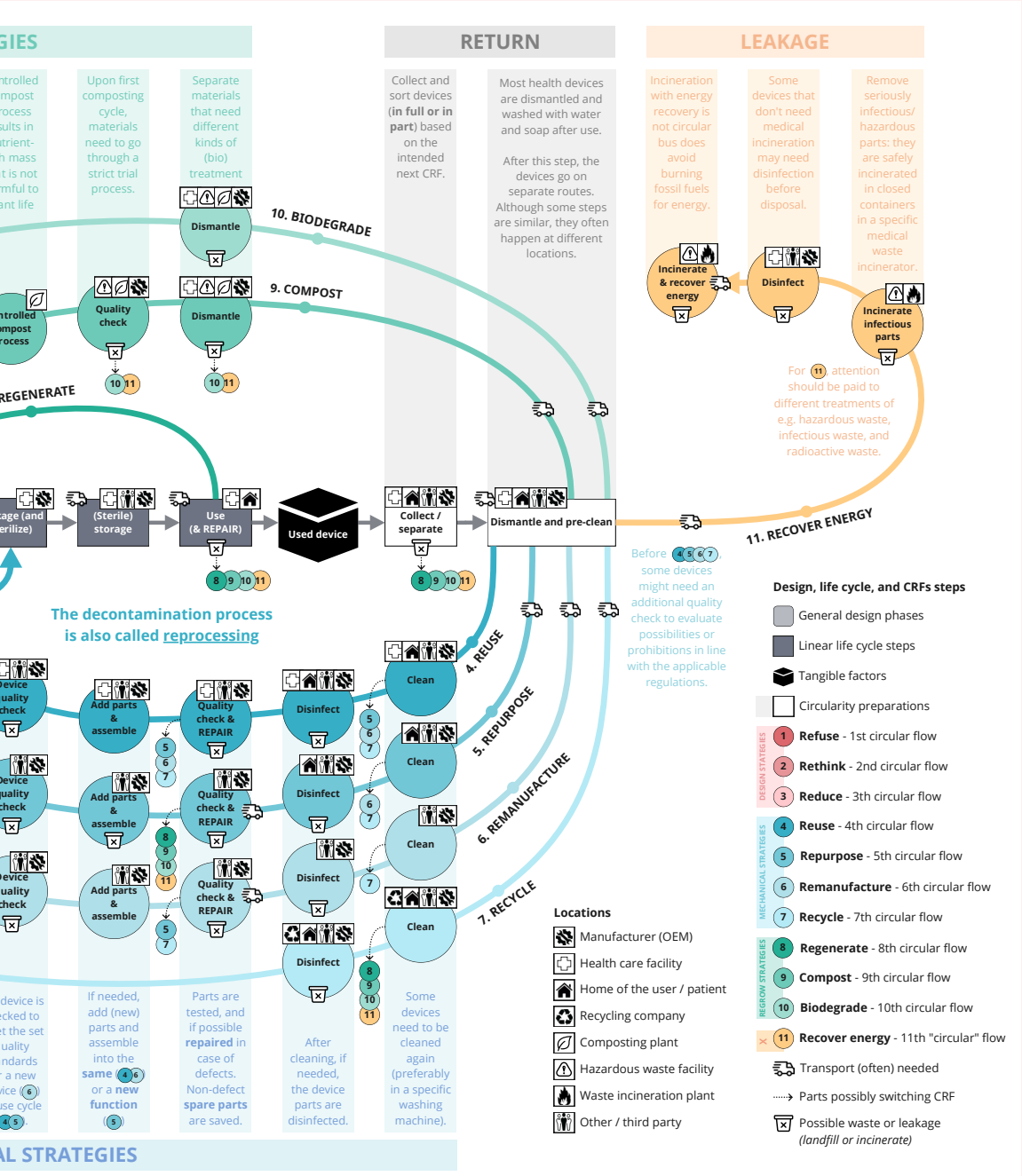


Figure 54: Updated Visual Taxonomy (earlier version)


GIES
RETURN
LEAKAGE
Upon first composting cycle, materials need to go through a strict trial process.
Separate materials that need different kinds of (bio) treatment
Collect and sort devices (in full or in part) based on the intended next CRF.
Most health devices are dismantled and washed with water and soap after use.
After this step, the devices go on separate routes. Although some steps are similar, they often happen at different locations.
Incineration with energy recovery is not circular bus does avoid burning fossil fuels for energy.
Some devices that don't need medical incineration may need disinfection before disposal.
Remove seriously infectious/ hazardous parts: they are safely incinerated in closed containers in a specific medical waste incinerator.
Dismantle
10. BIODEGRADE
Quality check
Dismantle
9. COMPOST
Incinerate & recover energy
Disinfect
Incinerate infectious parts
REGENERATE
For 11 attention should be paid to different treatments of e.g. hazardous waste, infectious waste, and radioactive waste.
(Sterile) storage
Use (& REPAIR)
Used device
Collect / separate
Dismantle and pre-clean
11. RECOVER ENERGY
Before 4 5 6 7 some devices might need an additional quality check to evaluate possibilities or prohibitions in line with the applicable regulations.
The decontamination process is also called reprocessing
4. REUSE
5. REPURPOSE
6. REMANUFACTURE
7. RECYCLE
Add parts & assemble
Quality check & REPAIR
Disinfect
Clean
If needed, add (new) parts and assemble into the same 4 6 or a new function 5
Parts are tested, and if possible repaired in case of defects. Non-defect spare parts are saved.
After cleaning, if needed, the device parts are disinfected.
Some devices need to be cleaned again (preferably in a specific washing machine).
AL STRATEGIES
Locations
Manufacturer (OEM)
Health care facility
Home of the user / patient
Recycling company
Composting plant
Hazardous waste facility
Waste incineration plant
Other / third party
Design, life cycle, and CRFs steps
General design phases
Linear life cycle steps
Tangible factors
Circularity preparations
DESIGN STATEGIES
1 Refuse - 1st circular flow
2 Rethink - 2nd circular flow
3 Reduce - 3th circular flow
MECHANICAL STRATEGIES
4 Reuse - 4th circular flow
5 Repurpose - 5th circular flow
6 Remanufacture - 6th circular flow
7 Recycle - 7th circular flow
REGROW STRATEGIES
8 Regenerate - 8th circular flow
9 Compost - 9th circular flow
10 Biodegrade - 10th circular flow
11 Recover energy - 11th "circular" flow
Transport (often) needed
Parts possibly switching CRF
Possible waste or leakage (landfill or incinerate)

Chapter 3 – Appendix D
Full Search Strings

The following sections present the complete search strings used in search phase one and phase two, exemplified for the Medline search.

Table 23: Search Strategies Phase 1

Database searched	Platform	Years of coverage	Records	Records after duplicates removed
Medline ALL	Ovid	1946 - Present	1685	1678
Embase	Embase.com	1971 - Present	2523	1569
Web of Science Core Collection*	Web of Knowledge	1975 - Present	532	180
Total			**4740**	**3427**

D.1 Medline Search String Search Phase 1

(* Equipment Reuse/ OR * Recycling/ OR ((* Surgical Equipment/ OR * Disposable Equipment/ OR exp * "Equipment and Supplies"/ OR * Equipment Design/) AND (* Sustainable Development/ OR * Carbon Footprint/ OR * Waste Management/ OR * Refuse Disposal/ OR * Medical Waste Disposal/ OR * Environment/)) OR (circularit* OR ((repair* OR reuse* OR reusab* OR redistribut* OR restoration* OR recondition* OR regenerat* OR recover* OR refurbish* OR recontextuali* OR reprocess* OR recycl* OR sustainab* OR closed-loop* OR carbon-footprint* OR downcycl* OR upcycl* OR Resterili* OR multi-use OR repurpos* OR waste-collection* OR waste-separation* OR waste-management* OR environmental*-friend*) ADJ6 (device* OR resource* OR equipment* OR material* OR medical-product* OR instrument*)) OR green-team*).ti.) AND (exp * Drug Therapy/ OR exp * Delivery of Health Care/ OR exp * Hospitals/ OR exp * Surgical Procedures, Operative/ OR diagnostic procedure/ OR ((drug* ADJ3 therap*) OR pharmaceutic* OR health-care* OR healthcare* OR hospital* OR medical* OR surger* OR surgical* OR diagnos* OR rehabilitation* OR intensive-care OR icu OR (operating ADJ (room* OR theat*))).ti.) NOT (* DNA repair/ OR (((surgical* OR dna OR tissue OR wound) ADJ3 repair*) OR repair-device*).ti.) NOT (news OR congres* OR abstract* OR book* OR chapter* OR dissertation abstract*).pt.

Table 24: Search Strategies Phase 2

Database searched	Platform	Years of coverage	Records	Records after duplicates removed
Medline ALL	Ovid	1946 - Present	284	283
Embase	Embase.com	1971 - Present	547	412
Web of Science Core Collection*	Web of Knowledge	1975 - Present	98	38
Total			929	733

D.2 Medline Search String Search Phase 2

(* Equipment Reuse/ OR * Recycling/ OR ((* Surgical Equipment/ OR * Disposable Equipment/ OR exp * “Equipment and Supplies”/ OR * Equipment Design/) AND (* Sustainable Development/ OR * Carbon Footprint/ OR * Waste Management/ OR * Refuse Disposal/ OR * Medical Waste Disposal/ OR * Environment/)) OR (circularit* OR (circular* ADJ3 (econom* OR material* OR product*)) OR ((repair* OR reuse* OR reusab* OR recondition* OR regenerat* OR recover* OR refurbish* OR recontextuali* OR reprocess* OR recycl* OR sustainab* OR closed-loop* OR carbon-footprint* OR downcycl* OR upcycl* OR Resterili* OR multi-use OR repurpos* OR waste-collection* OR waste-separation* OR waste-management* OR environmental*-friend*) ADJ6 (device* OR resource* OR Consumable* OR Packaging* OR Disposable* OR equipment* OR material* OR medical-product* OR instrument*)) OR green-team* OR (environment* ADJ3 sustainab*)).ti.) AND (exp * Drug Therapy/ OR exp * Delivery of Health Care/ OR exp * Hospitals/ OR exp * Surgical Procedures, Operative/ OR * diagnostic procedure/ OR ((drug* ADJ3 therap*) OR pharmaceutic* OR health-care* OR healthcare* OR hospital OR hospitals OR medical* OR surger* OR dentist* OR surgical* OR diagnos* OR rehabilitation* OR intensive-care OR icu OR (operating ADJ (room* OR theat*)) OR medical*).ti.) NOT (* DNA Repair/ OR (((surgical* OR dna OR tissue OR wound) ADJ3 repair*) OR repair-device*).ti.) NOT (news OR congres* OR abstract* OR book* OR chapter* OR dissertation abstract*).pt. AND (Review/ OR Systematic Review / OR Meta-Analysis / OR (review* OR meta-analy*).ti. OR (((literature* OR systematic* OR scoping OR comprehensive*) ADJ3 (review)) OR ((pubmed OR medline OR embase) AND (review))).ab,ti,kw.)

Chapter 3 – Appendix E

Updated Visual After Systematic Literature Review

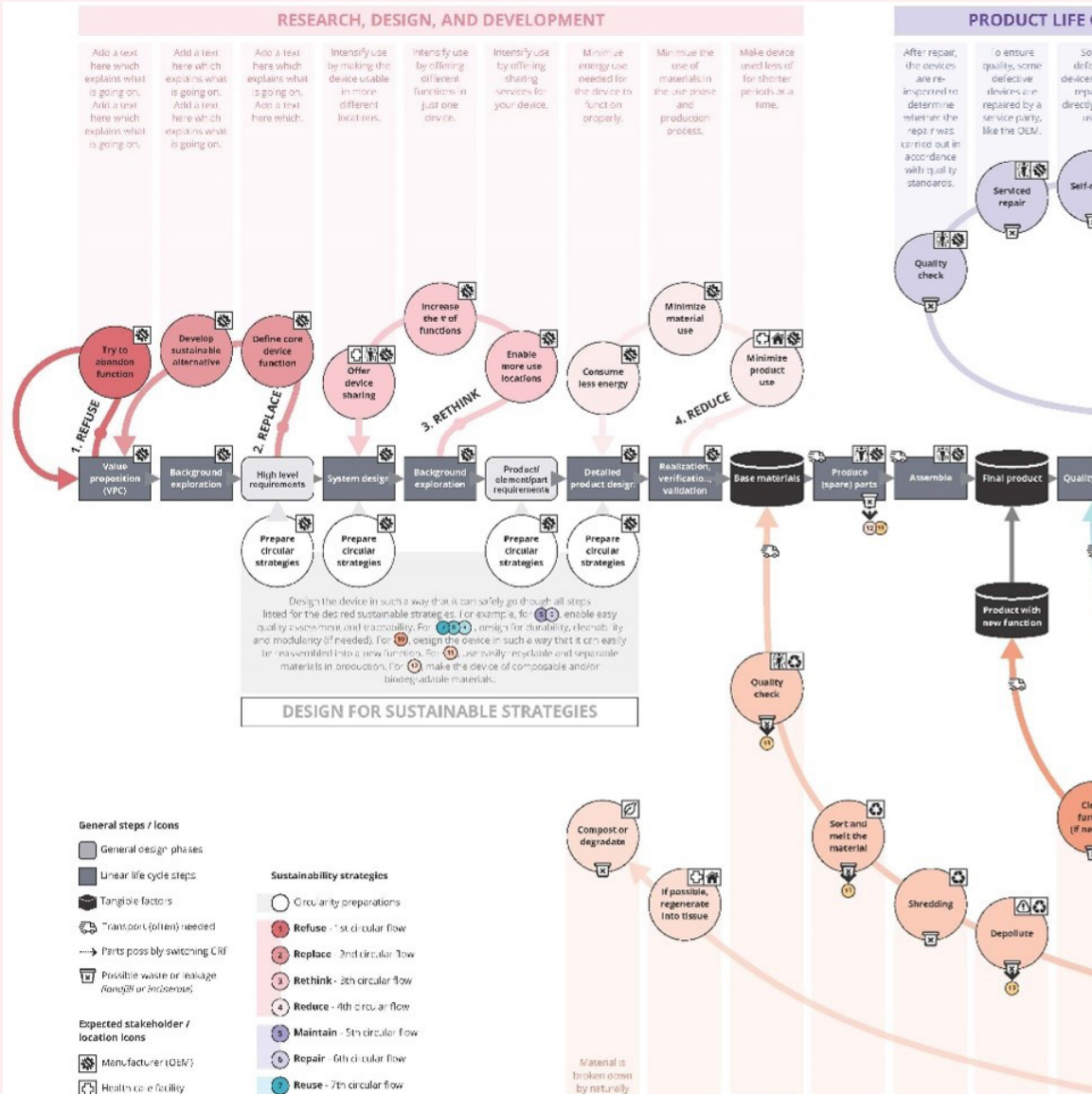
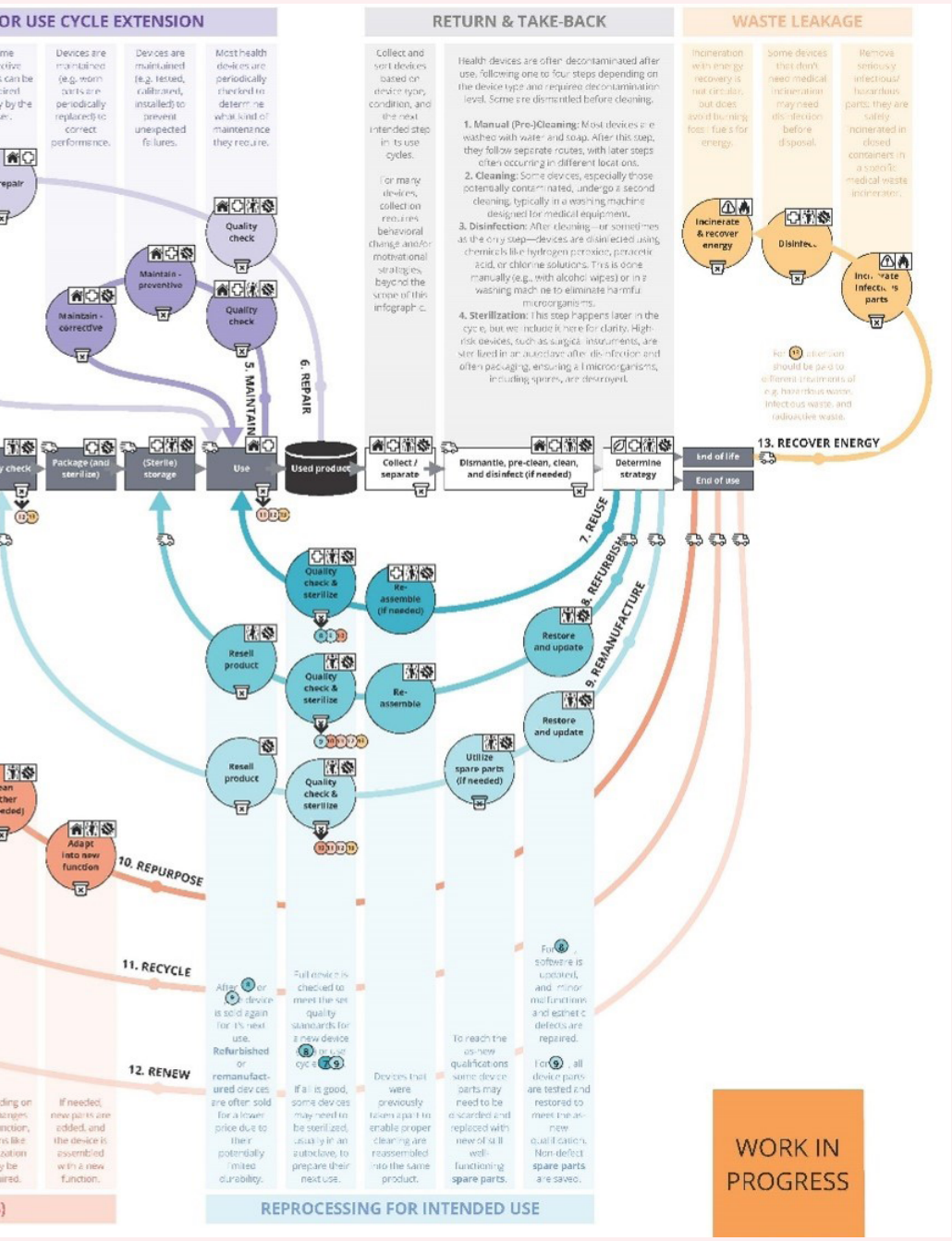


Figure 55: Visual Taxonomy Updated Based on Literature Review (earlier version)


OR USE CYCLE EXTENSION
RETURN & TAKE-BACK
WASTE LEAKAGE
Devices are maintained (e.g. worn parts are periodically replaced) to correct performance.
Devices are maintained (e.g. tested, calibrated, installed) to prevent unexpected failures.
Most health devices are periodically checked to determine what kind of maintenance they require.
Collect and sort devices based on device type, condition, and the next intended step in its use cycles.
For many devices, collection requires behavioral change and/or motivational strategies, beyond the scope of this infographic.
Health devices are often decontaminated after use, following one to four steps depending on the device type and required decontamination level. Some are dismantled before cleaning.
1. Manual (Pre-)Cleaning: Most devices are washed with water and soap. After this step, they follow separate routes, with later steps often occurring in different locations.
2. Cleaning: Some devices, especially those potentially contaminated, undergo a second cleaning, typically in a washing machine designed for medical equipment.
3. Disinfection: After cleaning—or sometimes as the only step—devices are disinfected using chemicals like hydrogen peroxides, peracetic acid, or chlorine solutions. This is done manually (e.g., with alcohol wipes) or in a washing machine to eliminate harmful microorganisms.
4. Sterilization: This step happens later in the cycle, but we include it here for clarity. High-risk devices, such as surgical instruments, are sterilized in an autoclave after disinfection and often packaging, ensuring all microorganisms, including spores, are destroyed.
Incineration with energy recovery is not circular, but does avoid burning fossil fuels for energy.
Some devices that don't need medical incineration may need disinfection before disposal.
Remove seriously infectious/hazardous parts; they are safely incinerated in closed containers in a specific medical waste incinerator.
Incinerate & recover energy
Disinfect
Incinerate infectious parts
For (13) attention should be paid to different treatments of e.g. hazardous waste, infectious waste, and radioactive waste.
13. RECOVER ENERGY
Quality check
Maintain - preventive
Maintain - corrective
Quality check
5. MAINTAIN
6. REPAIR
Package (and sterilize)
(Sterile) storage
Use
Used product
Collect / separate
Dismantle, pre-clean, clean, and disinfect (if needed)
Determine strategy
End of life
End of use
7. REUSE
8. REFURBISH
9. REMANUFACTURE
Quality check & sterilize
Re-assemble (if needed)
Restore and update
Resell product
Quality check & sterilize
Re-assemble
Restore and update
Resell product
Quality check & sterilize
Utilize spare parts (if needed)
Adapt into new function
10. REPURPOSE
11. RECYCLE
12. RENEW
After (8) or (9) device is sold again for its next use. Refurbished or remanufactured devices are often sold for a lower price due to their potentially limited durability.
Full device is checked to meet the set quality standards for a new device (8) or use cycle (7) (9).
If all is good, some devices may need to be sterilized, usually in an autoclave, to prepare their next use.
Devices that were previously taken apart to enable proper cleaning are reassembled into the same product.
To reach the as-new qualifications some device parts may need to be discarded and replaced with new of still well-functioning spare parts.
For (8) software is updated, and minor malfunctions and esthetic defects are repaired.
For (9) all device parts are tested and restored to meet the as-new qualifications. Non-defect spare parts are saved.
If needed, new parts are added, and the device is assembled with a new function.
REPROCESSING FOR INTENDED USE
WORK IN PROGRESS

Chapter 3 – Appendix F

Included/Excluded Review Articles

In this appendix, we present two tables: one with all articles that were excluded during the full-text review stage and the main reasons for exclusion (as presented in the PRIMA diagram), and one representing a simplified version of our extraction table, displaying all included articles and which terms which were mentioned in which articles, including the degree to which the articles provided definitions for those terms.

Table 25: Main Reasons for Article Exclusion in Full Text Review Stage

Title	Authors	Pub. date	Main reason for exclusion
Healthcare Environmental Footprint: Proposal to Deliver Sustainability through an Innovative Value Stream Using a Circular Economy Approach	Leiva, W.	1-7-2023	Not a scientific literature review
Healthcare Waste and Sustainability: Implications for a Circular Economy	Mahjoob, A.; Alfadhli, Y.; and Omachonu, V.	1-5-2023	Not a scientific literature review
Environmentally Sustainable Endoscopy Practices	Jain, M.	1-1-2023	Not a scientific literature review
Reusable personal protective equipment in Canadian healthcare: Safe, secure, and sustainable	Varangu, L.; Cowan, K.; Amin, O.; Sarrazin, M.; Dawson, M.; Rubinstein, E.; Miller, F. A.; Hirst, L.; Trbovich, P.; Waddington, K.	1-7-2023	Not a scientific literature review
Technical evaluation of steam sterilisation coupled with gasification to improve circularity of Australian hospital waste management: A case study	Harris, P.; McCabe, B. K.	1-1-2024	Not a scientific literature review
Environmental Sustainability and MRI: Challenges, Opportunities, and a Call for Action	Chaban, Y. V.; Vosshenrich, J.; McKee, H.; Gunasekaran, S.; Brown, M. J.; Atalay, M. K.; Heye, T.; Markl, M.; Woolen, S. A.; Simonetti, O. P.; Hanneman, K.	1-1-2024	Not a scientific literature review
How to choose between single-use and reusable medical materials for sustainable nursing: Methodological lessons learned from a national study	Vanderwee, K.; Demarre, L.; Malfait, S.; Kieckens, E.; De Waegemaeker, P.; Duprez, V.; Fraeyman, N.	29-5-2024	Not a scientific literature review
Environmentally sustainable kidney care through transplantation: Current status and future challenges	Anastasopoulos, N. A.; Papalois, V.	1-8-2024	Not a scientific literature review

Regulatory landscape, risks, and solutions for refurbished medical devices: a comparative analysis in the US, EU, Malaysia, and Ghana	Pinheiro, A. M.; Chettri, B.; Mehra, A.; Deepti, I.; Ravi, R.;	11-8-2024	Not a scientific literature review
Reusable instruments are more cost-effective than disposable instruments for laparoscopic cholecystectomy	Apelgren, K. N.; Blank, M. L.; Slomski, C. A.; Hadjis, N. S.	1-1-1994	Not a scientific literature review
Special problems associated with reprocessing instruments in outpatient care facilities: Physical spaces, education, infection preventionists, industry, reflections	Bringhurst, J.	1-1-2019	Not a scientific literature review
Reducing Disposable Surgical Items: Decreasing Environmental Impact and Costs at a Children's Hospital	Cunningham, A. J.; Krishnaswami, S.; Schofield, C.; Kenron, D.	1-1-2020	Not a scientific literature review
Reuse of disposable laparoscopic instruments: cost analysis	DesCoteaux, J. G.; Poulin, E. C.; Lortie, M.; Murray, G.; Gingras, S.	1-12-1995	Not a scientific literature review
Health service planning and sustainable development:considering what, where and how care is delivered through a pro-environmental lens	Desmond, S.	1-1-2018	Not a scientific literature review
Sustainability in Dentistry: A Multifaceted Approach Needed	Duane, B.; Stancliffe, R.; Miller, F. A.; Sherman, J.; Pasdeki-Clewer, E.	1-1-2020	Not a scientific literature review
Microbiological monitoring of endoscopes: 5-year review	Gillespie, E. E.; Kotsanas, D.; Stuart, R. L.	30-10-2007	Not a scientific literature review
Standards of Infection Prevention in Reprocessing Flexible Gastrointestinal Endoscopes	Herrin, A.; Loyola, M.; Bocian, S.; Diskey, A.; Friis, C. M.; Herron-Rice, L.; Juan, M. R.; Schmelzer, M.; Selking, S.	1-9-2016	Not a scientific literature review
Products liability implications of reprocessing and reuse of single-use medical devices	Hogan, J. M.; Colonna, T. E.	1-1-1998	Not a scientific literature review
Becoming environmentally sustainable in healthcare: an overview	Jamieson, M.; Wicks, A.; Boulding, T.	1-9-2015	Not a scientific literature review
A technique for re-utilizing catheter insertion sites in children with difficult central venous access	Johnson, S. M.; Garnett, G. M.; Woo, R. K.	1-1-2017	Not a scientific literature review
Managing environmental sustainability in a healthcare setting	Langstaff, K.; Brzozowski, V.	1-3-2017	Not a scientific literature review
The nurse's role on green teams: an environmental health opportunity	McDermott-Levy, R.	1-3-2011	Not a scientific literature review
The role of biofilms in reprocessing medical devices	Roberts, C. G.	1-5-2013	Not a scientific literature review
Creating an Environmentally Sustainable Neonatal Intensive Care Unit	Shepley, M. M.; Song, Y. L.; Marshall-Baker, A.	1-12-2016	Not a scientific literature review

Assessing the challenges to medical waste management during the COVID-19 pandemic: Implications for the environmental sustainability in the emerging economies	Tushar, S. R.; Alam, M. F. B.; Bari, Abmm; Karmaker, C. L.	18-1-2023	Not a scientific literature review
Reprocessing Single-Use Devices in the Ambulatory Surgery Environment	Ubaldi, K.	4-2-2019	Not a scientific literature review
Modelling the factors in implementation of environmental sustainability in healthcare organisations	Vaishnavi, V.; Suresh, M.	1-1-2023	Not a scientific literature review
Key considerations on the development of biodegradable biomaterials for clinical translation of medical devices: With cartilage repair products as an example	Wang, L.; Guo, X.; Chen, J.; Zhen, Z.; Cao, B.; Wan, W.; Dou, Y.; Pan, H.; Xu, F.; Zhang, Z.; Wang, J.; Li, D.; Guo, Q.; Jiang, Q.; Du, Y.; Yu, J.; Heng, B. C.; Han, Q.; Ge, Z.	1-3-2022	Not a scientific literature review
Reuser friendly: a review of the regulation of and the product liability regarding the reuse of single-use medical devices	Wood, J. M.; Heyman, G. F.	1-1-2001	Not a scientific literature review
Climate Change and the Professional Obligation to Socialize Physicians and Trainees into an Environmentally Sustainable Medical Culture	Wortzel, J. R.; Guerrero, A. P. S.; Aggarwal, R.; Coverdale, J.; Brenner, A. M.	10-2-2022	Not a scientific literature review
Environmental sustainability and the carbon emissions of pharmaceuticals	Richie, C.	5-2-2022	Not related to healthcare
Affecting medical equipment maintenance management: A systematic review	Bahreini, R.; Doshmangir, L.; Imani, A.;	1-1-2018	Not related to environmental sustainability
Assessment of medical equipment maintenance management: proposed checklist using Iranian experience	Arab-Zozani, M.; Imani, A.; Doshmangir, L.; Dalal, K.; Bahreini, R.;	1-1-2021	Not related to environmental sustainability
Sustainable equipment donation in otolaryngology in low-resource settings	De Cates, C.; Guéroult, A. M.; Narantsolmon, G. E.	1-1-2024	Not related to environmental sustainability
Recent advances on sustainable cellulosic materials for pharmaceutical carrier applications	Yan, G.; Chen, B.; Zeng, X.; Sun, Y.; Tang, X.; Lin, L.	15-9-2020	Not related to environmental sustainability
Reprocessing single-use medical devices	Cohoon, B. D	1-3-2002	Not related to environmental sustainability
Biocatalytic remediation of pharmaceutically active micropollutants for environmental sustainability	Bilal, M.; Lam, S. S.; Iqbal, H. M. N.	15-1-2022	Not related to materials, devices, consumables, equipment, or products
Environmental sustainability in the intensive care unit: challenges and solutions	Huffling, K.; Schenk, E.	1-7-2014	Not related to materials, devices, consumables, equipment, or products

Table 26: Analysis of Terms and Definitions from Full-Text Analysis (n=68 Total Reviewed)

Title	Authors	Pub. date
Implementation approaches to improve environmental sustainability in operating theatres: a systematic review	Davies, J. F.; Ikin, B.; Francis, J. J.; McGain, F.	20-6-2023
Sustainable practices in hospital and operating theatres	Anract, J.; Pradere, B.; Pinar, U.	1-9-2024
Environmentally sustainable gastroenterology practice: Review of current state and future goals	Sonaiya, S.; Marino, R.; Agollari, K.; Sharma, P.; Desai, M.	1-4-2024
A systematic review comparing the safety, cost and carbon footprint of disposable and reusable laparoscopic devices	Chauvet, P.; Enguix, A.; Sautou, V.; Slim, K.	1-4-2024
Improving environmental sustainability of intensive care units: A mini-review	See, K. C.	9-9-2023
Innovations towards achieving environmentally sustainable operating theatres: A systematic review	Perry, H.; Reeves, N.; Ansell, J.; Cornish, J.; Torkington, J.; Morris, D. S.; Brennan, F.; Horwood, J.	1-6-2023
Healing Patient, Harming Planet? Review of Waste Production and Recyclability of Surgical Instrument Packaging	Lee, Y. K.; Hariri, A.; Ghedia, R.; Tikka, T.; Kim, D.	1-1-2023
Methods and evaluation metrics for reducing material waste in the operating room: a scoping review	Balch, J. A.; Krebs, J. R.; Filiberto, A. C.; Montgomery, W. G.; Berkow, L. C.; Upchurch, G. R.; Loftus, T. J.	1-1-2023
Environmental impact of cardiovascular healthcare	Barratt, A. L.; Li, Y.; Gooroovadoo, I.; Todd, A.; Dou, Y.; McAlister, S.; Semsarian, C.	1-1-2023
Sustainability across the Medical Device Lifecycle: A Scoping Review	Montesinos, L.; Rifa, P. C.; Fabregat, M. R.; Maldonado-Romo, J.; Capacci, S.; Maccaro, A.; Piaggio, D.	1-2-2024
Exploring Circular Economy Practices in the Healthcare Sector: A Systematic Review and Bibliometric Analysis	D'Alessandro, C.; Szopik-Depczynska, K.; Tarczynska-Luniewska, M.; Silvestri, C.; Ioppolo, G.	1-1-2024
The extent to which circular economy principles have been applied in the design of medical devices for low-resource settings in Sub-Saharan Africa. A systematic review	Samenjo, K. T.; Oosting, R. M.; Bakker, C.; Diehl, J. C.	1-4-2023

	Terms found																										
	(0 = not mentioned, 1 = not defined, 2 = clear in-context definition, 3 = clearly defined)																										
	Replace	Recycle	Reduce	Reuse	Maintain	Repair	Restore	Repurpose	Rethink	Reprocessing	Refuse	Retain	Refurbish	Research	Redistribution	Recover	Remanufacture	(re)design	Slowing loops	Closing loops	Biodegrade	Renew	Share	Regenerate	Resterilise	(bio)remediate	Prevent
	1	1	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
	0	1	3	2	2	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
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	3	3	3	1	2	3	2	3	3	3	0	2	3	0	0	2	3	2	0	2	0	0	0	0	0	0	2

Circular economy for medical devices: Barriers, opportunities and best practices from a design perspective	Hoveling, T.; Nijdam, A. S.; Monincx, M.; Faludi, J.; Bakker, C.	1-9-2024
Healthcare waste in Bangladesh: Current status, the impact of Covid-19 and sustainable management with life cycle and circular economy framework	Dihan, M. R.; Abu Nayeem, S. M.; Roy, H.; Islam, M. S.; Islam, A.; Alsukaibi, A. K. D.; Awual, M. R.	1-5-2023
Current evidence on intermittent catheterization: sterile single-use catheters or clean reused catheters and the incidence of UTI	Getliffe, K.; Fader, M.; Allen, C.; Pinar, K.; Moore, K. N.	1-5-2007
Environmental sustainability in healthcare: Time to make outpatient care in orthopaedics and rheumatology greener	Tsagkaris, C.; Nikolakea, M.; Laskaratou, E. D.; Samaras, C.; Huang, H.; Laubscher, L.; Bobirca, A.	1-5-2023
A review of Spaulding's classification system for effective cleaning, disinfection and sterilization of reusable medical devices: Viewed through a modern-day lens that will inform and enable future sustainability	Rowan, N. J.; Kremer, T.; McDonnell, G.	20-6-2023
Management of COVID-19 healthcare waste based on the circular economy hierarchy: A critical review	Voudrias, E. A.	27-9-2023
Barriers and enablers to implementing environmentally sustainable practices in healthcare: A scoping review and proposed roadmap	Aboueid, S.; Beyene, M.; Nur, T.	1-11-2023
Waste management in the operating theatre	Talbot, S.; Moore, D.	1-1-2024
Making minimally invasive procedures more sustainable: A systematic review comparing the environmental footprint of single-use versus multi-use instruments	Martins, R. S.; Salar, H.; Salar, M.; Luo, J.; Poulikidis, K.; Razi, S. S.; Latif, M. J.; Tafuri, K.; Bhora, F. Y.	1-1-2024
Environmental sustainability in obstetrics and gynaecology: A systematic review	Cohen, E. S.; Kouwenberg, L. H. J. A.; Moody, K. S.; Sperna Weiland, N. H.; Kringos, D. S.; Timmermans, A.; Hehenkamp, W. J. K.	1-1-2024
Barriers and facilitators to recycling waste in hospitals: A mixed methods systematic review	Jungbluth, L.; Goodwin, D.; Tull, F.; Bragge, P.	1-1-2024
Environmental Impact of Flexible Cystoscopy: A Comparative Analysis Between Carbon Footprint of Isiris R Single-Use Cystoscope and Reusable Flexible Cystoscope and a Systematic Review of Literature	Jahrreiss, V.; Sarrot, P.; Davis, N. F.; Somani, B.	1-4-2024
igital technologies to unlock safe and sustainable opportunities for medical device and healthcare sectors with a focus on the combined use of digital twin and extended reality applications: A review	Rowan, N. J.	20-5-2024

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	0	1	3	2	2	2	0	0	0	1	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	2	

Interventions to achieve environmentally sustainable operating theatres: an umbrella systematic review using the behaviour change wheel	Almukhtar, A.; Batcup, C.; Bowman, M.; Winter Beatty, J.; Leff, D.; Demirel, P.; Judah, G.; Porat, T.	2-8-2024
Improving Environmental Sustainability of Operating Theatres: A Systematic Review of Staff Attitudes, Barriers, and Enablers	Lodhia, S., Pegna, V., Abrams, R., Jackson, D., Rockall, T. A., Rizan, C.	10-5-2024
Circular business models in the medical device industry: paths towards sustainable healthcare	Guzzo, D.; Carvalho, M. M.; Balkenende, R.; Mascarenhas, J.	1-1-2020
Towards design strategies for circular medical products	Kane, G. M.; Bakker, C. A.; Balkenende, A. R.	1-9-2017
Big Data-Enabled Solutions Framework to Overcoming the Barriers to Circular Economy Initiatives in Healthcare Sector	Kazancoglu, Y.; Sagnak, M.; Lafci, C.; Luthra, S.; Kumar, A.; Tacoglu, C.	7-2-2021
Medical instrument reprocessing: current issues with cleaning and cleaning monitoring	Alfa, M. J.	6-2-2019
Surgical Instrument Reprocessing in Resource-Constrained Countries: A Scoping Review of Existing Methods, Policies, and Barriers	Forrester, J. A.; Powell, B. L.; Forrester, J. D.; Fast, C.; Weiser, T. G.	1-8-2018
Effectiveness of autoclaving in sterilizing reusable medical devices in healthcare facilities	Panta, G.; Richardson, A. K.; Shaw, I. C.	10-2-2019
Advances in Endoscope Reprocessing Technology and Its Impact on Pathogen Transmission	Shellnutt, C.	6-11-2016
Environmental sustainability in robotic and laparoscopic surgery: systematic review	Papadopoulou, A.; Kumar, N. S.; Vanhoestenberghe, A.; Francis, N. K.	9-2-2022
Decontamination interventions for the reuse of surgical mask personal protective equipment: a systematic review	Zorko, D. J.; Gertsman, S.; O'Hearn, K.; Timmerman, N.; Ambu-Ali, N.; Dinh, T.; Sampson, M.; Sikora, L.; McNally, J. D.; Choong, K.	1-10-2020
Revisiting the Evidence for the Reuse of Enteral Feeding Equipment in Ambulatory Patients: A Systematic Review	Osland, E. J.; Andersen, S.; Coleman, E.; Marshall, B.	1-1-2021
Decontamination and reuse of surgical masks and N95 filteringfacepiece respirators during the COVID-19 pandemic: A systematic review	Seresirikachorn, K.; Phoophiboon, V.; Chobarporn, T.; Tiankanon, K.; Aeumjaturapat, S.; Chusakul, S.; Snidvongs, K.	1-1-2022
A framework for assessing the circularity and technological maturity of plastic waste management strategies in hospitals	Fletcher, C. A.; St Clair, R.; Sharmina, M.	1-7-2021
Circular economy adoption challenges in medical waste management for sustainable development: An empirical study	Kandasamy, J.; Kinare, Y. P.; Pawar, M. T.; Majumdar, A.; Vimal, K. E. K.; Agrawal, R.	1-10-2022
Possible involvement of reusable towels in the high rate of Bacillus species-positive blood cultures in Japanese hospitals	Saito, N.; Kondo, J.; Haruki, S.; Itoga, M.; Yamamoto, A.; Kimura, M.; Inoue, F.; Kobayashi, M.; Tsutaya, S.; Kojima, K.; Ueki, S.; Hirokawa, M.; Kayaba, H	1-1-2016

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Preventing infection from reusable medical equipment: a systematic review	Sopwith, W.; Hart, T.; Garner, P.	27-3-2001
Infections and exposures: reported incidents associated with unsuccessful decontamination of reusable surgical instruments	Southworth, P. M.	1-11-2014
Linking Environmental Sustainability, Health, and Safety Data in Health Care: A Research Roadmap	Kaplan, S. B.; Forst, L.	1-8-2017
Environmental sustainability in hospitals – a systematic review and research agenda	McGain, F.; Naylor, C.	1-10-2014
The Green Print: Advancement of Environmental Sustainability in Healthcare	Sherman, J. D.; Thiel, C.; MacNeill, A.; Eckelman, M. J.; Dubrow, R.; Hopf, H.; Lagasse, R.; Bialowitz, J.; Costello, A.; Forbes, M.; Stancliffe, R.; Anastas, P.; Anderko, L.; Baratz, M.; Barna, S.; Bhatnagar, U.; Burnham, J.; Cai, Y.; Cassels-Brown, A.; Cimprich, A. F. P.; Cole, H.; Coronado-Garcia, L.; Duane, B.; Grisotti, G.; Hartwell, A.; Kumar, V.; Kurth, A.; Leapman, M.; Morris, D. S.; Overcash, M.; Parvatker, A. G.; Pencheon, D.; Pollard, A.; Robaire, B.; Rockne, K.; Sadler, B. L.; Schenk, B.; Sethi, T.; Sussman, L. S.; Thompson, J.; Twomey, J. M.; Vermund, S. H.; Vukelich, D.; Wasim, N.; Wilson, D.; Young, S. B.; Zimmerman, J.; Bilec, M. M.	1-1-2020
A Roadmap for Environmental Sustainability of Plastic Use in Anesthesia and the Perioperative Arena	Xiao, M. Z. X.; Abbass, S. A. A.; Bahrey, L.; Rubinstein, E.; Chan, V. W. S.	10-2-2021
Extended use or reuse of single-use surgical masks and filtering face-piece respirators during the coronavirus disease 2019 (COVID-19) pandemic: A rapid systematic review	Toomey, E. C.; Conway, Y.; Burton, C.; Smith, S.; Smalle, M.; Chan, X. S.; Adisesh, A.; Tanveer, S.; Ross, L.; Thomson, I.; Devane, D.; Greenhalgh, T.	1-2-2021
Performance and impact of disposable and reusable respirators for healthcare workers during pandemic respiratory disease: a rapid evidence review	Burton, C.; Coles, B.; Adisesh, A.; Smith, S.; Toomey, E.; Chan, X. H. S.; Ross, L.; Greenhalgh, T.	9-2-2021
Reuse of single use medical devices in Canada: Clinical and economic outcomes, legal and ethical issues, and current hospital practice	Hailey, D.; Jacobs, P. D.; Ries, N. M.; Polisena, J.	1-9-2008
Reusable and disposable insulin pens for the treatment of diabetes: understanding the global differences in user preference and an evaluation of inpatient insulin pen use	Perfetti, R.	1-6-2010

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	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

Disposable face masks and reusable face coverings as non-pharmaceutical interventions (NPIs) to prevent transmission of SARS-CoV-2 variants that cause coronavirus disease (COVID-19): Role of new sustainable NPI design innovations and predictive mathematical modelling	Rowan, N. J.; Moral, R. A.	10-6-2021
Addressing the environmental sustainability of eye health-care delivery: a scoping review	Buchan, J. C.; Thiel, C. L.; Steyn, A.; Somner, J.; Venkatesh, R.; Burton, M. J.; Ramke, J.	6-2-2022
Environmental sustainability in anaesthesia and critical care	McGain, F.; Muret, J.; Lawson, C.; Sherman, J. D.	12-8-2020
Environmentally sustainable dermatology	Allwright, E.; Abbott, R. A.	23-2-2023
Considerations for environmentally sustainable head and neck surgical oncology practice	Sanabria, A.; Kowalski, L. P.; Nixon, I. J.; Shaha, A.; De Bree, R.; Makitie, A. A.; Rinaldo, A.; Ferlito, A.	1-11-2020
Barriers to environmentally sustainable initiatives in oral health care clinical settings	de Leon, M. L.	10-2-2020
Environmental sustainability in healthcare: Time to make outpatient care in orthopaedics and rheumatology greener	Tsagkaris, C.; Nikolakea, M.; Laskaratou, E. D.; Samaras, C.; Huang, H.; Laubscher, L.; Bobirca, A.	14-2-2023
Biopolymer: A Sustainable Material for Food and Medical Applications	Baranwal, J.; Barse, B.; Fais, A.; Delogu, G. L.; Kumar, A.	28-2-2022
Greener Operations: a James Lind Alliance Priority Setting Partnership on environmentally sustainable peri-operative practice	Clayton-Smith, M.; Narayanan, H.; Shelton, C.; Bates, L.; Brennan, F.; Deido, B.; Donnellon, M.; Dorey, J.; Evans, B.; Gower, J.; Hamdaoui, Y.; Hitchman, J.; Kinsella, S. M.; Knagg, R.; Lawson, C.; Morris, D.; Pegna, V.; Radcliffe, T.; Schaff, O.; Sheppard, T.; Strong, J.; Jones, D.	1-1-2016
Environmental Sustainability in Orthopaedic Surgery	Engler, I. D.; Curley, A. J.; Fu, F. H.; Bilec, M. M.	1-6-2022
Greening the operating room	Guetter, C. R.; Williams, B. J.; Slama, E.; Arrington, A.; Henry, M. C.; Moller, M. G.; Tuttle-Newhall, J. E.; Stein, S.; Crandall, M.	10-2-2018
Greening the operating room	Papadopoulou, A.; Kumar, N. S.; Vanhoestenberghe, A.; Francis, N. K.	9-2-2022
Innovations towards achieving environmentally sustainable operating theatres: A systematic review	Perry, H.; Reeves, N.; Brennan, F.; Morris, D.; Torkington, J.; Horwood, J.	28-4-2022
Environmental Sustainability in the Orthopaedic Operating Room	Smith, J. T.; Boakye, L. A. T.; Ferrone, M. L.; Furie, G. L.	11-2-2022
Initiatives to broaden safety concerns in anaesthetic practice: The green operating room	Beloeil, H.; Albaladejo, P.	1-5-2021
Empowering Surgeons, Anesthesiologists, and Obstetricians to Incorporate Environmental Sustainability in the Operating Room	Yates, E. F.; Bowder, A. N.; Roa, L.; Velin, L.; Goodman, A. S.; Nguyen, L. L.; McClain, C. D.; Meara, J. G.; Cooper, Z.	6-2-2021
Environmental sustainability in orthopaedic surgery : a scoping review	Phoon, K. M.; Afzal, I.; Sochart, D. H.; Asopa, V.; Gikas, P.; Kader, D.	1-8-2022

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Chapter 3 – Appendix G

Full Table of Terms and Definitions

Table 27: Full Table of Terms and Definitions

Term used for CE strategy *(mentioned by # of reviewed articles; n=68)*	Healthcare literature (from review)	Healthcare bodies
	Meaning of term use in review articles	Definitions from MDR-EU 2017/745 **(MDR)** and FDA medical device regulation **(FDA)**
Reuse (62)	• Reusing is the opposite of a disposable/single use (18x) • Using devices again after decontamination (17x) • Using the same device on multiple patients (7x) • Reusing single-use or disposable devices (5x) • Using materials again (1x) • Using devices again on the same patient (single-patient reuse) (1x)	• "Reusable medical devices are devices that health care providers can reprocess and reuse on multiple patients." (FDA 37)
Reduce (54)	• Reducing waste (29x) • Reducing resources (including materials, energy use, and water use in production and use) (29x) • Reduce environmental impact (19x) • Reduce healthcare care need (e.g. reducing sterilization risks) / unnecessary care (13x) • Reducing use of unsustainable devices (e.g. disposable, non-recyclable, unnecessary packaging) (4x) • Reducing use of chemicals/toxins (3x) • Reducing need for novel products and equipment (2x)	No definition available
Recycle (53)	• Reusing raw material after processing (decontaminate, shred, melt and remould) (10x) • Sterilize and reuse device/component/material (2x) • Chemical recycling (1x)	• "The processing of waste to make new articles." (FDA 38)

	Non-healthcare bodies	Circular economy frameworks	
	Definitions from Waste Framework Directive **(WFD)** ISO 59004:2024 **(ISO)**, and Re-defining Value report **(UNEP)**	Definitions from EMF Butterfly Diagram **(EMF)**, PBL 10R framework **(PBL)**, and Value Hill **(VH)**	***Manner of integrating into visual taxonomy***
	• "Operation by which products or components that are not waste are used again for the same purpose for which they were conceived." (WFD 14) • "Use a product or its component parts after their initial use, for the same purpose for which they were originally designed." (ISO 13) • "Using again of a product, object or substance that is not waste, for the same purpose for which it was conceived, without the necessity of repair or refurbishment." (UNEP 10)	• "The repeated use of a product or component for its intended purpose without significant modification." (EMF 31) • "Re-use by another consumer of discarded product which is still in good condition and fulfils its original function." (PBL 8)	*Included as the fifth circularity strategy.*
	No definition available	• "Increase efficiency in product manufacture or use by consuming fewer natural resources and materials." (PBL 8)	*Included as the fourth circularity strategy.*
	• "Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes." (WFD 14) • "Activities to obtain recovered resources for use in a process or a product, excluding energy recovery." (ISO 13) • "Operations usually involve the reprocessing of waste into products, materials, or substances, though not necessarily for the original purpose, and does not cover operations that recover energy from waste." (UNEP 10)	• "Transform a product or component into its basic materials or substances and reprocessing them into new materials." (EMF 31) • "Process materials to obtain the same (high grade) or lower (low grade) quality." (PBL 8) • "Recycling facility transforms waste into raw materials." (VH 9)	*Included as the eleventh circularity strategy.*

Reprocess (48)	• Decontaminate (+ package) single-use devices for reuse (17x) • Decontamination or reusables (13x) • Decontamination process + reuse process (1x) • Overarching term for all R-strategies (1x) • Product recovery after repair, cleaning, sterilization and repackaging (1x)	• "A process carried out on a used device in order to allow its safe reuse including cleaning, disinfection, sterilisation and related procedures, as well as testing and restoring the technical and functional safety of the used device." (MDR 16) • "A process carried out on a used device in order to allow its safe reuse. It includes its cleaning, disinfection, sterilisation and related procedures, as well as testing and restoring the technical and functional safety of the used device." (FDA 15)
Prevent (32)	• Prevent ... • ... (unnecessary) care and device consumption (including e.g. preventive care and infection prevention) (19x) • ... climate change/pollution (9x) • ... waste (including e.g. use of disposables and disposal of unused but opened instruments) (7x) • ... product obsolescence (including preventive maintenance) (6x) • ... material scarcity (1x) • ... mixed waste streams (1x)	No definition available
(Re)design (32)	• Design for sustainability/circularity (enabling R-strategies) (41x) including design for ... • ... sterilization (6x) • ... waste management (3x) • ... waste reduction (3x) • ... recyclability (3x) • ... behavioural change (2x) • ... durability (2x) • ... eco-design (1x) • ... maintenance (1x) • ... modularity (1x) • ... refurbishment (1x) • ... end-of-life (1x) • ... disassembly (1x)	No definition available

	No definition available	No definition available	*Overarching term to describe end of use strategies that maintain product integrity (reuse, maintain, repair, refurbish, and remanufacture).*
	• "Measures taken before a substance, material or product has become waste, that reduce: (a) the quantity of waste, including through the re-use of products or the extension of the life span of products; (b) the adverse impacts of the generated waste on the environment and human health; or (c) the content of hazardous substances in materials and products." (WFD 14)	No definition available	*Partially disregarded due to too broad definition scope (e.g., preventing climate change), and partially scaled under refuse (completely refusing device use or unnecessary procedures), replace (substituting devices or procedures by more sustainable alternatives), and reduce (minimizing unnecessary device use and procedures).*
	• Eco-design is "design and development based on a life cycle perspective aimed at supporting sustainable development." (ISO 13) • Design for circularity is "design and development based on the circular economy principles." (ISO 13)	• "Designing products with their end-of-life in mind by making them easy to maintain, repair, upgrade, refurbish or remanufacture." (VH 9)	*Partially disregarded and partially scaled under other strategies, as this could refer to the (re) design of a product or procedure to enable any of the other strategies (e.g. to rethink the system, to replace the product or even to reduce energy consumption), making the term in itself too broad to include separately.*

Replace (31)	• Replace with more sustainable alternative (e.g. reusable or recyclable vs. disposable alternative) (23x) including ... • ... Replacing materials (11x) • ... Replacing equipment (12x) • ... Replacing procedures (5x) • Digitization (5x) • Replacing parts or components in repair or remanufacturing (4x)	No definition available
Maintain (23)	• Preventive maintenance (8x) • Maintain clinical environment quality and safety (including preventive maintenance) (7x) • Lifetime extension (2x) • Maintaining value (2x) • Maintaining availability (1x) • Corrective maintenance (1x)	• "Servicing is the repair and/or preventive or routine maintenance of one or more parts in a finished device, after distribution, for purposes of returning it to the safety and performance specifications established by the original equipment manufacturer (OEM) and to meet its original intended use." (FDA 39)
Repair (22)	• Recover functional obsolescence (corrective maintenance) (6x) • Lifetime extension (5x)	• "Servicing is the repair and/or preventive or routine maintenance of one or more parts in a finished device, after distribution, for purposes of returning it to the safety and performance specifications established by the original equipment manufacturer (OEM) and to meet its original intended use." (FDA, 39)

	No definition available	No definition available	*Included as the second circularity strategy.*
	No definition available	• "Keep a product in its existing state of quality, functionally and/or cosmetically, to guard against failure or decline. It is a practice that retains the highest value of a product by extending its use period." (EMF 31) • "Repair and maintenance of defective product so it can be used with its original function." (PBL 8) • "Repair & Maintenance Service repairs, maintains, and possibly upgrades products that are still in use." (VH 9)	*Included as the sixth circularity strategy.*
	• "Restore a product to a condition needed for the product to function according to its intended purpose." (ISO 13) • "Fixing of a specified fault in an object that is a waste or a product and/or replacing defective components, in order to make the waste or product a fully functional product to be used for its originally intended purpose." (UNEP 10)	• "Operation by which a faulty or broken product or component is returned back to a usable state to fulfil its intended use." (EMF 31) • "Repair and maintenance of defective product so it can be used with its original function." (PBL 8) • "Repair & Maintenance Service repairs, maintains, and possibly upgrades products that are still in use." (VH 9)	*Included as the seventh circularity strategy.*

Recover (21)	• Recover/retain material/waste (15x) Including ... • ... through recycling (2x) • ... for recycling (1x) • Energy recovery (incineration) (5x) • Recover product/material value (3x) • Overarching term for all R-strategies (1x)	No definition available
Remanufacture (19)	• Provide used equipment in as new or better than new condition through cleaning, significant renovation, quality control, and repackaging (5x) • Products back into service after parts replacement (2x) • Clean & pack SUDs for reuse (1x) • Clean, quality control, certification, repack, redistribute SUDs (1x)	• "The processing, conditioning, renovating, repackaging, restoring, or any other act done to a finished device that significantly changes the finished device's performance or safety specifications, or intended use." (FDA39)
Rethink (18)	• Making systems/processes more environmentally sustainable (9x) including ... • ... patient transport (2x) • ... purchasing (2x) • ... telemedicine (2x) • ... packaging strategy (1x) • ... production (1x) • ... delivery (1x) • Sustainable redesign of product and procedures (3x) • Avoid unnecessity treatment/resources (3x) • Changing beliefs and practices (2x) • Choose sustainable alternative (1x) • Reduce length of hospital stay (1x) • Intensify product utilization (1x)	No definition available

	• "Any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. Annex II sets out a non-exhaustive list of recovery operations." (WFD 14) • Energy recovery is the "generation of useful energy through direct and controlled transformation of recovered resources." (ISO 13) • Recoverable resource is a "resource that can be recovered and used again after it has already been processed or used." (ISO 13) • Recover value is the "process to recuperate the value of the object of consideration." (ISO 13)	• "Incineration of materials with energy recovery." (PBL 8) • "Recovery provider provides take back systems and collection services to recover useful resources out of disposed products or by-products." (VH 9)	*Part of the definitions were disregarded as being too broad. However, recover energy (through incineration) was included as the thirteenth (last) circularity strategy.*
	• "Return an item to a like-new condition from both a quality and performance perspective using an industrial process." (ISO 13) • "A standardized industrial process that takes place within industrial or factory settings, in which cores are restored to original as-new condition and performance, or better. The remanufacturing process is in line with specific technical specifications, including engineering, quality, and testing standards, and typically yields fully warranted products." (UNEP 10) • "Re-engineer products and components to as-new condition with the same, or improved, level of performance as a newly manufactured one." (EMF 31)	• "Use parts of discarded product in a new product with the same function." (PBL 8) • "Remanufacturer provides products from recaptured materials and components." (VH 9)	*Included as the ninth circularity strategy.*
	No definition available	• "Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market)" (PBL 8)	*Included as the third circularity strategy, merging the healthcare definitions (sustainability system adaptations) with the PBL definition.*

Renew (17)	• Renewable energy (8x) • Using biodegradable polymers (4x) • Repair or remanufacturing (1x)	No definition available
Repurpose (15)	• Use discarded product for different purpose or function (3x) • Use discarded product in a different context (including environmental restructuring) (3x) • Use discarded product/part in new product (with a different function) (3x) • Use discarded product/part in different location (e.g. developing countries) (2x) • Maximize product life cycle (1x)	No definition available
Refurbish (13)	• Transform obsolete products to contemporary standards (e.g. performance, safety) while remaining intended use (3x) • Like remanufacturing, bring device into conformity with regulation (3x) • Put back into service after parts replacement (resulting is lower quality) (2x) • Repair, upgrades, cosmetic changes, performance check, reinstallation, warranty (2x)	• "The complete rebuilding of a device already placed on the market or put into service, or the making of a new device from used devices, to bring it into conformity with this Regulation, combined with the assignment of a new lifetime to the refurbished device." (MDR 16)
Biodegrade (11)	• Using biodegradable polymers (intended for composting) (6x) • Using biodegradable medications (2x) • Using biodegradable coating (1x) • Energy recovery (1x)	No definition available
Refuse (10)	• Refuse disposal/prevent waste (2x) • Refuse (new) devices (2x) • Refuse harmful substances (1x) • Refuse consumption (1x) • Refuse purchase (1x) • Refuse redundant products, procedures and services (1x) • Refuse non-circular practices (1x)	No definition available

	• 1) Renewable energy: “energy from a renewable resource.”, 2) Renewable resource: “resource that can be naturally or artificially grown or replenished within a foreseeable time frame by processes found in nature.” (ISO 13)	• 1) Renewable materials: “materials that are continually replenished at a rate equal to or greater than the rate of depletion.”, 2) Renewable energy: “energy derived from resources that are not depleted on timescales relevant to the economy, i.e. not geological timescales.” (EMF 31)	*Included as the twelfth circularity strategy.*
	• “Adapt a product or its component parts for use in a different function than it was originally intended for, without making major modifications to its physical, chemical or mechanical structure.” (ISO 13)	• “Use discarded product or its parts in a new product with a different function.” (PBL 8)	*Included as the tenth circularity strategy.*
	• “Restore an item, during its expected service life, to a useful condition for the same purpose with at least similar quality and performance.” (ISO 13) • “Modification of an object that is a waste or a product that takes place within maintenance or intermediate maintenance operations to increase or restore performance and/or functionality or to meet applicable technical standards or regulatory requirements, with the result of making a fully functional product to be used for a purpose that is at least the one that was originally intended. The restoration of functionality, but not value, enables a partial new service life for the product.”(UNEP 10)	• “Restore an old product and bring it up to date.” (PBL 8) • “Return a product to good working order. This can include repairing or replacing components, updating specifications, and improving cosmetic appearance.” (EMF 31) • “Refurbisher refurbishes used products if necessary and re-sells them.” (VH 9)	*Included as the eighth circularity strategy.*
	No definition available	• “Able to be broken down into carbon dioxide, water, and biomass by the natural action of microorganisms over an unspecified length of time and in undefined conditions.” (EMF 40)	*Scaled under the definition of renew.*
	No definition available	• “Make product redundant by abandoning its function or by offering the same function with a radically different product.” (PBL 8)	*Included as the first circularity strategy.*

Restore (9)	• Restore value (2x) • "Repair" product/material (3x) • Restore trust in circular device (1x)	No definition available
Closing loops (9)	• • Developing value from waste (2x) • Minimizing waste (1x) • Analogy for "circular economy": resources that have entered this loop remain accounted for (1x)	No definition available
Research (8)	• Life cycle analyses (4x) • "Green" device development (3x) • Cost comparisons (1x) • Renewable energy source (1x) • Lean & 6-sigma methods (1x)	No definition available
Retain (5)	• Retaining value in circularity (4x) •	• Retaining value by recycling (2x) • Retain product use over time (1x) • Retain functionality in CE (1x)
Regenerate (4)	• Regenerative medicine (1x) • Regenerating natural systems (e.g. composting or anaerobic digestion) (2x)	No definition available
Redistribute (4)	• One of the technical circular cycles (1x)	No definition available
Share (3)	• Sharing of products or equipment (2x)	No definition available

	No definition available	No definition available	*Scaled under the definition of repair.*
	• Closed loop system is a "system by which products or resources are used and then recovered and turned into new products or recovered resources, without losing their inherent properties." (ISO 13)	No definition available	*Excluded due to limited clarity in definitions while also encompassing multiple other strategies.*
	No definition available	No definition available	*Disregarded due to it having a too broad definition and not describing one circularity strategy on its own.*
	No definition available	No definition available	*No definition available*
	• "Improve or restore a degraded ecosystem." (ISO 13)	• "Regenerative production provides food and materials in ways that support positive outcomes for nature, which include but are not limited to: healthy and stable soils, improved local biodiversity, improved air and water quality." (EMF 31)	*Scaled under the definition of renew.*
	No definition available	• "Divert a product from its intended market to another customer so it is used at high value instead of becoming waste." (EMF 31) • While not providing a direct definition, 9 seems to use redistribute as a term to indicate an essential part of reuse. (VH 9)	*Integrated as a part of the strategies for which (re)distribution is needed in the processes performed after the use cycle.*
	No definition available	• "The use of a product by multiple users. It is a practice that retains the highest value of a product by extending its use period." (EMF 31) • "Sharing Platforms enable an increased utilization rate of products by enabling or offering shared use/access or ownership through which, different users use the product sequentially."(VH 9)	*Scaled under the definition of rethink, following the PBL definition.*

Resterilise (2)	• Sterilizing (again) for reuse (1x)	No definition available
Slowing loops (1)	• Durable design (1x) • Enabled by reuse (1x) • Increasing product longevity (1x)	No definition available
(bio)remediate (1)	• Chemical recycling by microbial action (1x)	No definition available

	No definition available	No definition available	*Integrated as a part of the strategies for which sterilization is needed in the processes performed after the use cycle.*
	No definition available	No definition available	*Excluded due to limited clarity in definitions while also encompassing multiple other strategies.*
	No definition available	• "The use of a product by multiple users. It is a practice that retains the highest value of a product by extending its use period." (EMF 31)	*Scaled under the definition of renew.*

Chapter 3 – Appendix H
Practical Application of Visual Taxonomy

This appendix illustrates the practical application of the proposed visual taxonomy through a concise case study focused on the lifecycle management of an endoscope. This example demonstrates how circular economy (CE) strategies can guide decision-making at various stages—from research and design through reuse, refurbishment, and end-of-life treatment. To ground the theoretical framework in a real-world healthcare context, Table 28 presents a detailed, chronological overview of key CE considerations, responsible actors, required information, expected conclusions, and recommended actions specific to the endoscope lifecycle.

The case centres on the intended circular design of an endoscope—a flexible medical device primarily used for internal diagnostic and therapeutic procedures in minimally invasive surgeries. Its main functions include visualizing internal organs, collecting biopsy samples, and enabling targeted interventions.

Following the Circular Healthcare Flows visual, the table walks through a step-by-step decision-making process across different CE strategies in chronological order. It is important to note that actions linked to different strategies may sometimes conflict. While prioritizing higher-level CE strategies in the hierarchy is generally advised, decisions must be context sensitive. For instance, if reuse requires design choices (e.g., screws for easy disassembly) that complicate recycling, a system-level sustainability assessment should inform the trade-off rather than opting blindly for one strategy.

The table's responsible actors reflect the specific endoscope context: since the device is used mainly within hospitals and rarely by patients themselves, patient responsibility in CE strategy application is minimal during active use.

Lastly, the visual taxonomy emphasizes potential transitions and failure modes between CE strategies. Though detailed scenarios of such transitions are beyond this example's scope, users are encouraged to consider contingencies—for example, if an endoscope fails to meet reuse quality standards after reprocessing, should it proceed to refurbishment, remanufacturing, or recycling?

Table 28: Endoscope example of CE strategy considerations

Visual Taxonomy Stage	CE Strategy Consider-ation	Main Responsible Actor(s)	Required Information for Endoscope Case	Expected Conclusion	Examples of Recommended Actions
Research, Design, and Development	Refuse — rejecting device use if function can be avoided	Manufacturer, Healthcare Facility	- Core device function - Added clinical value - Harm/risk from refusal	Endoscope essential for diagnosis and therapy; refusal compromises patient care	Refusal is not feasible in this case; proceed only when clinically necessary.

Research, Design, and Development	Replace — substitute device with lower-impact alternative	Manufacturer, Healthcare Facility	- Functional equivalence of alternatives - Environmental impact of alternatives	Alternatives (e.g., capsule endoscopy, imaging) lack full therapeutic capability; unclear environmental benefit	Replacement is not worthwhile for full function; continue with endoscope and explore other CE strategies.
Research, Design, and Development	Rethink — systemically enhance procedures for sustainability	Manufacturer, Healthcare Facility, Service Providers	- Potential for device sharing - Multifunctionality opportunities - Feasibility of use in other care settings	Endoscopes can support combined diagnostic-therapeutic use, shared across departments to reduce device numbers	Implement device-sharing programs, combine diagnostic-therapeutic sessions, and enable multifunctional use and shared clinician training.
Research, Design, and Development	Reduce — minimize resource use and unnecessary procedures	Manufacturer, Healthcare Facility, Patient	- Procedure frequency rationale - Consumables per procedure - Energy/water consumption	Reducing unnecessary procedures and consumables lowers environmental footprint	Perform only clinically necessary procedures, minimize disposable accessory use, and optimize sterilization processes.
Performance Sustainment	Maintain — preserve function to extend lifespan	Healthcare Facility, Service Providers, Manufacturer	- Maintenance schedules - Usage logs	Regular maintenance prevents premature replacement and ensures safety	Implement strict maintenance protocols, provide staff training, and track device usage for timely upkeep.
Performance Sustainment	Repair — restore faulty components	Manufacturer, Service Providers, Healthcare Facility	- Common failure modes - Repair feasibility- Safety standards	Typical failures (light cables, insertion tubes, lenses, controls) are repairable under safety standards	Prioritize durable design of critical parts and facilitate easy repair and replacement processes.
Reprocessing for Intended Use	Reuse — reuse components after decontamination	Healthcare Facility, Service Providers, Manufacturer	- Decontamination protocols - Component reusability limits - Traceability requirements	Reuse feasible with appropriate sterilization and traceability; extends device lifespan	Design for durability and easy disassembly; develop validated decontamination protocols and maintain traceability.
Reprocessing for Intended Use	Refurbish — restore devices to good condition	Manufacturer, Service Providers	- Device condition assessment - Repair/upgrade needs - Refurbish cycle limits - Traceability	Some components fail earlier; refurbishment restores function and safety	Enable easy dismantling and repair; set refurbishment limits per component; ensure traceability throughout.

Reprocessing for Intended Use	Remanufacture — restore devices to as-new condition	Manufacturer, Service Providers	- Device condition post-refurbishment - Component availability – Certification - Updateability	After multiple reuse/ refurbish cycles, full remanufacturing required for safety and modernization	Recover reusable components to produce as-new devices, meeting certification and updating standards as needed.
End of Intended Use Transformations	Repurpose — use discarded parts for new purposes	Manufacturer, Service Providers	- Alternative safe applications - Regulatory considerations	Parts may be reused for training, veterinary use, or in resource-limited settings	Repurpose safe components for training, veterinary care, or low-resource settings following safety regulations.
End of Intended Use Transformations	Recycle — convert materials into raw materials	Recycler, Hazardous Waste Facility, Service Providers	- Material composition - Recycling feasibility and logistics	Metals and some plastics recyclable but challenging separation; many plastics non-recyclable	Design for minimal material variety and easy separation; establish take-back schemes to improve recycling rates.
End of Intended Use Transformations	Renew — convert materials via natural processes	Composting Plants, Healthcare Facility	- Biodegradability of components - Suitability for regenerative processes	Limited applicability; biodegradable components minimal, no implantable residues	Renew is not feasible; components at end-of-life should be recycled or incinerated.
Leakage	Recover Energy — incinerate waste for energy recovery	Waste Incineration Plant, Healthcare Facility	- Incineration requirements - Medical waste protocols - Energy recovery efficiency	Non-recyclable parts safely incinerated with energy recovery; medical incineration standards met	Incinerate non-recyclable components in compliant medical waste facilities to recover energy while ensuring safety.

Based on this exercise, the principal recommendations for the endoscope emphasize enabling sustainable clinical use without compromising patient care. Complete refusal or replacement with alternatives is generally not feasible given the device's indispensable diagnostic and therapeutic functions. Instead, efforts should prioritize rethinking clinical workflows to facilitate device sharing and multifunctionality, alongside reducing unnecessary procedures and consumable usage to lower resource consumption. Extending the device's functional lifespan through rigorous maintenance, repair, and validated reuse protocols is critical. Upon reaching component end-of-life, refurbishment and remanufacturing should be employed to restore safety and performance. At end-of-life, repurposing safe parts, enhancing recyclability through design for disassembly and material selection, and safe energy recovery via incineration constitute key strategies to minimize environmental impact. Collectively, these recommendations represent a coherent, context-sensitive circular approach tailored to the unique requirements of endoscope lifecycle management.

appendices
chapter 5

Chapter 5 – Appendix A

Simplified Version of Product Journal Map

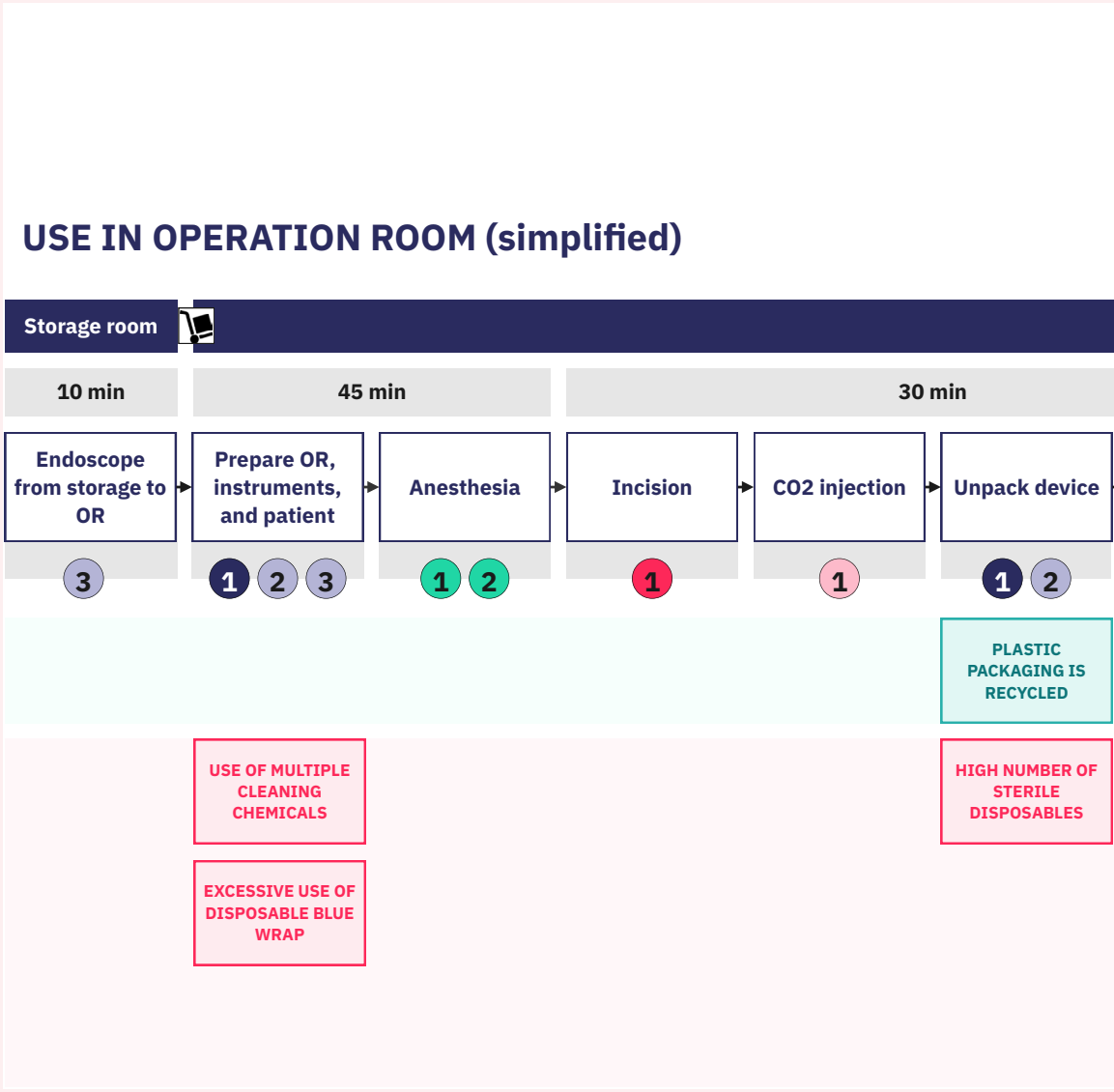
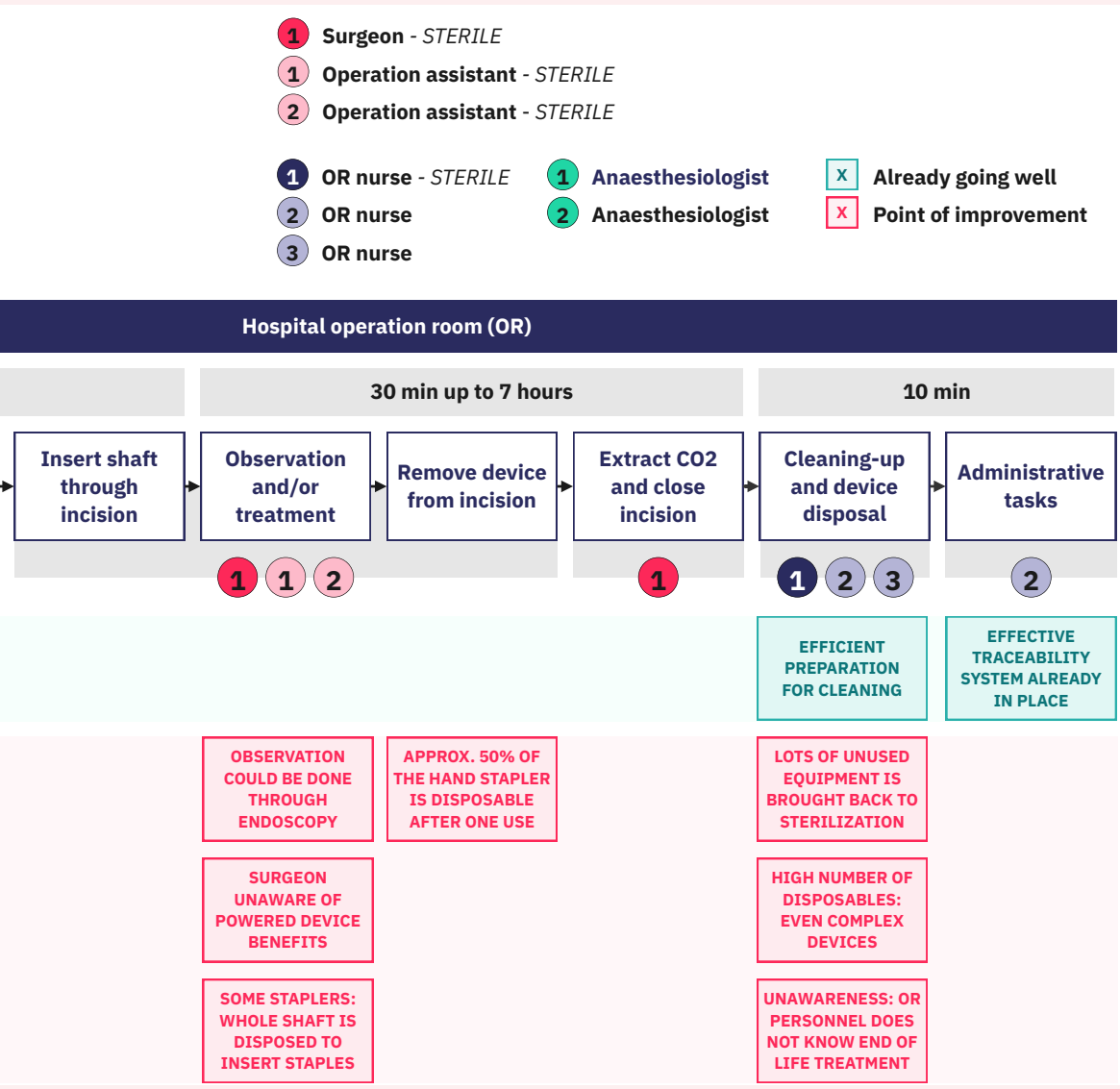


Figure 56: Simplified Version of Product Journey Map


1 Surgeon - STERILE
1 Operation assistant - STERILE
2 Operation assistant - STERILE
1 OR nurse - STERILE
2 OR nurse
3 OR nurse
1 Anaesthesiologist
2 Anaesthesiologist
X Already going well
X Point of improvement
Hospital operation room (OR)
30 min up to 7 hours
10 min
Insert shaft through incision
Observation and/or treatment
Remove device from incision
Extract CO2 and close incision
Cleaning-up and device disposal
Administrative tasks
1 1 2
1
1 2 3
2
EFFICIENT PREPARATION FOR CLEANING
EFFECTIVE TRACEABILITY SYSTEM ALREADY IN PLACE
OBSERVATION COULD BE DONE THROUGH ENDOSCOPY
APPROX. 50% OF THE HAND STAPLER IS DISPOSABLE AFTER ONE USE
LOTS OF UNUSED EQUIPMENT IS BROUGHT BACK TO STERILIZATION
SURGEON UNAWARE OF POWERED DEVICE BENEFITS
HIGH NUMBER OF DISPOSABLES: EVEN COMPLEX DEVICES
SOME STAPLERS: WHOLE SHAFT IS DISPOSED TO INSERT STAPLES
UNAWARENESS: OR PERSONNEL DOES NOT KNOW END OF LIFE TREATMENT

Chapter 5 – Appendix B
Standards and Regulations Research

Surgical staplers adhere to rigorous standards and regulations. These standards ensure not only the safety and effectiveness of the device but also align with increasing demands for environmental sustainability. As the healthcare industry faces mounting pressure to reduce its environmental footprint, integrating circular economy principles into medical device design has become imperative. This chapter provides an overview of the applicable standards and regulations for laparoscopic devices, categorized into general product-specific and environmentally focused guidelines. Additionally, it outlines corresponding design guidelines, identifying overlaps and potential contradictions, thus offering a holistic perspective on the challenges and opportunities in designing sustainable laparoscopic devices.

B.1 General Standards and Regulations

The following general standards and regulations apply to the design and production of laparoscopic devices:

- EU Medical Device Regulation (MDR) 2017/745
- ISO 13485:2016 - Quality Management Systems for Medical Devices
- ISO 14971:2019 - Risk Management for Medical Devices
- IEC 60601 Series - Medical Electrical Equipment
- IEC 60601-1: General safety and performance.
- IEC 60601-1-2: Electromagnetic compatibility.
- IEC 60601-2-2: High-frequency surgical equipment.
- ISO 11135:2014 - Sterilization of Health Care Products
- ISO 11607 Series - Packaging for Terminally Sterilized Medical Devices
- ISO 17664:2017 - Processing of Health Care Products
- ISO 10993 Series - Biological Evaluation of Medical Devices
- ISO 10993-1: Biocompatibility testing.
- IEC 62366-1:2015 - Usability Engineering for Medical Devices
- ISO 14155:2020 - Clinical Investigation of Medical Devices for Human Subjects
- ISO 11737 Series - Sterilization of Health Care Products
- FDA Regulations (if applicable)
- 21 CFR Part 820 - Quality System Regulation (QSR)
- 21 CFR Part 807 - Establishment Registration and Device Listing
- 21 CFR Part 814 - Premarket Approval (PMA)
- 21 CFR Part 803 - Medical Device Reporting (MDR)
- Medical Device Single Audit Program (MDSAP)
- General Product-Specific Design Guidelines

Based on the general standards and regulations listed, we propose the following design guidelines to be considered in the redesign of the laparoscopic device:

- Safety and Performance: Design must prioritize patient safety, efficacy, and compliance with international safety standards (ISO 13485, IEC 60601 series, MDR).

- Usability: Ensure user-friendly interface and ergonomics to minimize user errors and enhance clinical outcomes (IEC 62366-1).
- Sterilization Compatibility: Must be compatible with standard sterilization methods (ISO 11135, ISO 17664).
- Biocompatibility: Use materials that are biocompatible and suitable for prolonged patient contact (ISO 10993 series).
- Quality Management: Implement robust quality management systems (ISO 13485, FDA QSR).
- Risk Management: Thoroughly assess and mitigate risks associated with device use (ISO 14971).
- Clinical Evaluation: Conduct comprehensive clinical evaluations and trials to validate safety and effectiveness (ISO 14155).
- Packaging: Ensure sterile barrier and mechanical protection during transport and storage (ISO 11607 series).

B.2 Environmental Sustainability Related Standards and Regulations

The full list of environmental sustainability related standards and regulations we identified to be applicable to the laparoscopic device are listed below:

- Eco-design for Sustainable Products Regulation (ESPR)
- EU Directive 2012/19/EU - Waste Electrical and Electronic Equipment (WEEE) Directive
- EU Directive 2011/65/EU - Restriction of Hazardous Substances (RoHS) Directive
- EU Packaging and Packaging Waste Directive (PPWD)
- EU Directive 2008/98/EC - Waste Framework Directive (WFD)
- ISO 14001:2015 - Environmental Management Systems
- ISO 14040:2006 - Life Cycle Assessment (LCA) Principles and Framework
- REACH Regulation (EC) No 1907/2006
- Right to Repair Legislation (EC 2023)
- ISO 14025:2006 - Environmental Labels and Declarations
- ISO 20400:2017 - Sustainable Procurement
- ISO 59004:2024 - Circular Economy — Vocabulary, Principles, and Guidance for Implementation
- California Proposition 65 (if applicable)
- EU Battery Regulation (2025)

B.3 Environmental Sustainability Design Guidelines

- Resource Efficiency: Minimize material use and select environmentally friendly materials, including recycled or recyclable content (ESPR, ISO 14001).
- Energy Efficiency: Optimize energy use during manufacturing and, if applicable, during use (ESPR).
- Hazardous Substance Management: Avoid or minimize hazardous substances in materials and components (RoHS Directive, REACH).
- Design for Disassembly: Facilitate easy disassembly for repair, recycling, or safe disposal (Right to Repair).

- EoL Management: Plan for efficient recycling and safe disposal, including compliance with WEEE and PPWD (WEEE Directive, PPWD).
- Eco-Labelling and Transparency: Provide clear information on environmental impact, recyclability, and proper disposal methods (ISO 14025).
- Life Cycle Assessment: Conduct LCAs to understand and minimize environmental impacts throughout the product lifecycle (ISO 14040).
- Sustainable Procurement: Prioritize suppliers and materials that adhere to sustainability standards (ISO 20400).

B.4 Overlap and Contradictions

Balancing general product requirements with environmental sustainability guidelines can present both opportunities and challenges. Below, we explore the areas of overlap and potential contradictions between these two sets of design requirements.

B.4.1 Overlap

- Materials Selection: Both lists emphasize selecting biocompatible and non-toxic materials that are safe for patients and the environment.
- Risk Management: Both require a comprehensive assessment of risks, whether for patient safety (ISO 14971) or environmental impact (ISO 14001).
- Packaging: While the general guidelines focus on maintaining sterility and safety, sustainability guidelines emphasize minimizing environmental impact through recyclable packaging materials.

B.4.2 Contradictions

- Design for Durability vs. Disassembly: General guidelines often prioritize durable and robust designs for safety and long-term use. In contrast, sustainability guidelines may require designs that facilitate easy disassembly for recycling or repair, which could sometimes compromise the structural integrity and durability of the device.
- Single use vs. Reusability: General medical device standards may necessitate single use devices for hygiene and safety, while sustainability standards advocate for reusable components or devices to reduce waste.
- Use of recycled materials: While recycling is favourable in circular economy contexts, ISO 11607 recommends against this (even for primary packaging), and advocates for full traceability of such materials: which current technologies, it is therefore unlikely that anything other than virgin manufacturing will be used in recycled materials, due to insufficient controls to allow the safe use of other recycled material in sterile barrier systems.

Chapter 5 – Appendix C
Design Requirements

Designing laparoscopic staplers that are both effective and environmentally sustainable presents unique challenges and opportunities. This chapter outlines key design considerations derived from previous research (Hoveling et al., 2024), industry standards and regulations (Appendix B), and prior public as well as confidential deliverables from the Digital Health in the Circular Economy (DiCE) project (Deliverables & Reports - Digital Health in the Circular Economy, 2023). Additional non-circular requirements we added based on the performed OR observations. The goal is to provide a framework that balances high performance with environmental responsibility, ensuring that laparoscopic devices meet rigorous quality, safety, and usability standards while adhering to sustainable practices. Therefore, the final solidified list of design guidelines for the laparoscopic stapler is presented in the seven categories below, combining circular and non-circular requirements rather than separating them.

It is important to note that while a full list of all relevant design requirements is presented here, not all requirements are a priority in the redesign. For example, while requirement 7.1 suggests optimizing energy consumption during use as our earlier research suggests this can benefit circularity (Hoveling et al., 2024), this requirement should not be prioritized as the LCA results suggest that the use phase is not an impact hotspot for this specific product. However, this list also exemplifies what an integrated list of circular and non-circular design requirements could looks like for a laparoscopic device, rather than only serving as input for this specific redesign task.

C.1 Quality & Performance

- In the redesign, maintain or improve the quality, function, and usability of the laparoscopic device compared to previous models.
- Ensure reliable performance in insertion, tissue grabbing, stapling, and cutting functions.
- Design the laparoscopic device to handle various types and thicknesses of tissue through interchangeable cartridges and staples.
- Maximize the use of all functionalities of the laparoscopic device to enhance perceived value and reduce early disposal.
- Comply with FDA regulations (if applicable), including 21 CFR Part 820 and 21 CFR Part 814, while also adhering to ISO 13485:2016 and MDR 2017/745.

C.2 Patient Safety

- Design the laparoscopic device to close tissue properly without leakage, ensuring effective closure during the stapling process.
- Ensure stable operation to prevent instability that could cause damage or compromise the effectiveness of the device.

- Maintain sterility through its entire use phase, complying with ISO 11135:2014 and ISO 11607 Series for sterilization and packaging.
- Conduct thorough risk assessments and implement measures to mitigate risks associated with device use, as outlined in ISO 14971:2019.

C.3 Usability & Ergonomics

- Design the laparoscopic device to be easily handled by users with varying hand sizes and strengths, with an appropriately sized handle and minimal force required for operation.
- Ensure the laparoscopic device is suitable for use in various healthcare settings, facilitating easy transport and handling.
- Provide clear and user-friendly instructions for use, maintenance, and disposal.
- Incorporate features that facilitate troubleshooting and repair.
- C.4 Manufacturing & Production
- Ensure the laparoscopic device can be mass-produced using standardized techniques to maintain cost-effectiveness and scalability.
- Enable faster production adjustments and support by localizing manufacturing and distribution.
- Design the laparoscopic device to use minimal materials while maintaining quality and functionality. Accommodate various production methods beyond injection moulding.

C.5 Durability & Maintenance

- Ensure materials and components are durable enough to withstand necessary chemicals, temperatures, handling, UV exposure, and liquids.
- Design the laparoscopic device to tolerate exposure to various decontamination methods, especially the needed heat sterilization.
- Incorporate smooth surfaces and minimize hard-to-reach areas to prevent dirt and microbe accumulation.
- Provide clear guidelines for authorized parties on cleaning, disinfecting, and decontaminating the product. Ensure accessible product use history information for quality checks and decontamination.
- C.6 Information & Traceability
- Provide a digital product passport detailing materials, sustainability, and recyclability, in line with ESPR and ISO 14025:2006.
- Implement a system to track and record the number of use cycles and unique device identification for inventory management and tracking.

C.7 Materials & Components

- Minimize material use and select environmentally friendly materials, including recycled or recyclable content.

- Minimize the use of critical raw materials, such as tungsten and cobalt, where possible. Opt for alternative materials to mitigate supply chain risks and adhere to the EU Critical Raw Materials Regulation.
- Optimize energy consumption during manufacturing and use.
- Comply with chemical restrictions environmental legislations (EU REACH Restriction, Stockholm convention on persistent organic pollutants, EU Restriction on Hazardous Substances in EEE & EU Battery Regulation) and avoid other substances of concern (EU REACH SVHC and similar).
- Design for easy disassembly to facilitate repair, recycling, or safe disposal. Ensure compliance with Right to Repair legislation and WEEE Directive (2012/19/EU).
- Avoid black plastics due to sorting difficulties and select polymers with densities of less than 1.1 g/cm^3.
- Use packaging materials that are recyclable and reusable, with minimal hazardous substances (comply with requirements under EU PPWR).
- Provide clear labelling on packaging to facilitate recycling.

Chapter 5 – Appendix D

Stakeholder Survey

Consent form

Dear Participant,

Thank you for participating in this research, led by PhD candidate Tamara Hoveling from TU Delft as part of the Horizon Europe-funded DiCE project, which aims to reduce e-waste from health devices. This study focuses on the redesign of a single use endocutter (linear stapler). In this document, each of four conceptual redesigns developed by TU Delft will be explained separately, each followed by a short survey for your feedback. In some cases, a brief call may be scheduled to discuss your answers in detail.

By signing this form, you confirm that you are informed about the research, voluntarily agree to participate, and consent to the use of your anonymized answers in scientific publications. Participation is entirely voluntary, and you may withdraw at any time without reason. Please feel free to ask any questions. Note that data cannot be removed once your answers have been shared with the researcher.

Contact: Tamara Hoveling, t.hoveling@tudelft.nl

Name: _____ **Date:** _____

Name is needed for giving consent only. Your answers in this survey will be handled confidentially and will be published anonymously

Do you agree to participate in this research? ☐ yes ☐ no

After completing the survey, please sign below.

_____

First, please answer some general questions

1. **What is your current job title?**

_____

2. **Please state your expertise(s) below** *(For example, recycling, medical safety, business models, supply chain management)*

_____

3. **Years of experience in this expertise**

_____

4. **Do you have experience in the healthcare industry?**

☐ yes ☐ no

Explanation for Concept A - Fully Recyclable Device

The first concept is a fully recyclable device. The linear stapler is recycled directly after one use. In this process, the hospital separates the battery from the device, decontaminates the components, and sells both the battery and the device to recycling companies. At the recycling facility, materials such as ferrous and non-ferrous metals, as well as high- and low-value plastics, are separated and recycled for use in the production of new devices. Since this concept assumes the highest safety standards, it also presumes the use of virgin materials for production rather than recycled inputs.

The device is compact and designed with a “reduce” approach, using minimal materials. It consists of three click-separable compartments: a durable metal shaft made from recyclable surgical stainless steel, an injection-moulded plastic casing of sterilizable medical-grade polypropylene, and an electronics unit with a separable single-use battery. Clear icons guide users through a simple disassembly process to enable efficient recycling. For clarification, refer to Figure 57 (simplified system map) and Figure 58 (product design sketches

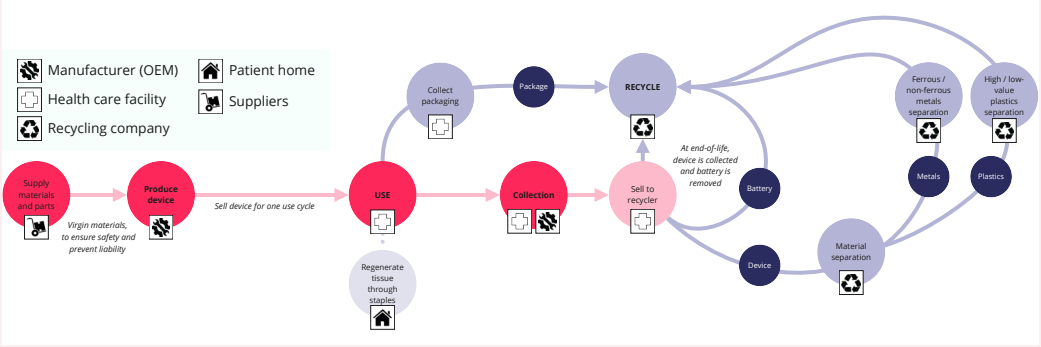


Figure 57: Simplified System Map Concept A

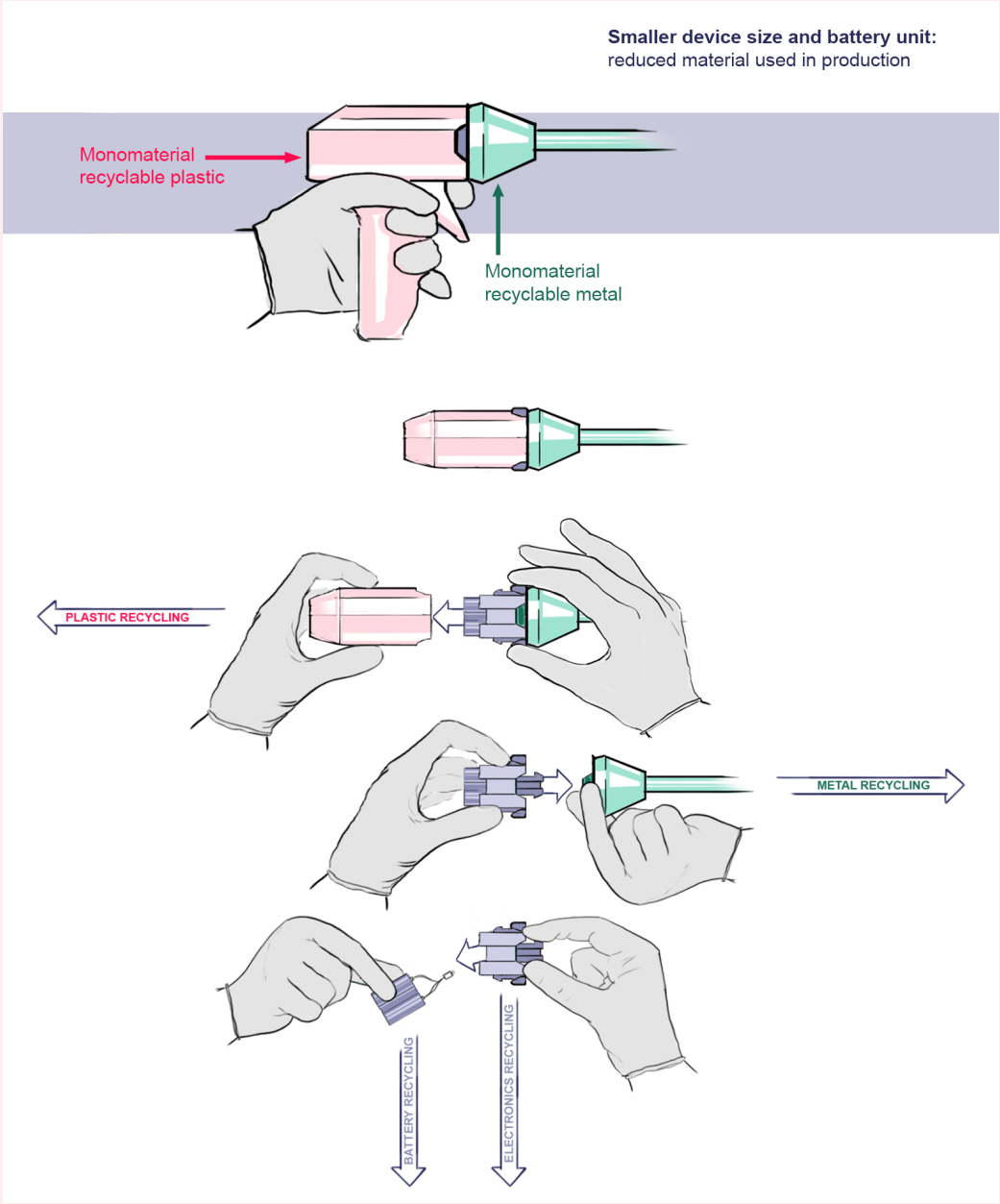


Figure 58: Product Design Sketches Concept A

Survey for Concept A - Fully Recyclable Device

For each perspective below, please indicate how you would rate each perspective below for the just-presented design concept. Check the box that best represents your assessment.

We understand that some of these perspectives may involve uncertainties requiring further research. Please feel free to base your answers on your professional judgment and experience—your estimations are valuable and will help guide future development.

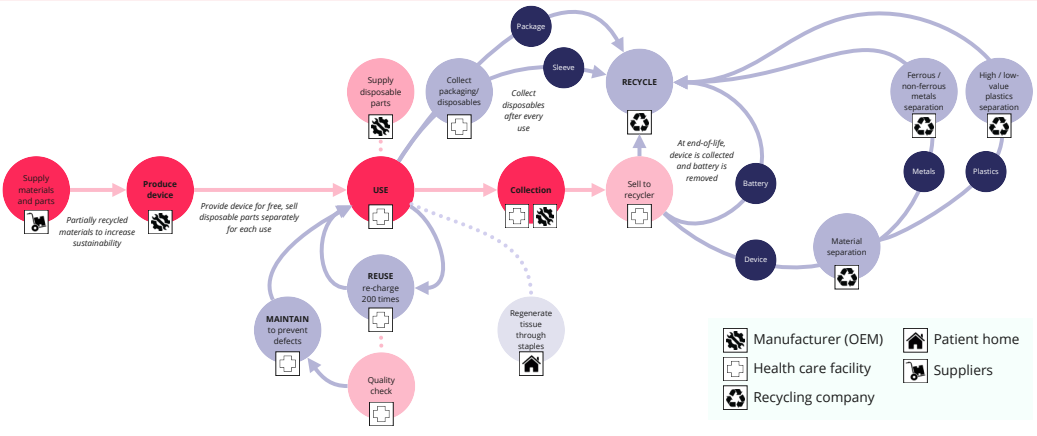
Perspective to rate ...	Very poor	Poor	Acceptable	Good	Very good
Environmental sustainability	☐	☐	☐	☐	☐
Explain why					
Financial viability	☐	☐	☐	☐	☐
Explain why					
Logistic feasibility	☐	☐	☐	☐	☐
Explain why					
Functionality and performance	☐	☐	☐	☐	☐
Explain why					
Ease of use and maintenance	☐	☐	☐	☐	☐
Explain why					
Regulatory compliance	☐	☐	☐	☐	☐
Explain why					
Technical feasibility	☐	☐	☐	☐	☐
Explain why					

2. What are your general thoughts about this concept?

Explanation for Concept B - Partially Reusable Device

The second concept is a partially reusable device. Unlike the fully recyclable model, this design allows the internal electronics unit to be reused while the outer components remain single-use and recyclable. After each procedure, hospital staff removes the electronics unit for recharging, while the sterile plastic casing and other disposable parts are sent for recycling. The device consists of three click-separable compartments: a durable metal shaft, a single-use sterile plastic casing, and a reusable electronics unit.

This design reduces electronic waste while ensuring a safe and efficient workflow. Clear icons guide hospital staff through the separation process, making disassembly straightforward. After approximately 200 uses, the reusable electronics unit is also recycled. By minimizing single-use electronic waste while maintaining high safety standards, this concept strikes a balance between sustainability and practicality. For clarification, refer to Figure 59 (simplified system map) and Figure 60 (product design sketches).



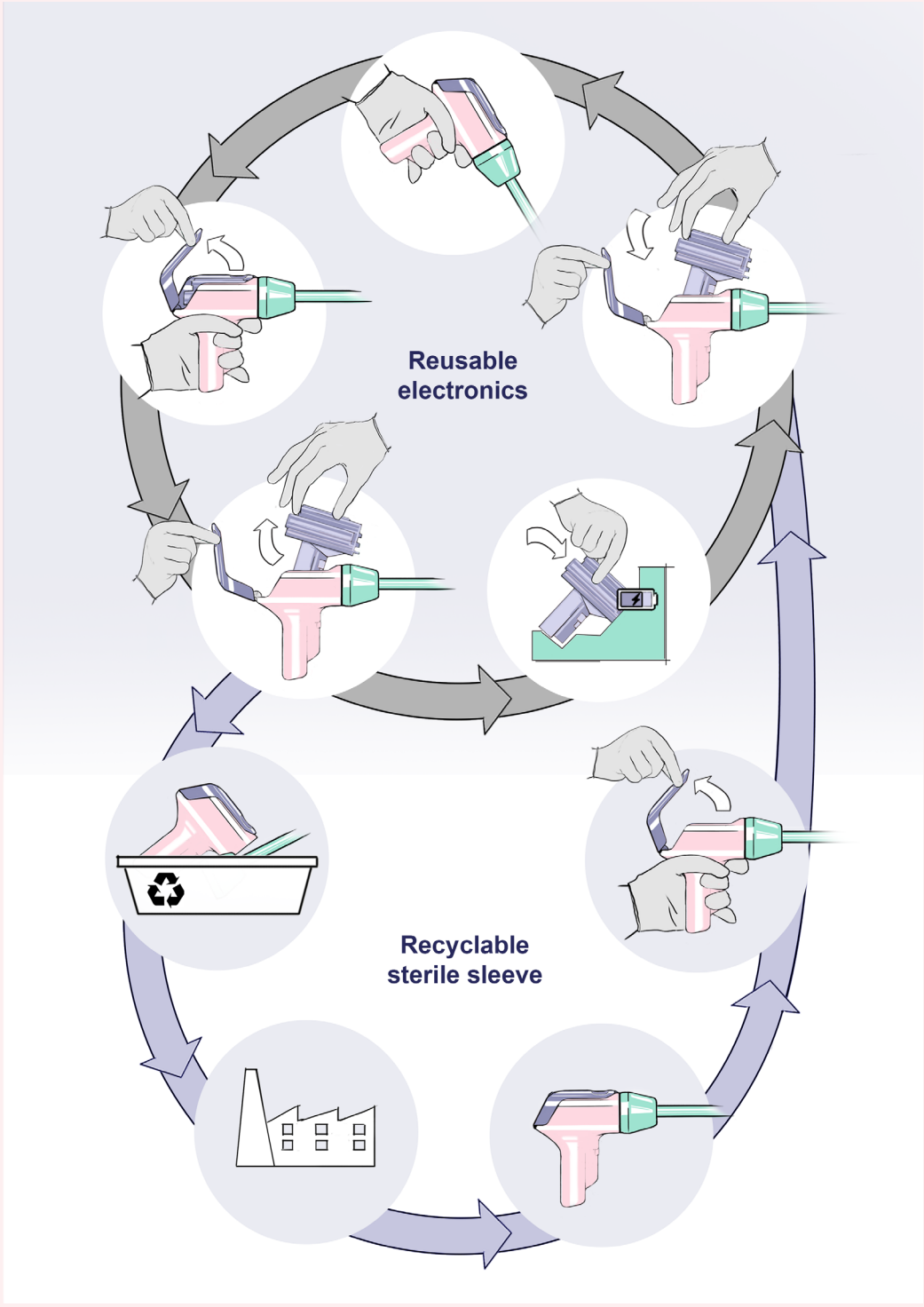


Figure 60: Product Design Sketches Concept B

Survey for Concept B - Partially Reusable Device

1. For each perspective below, please indicate how you would rate each perspective below for the just-presented design concept. Check the box that best represents your assessment.

We understand that some of these perspectives may involve uncertainties requiring further research. Please feel free to base your answers on your professional judgment and experience—your estimations are valuable and will help guide future development.

Perspective to rate ...	Very poor	Poor	Acceptable	Good	Very good
Environmental sustainability	☐	☐	☐	☐	☐
Explain why					
Financial viability	☐	☐	☐	☐	☐
Explain why					
Logistic feasibility	☐	☐	☐	☐	☐
Explain why					
Functionality and performance	☐	☐	☐	☐	☐
Explain why					
Ease of use and maintenance	☐	☐	☐	☐	☐
Explain why					
Regulatory compliance	☐	☐	☐	☐	☐
Explain why					
Technical feasibility	☐	☐	☐	☐	☐
Explain why					

2. What are your general thoughts about this concept?

Explanation for Concept C - Multifunctional Device

The third concept is a modular, multifunctional device with a reusable main unit and interchangeable click-on shafts for different surgical tasks. The main unit houses an electronics module, while the shafts and outer shell can be swapped depending on the procedure. After each use, the shafts and shell are sterilized, while the electronics unit is wiped down and recharged. A tracking system monitors usage, ensuring parts are replaced when they reach their limit and sent for recycling or refurbishment.

This design extends the device's lifespan, reduces waste, and offers flexibility for different surgeries. The click-on shafts are color-coded for easy identification and can also be used with robotic surgical arms. Once the electronics unit reaches its maximum charge cycles, it is returned to the manufacturer for inspection and potential refurbishment. If reuse is not possible, it is recycled. For clarification, refer to Figure 61 (simplified system map) and Figure 62 (product design sketches).

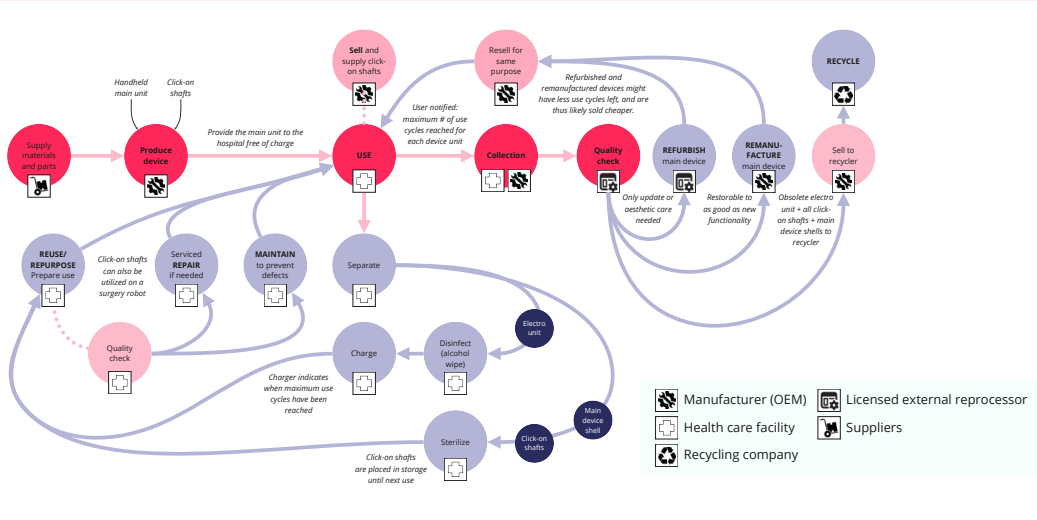


Figure 61: Simplified System Map Concept C

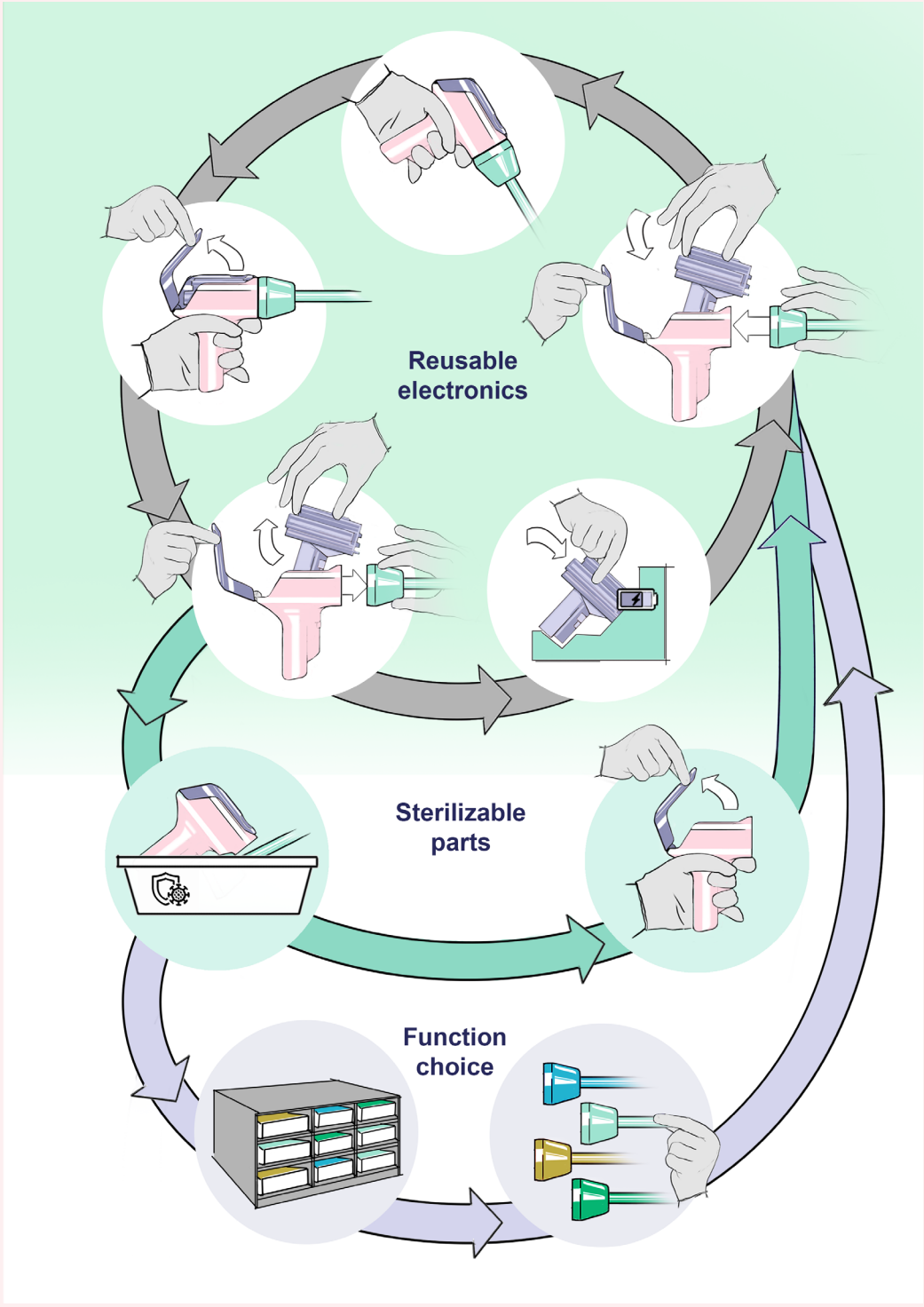


Figure 62: Product Design Sketches Concept C

Survey for Concept C - Multifunctional Device

For each perspective below, please indicate how you would rate each perspective below for the just-presented design concept. Check the box that best represents your assessment.

We understand that some of these perspectives may involve uncertainties requiring further research. Please feel free to base your answers on your professional judgment and experience—your estimations are valuable and will help guide future development.

Perspective to rate ...	Very poor	Poor	Acceptable	Good	Very good
Environmental sustainability	☐	☐	☐	☐	☐
Explain why					
Financial viability	☐	☐	☐	☐	☐
Explain why					
Logistic feasibility	☐	☐	☐	☐	☐
Explain why					
Functionality and performance	☐	☐	☐	☐	☐
Explain why					
Ease of use and maintenance	☐	☐	☐	☐	☐
Explain why					
Regulatory compliance	☐	☐	☐	☐	☐
Explain why					
Technical feasibility	☐	☐	☐	☐	☐
Explain why					

2. What are your general thoughts about this concept?

Explanation for Concept D – Manual Device

The fourth concept is a manual device designed for simplicity and reuse, focusing on minimizing reliance on electronics. This device is intended for full reuse without the need for complex separation or logistics in the operating room. After each use, the device is ready for cleaning and sterilization. Once it reaches the maximum number of reuse cycles, it is refurbished. When refurbishment is no longer possible, the device is then recycled. While the environmental impact of recycling and refurbishment may be minimal due to the lack of electronics, the focus is on creating a high-value, durable device.

As this concept explores a device entirely driven by manual force, the initial design approach focused on gathering insights and feedback from experts regarding the feasibility of a manual-driven device. Therefore, no detailed product sketches or storyboards were developed at this stage. This early stage aimed to assess whether a purely manual device could meet user needs before refining it further with specific technical details. For clarification of this concept, refer to Figure 63 (simplified system map).

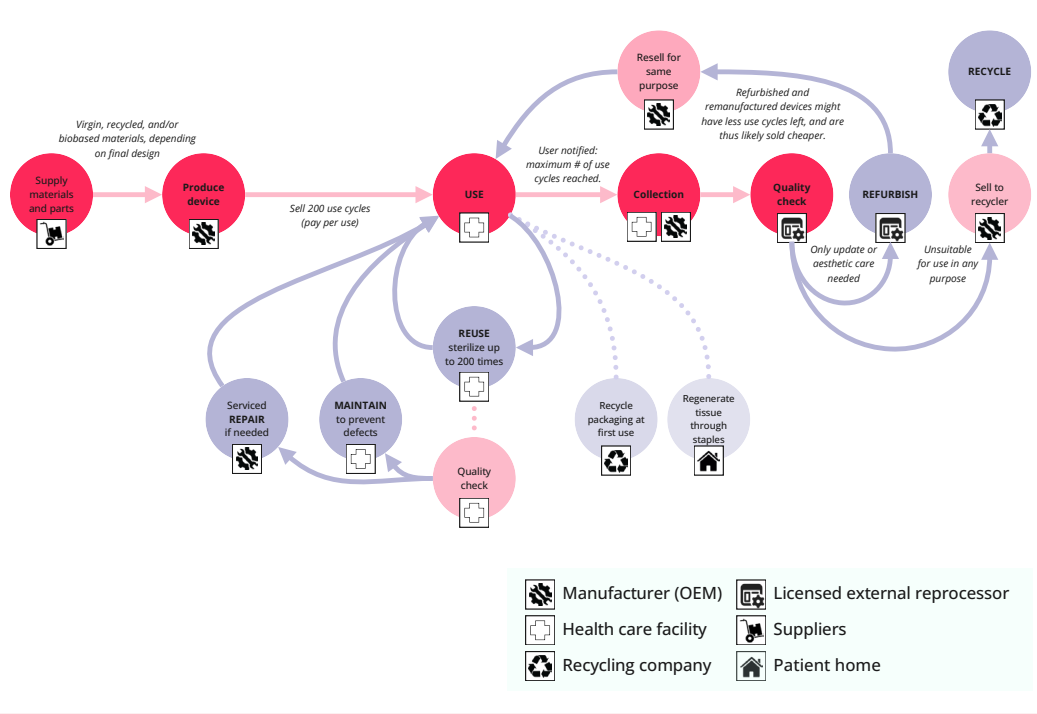


Figure 63: Simplified System Map Concept D

Survey for Concept D - Manual Device

For each perspective below, please indicate how you would rate each perspective below for the just-presented design concept. Check the box that best represents your assessment.

We understand that some of these perspectives may involve uncertainties requiring further research. Please feel free to base your answers on your professional judgment and experience—your estimations are valuable and will help guide future development.

Perspective to rate ...	Very poor	Poor	Acceptable	Good	Very good
Environmental sustainability	☐	☐	☐	☐	☐
Explain why					
Financial viability	☐	☐	☐	☐	☐
Explain why					
Logistic feasibility	☐	☐	☐	☐	☐
Explain why					
Functionality and performance	☐	☐	☐	☐	☐
Explain why					
Ease of use and maintenance	☐	☐	☐	☐	☐
Explain why					
Regulatory compliance	☐	☐	☐	☐	☐
Explain why					
Technical feasibility	☐	☐	☐	☐	☐
Explain why					

2. What are your general thoughts about this concept?

Final Questions – Concept Comparison

Thank you for your feedback on our concepts! To finalize this survey, please fill-in these final questions for comparison.

1. Of all four concepts, which one would be your overall favourite?

☐ A – Fully Recyclable Device

☐ B – Partially Reusable Device

☐ C – Multifunctional Device

☐ D – Manual Device

2. Why did you choose this concept?

_____

_____

3. Below, add any additional thoughts you'd like to share with us.

_____

_____

_____

_____

Thank you for completing this survey
Please do not forget to sign the consent form on page one

Climate change is widely recognized as the greatest threat to human health, yet healthcare itself contributes significantly to environmental harm. Environmental pressures beyond climate change, such as the encroachment on wild lands that increases pandemic risks and the growing demand for scarce resources used in modern technologies, also contribute to these health risks. Despite these challenges, many high-tech solutions continue to rely on scarce materials but are used only briefly, and an increasing number of products are designed to be disposable. Single-use items, whether packaging, medical disposables, or complex electronic devices, are often discarded after minimal patient contact, as this is perceived to maximize safety.

A particular challenge within this context is posed by medical devices containing electronic components. These devices depend on critical raw materials and energy-intensive production processes and are composed of complex multi-material assemblies. At end of life, their disposal raises environmental concerns, as collection and recycling systems achieve only partial material recovery, while improper treatment of electronic waste can release hazardous substances into the environment. Together with rapid technological development and strict regulatory requirements, these factors complicate the application of circular approaches in design. This dissertation examines not only why this is the case, but also how it can be improved.

The central research question of this dissertation is therefore:
How can medical devices containing electronic components be redesigned to support a circular economy while ensuring clinical and regulatory compliance?



TU Delft

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