Transitioning towards a circular (healthcare) economy

Circular economy principles, leadership, policy and decision-making

Bart van Straten, Bruno Bruins, Tim Horeman

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About the authors

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Bart van Straten is an expert in the circular healthcare economy and holds a doctorate in BioMedical Engineering from TU Delft. He is affiliated with several public institutions and private companies, including Van Straten Medical. He co-founded GreenCycl, an organization with the mission to decrease the amount of medical waste. Bart is a member of the research group Sustainable Surgery & Translational Technology at TU Delft, where he is a lecturer on medical device prototyping and related courses. Bart developed a Field Lab together with Tim Horeman for experimental research on reprocessing surgical waste into new raw materials and medical products. His research has led to his book 'Creating a circular healthcare economy'. Bart won several awards, including the Utrecht Circular Innovation Top 20, as builder of the world's first recycling process for hospital waste. His drive is to bridge the gap between science, business and healthcare professionals with the aim to make societal impact with inventions emerging from the scientific field.

Mr. drs. Bruno Bruins

Bruno Bruins is specialist in public administration and healthcare. Having a background in Law and Public Administration (University of Groningen), Bruno was co-teacher in the online MOOC courses from TU Extension School which were developed by Bart van Straten and Tim Horeman and instructs in this course aspects such as the climate law, the Green Deal and other circular economy strategies leading to sustainable healthcare.

Bruno is affiliated with recycling company Renewi and is a former member of the Dutch Council of State. He served as Minister for Medical Care under Prime Minister Mark Rutte from 26 October 2017 to 19 March 2020. Previously, he served as State Secretary for Education, Culture and Science from 29 June 2006 until 22 February 2007 under Prime Minister Jan Peter Balkenende.

Dr. ir. Tim Horeman

Tim Horeman is Associate Professor in Sustainable Surgery & Translational Technology and Academic Portfolio Director (APD) in Medical Technology at TU Delft. Tim has ample experience in the objective assessment of surgical skills and surgical instrument functioning based on interaction force, instrument motion and other data sources. Currently, Tim is leading the development of a new generation of sustainable surgical instruments for advanced (robot) surgery, which should foster the introduction of more functional instruments in less wealthy parts of the world.

As it is essential to bring lifesaving surgical innovations in reach of surgeons and healthcare workers, Tim became a distinguished serial medtech entrepreneur with a strong focus on surgical devices and evidence-based implementation studies. He is PI and (co-)founder of the international companies GreenCycl, MediShield & ForceSense, SATA Medical and SuperSeton, which have brought multiple innovations to the worldwide market of surgical equipment. Tim is (co-)author of over 80 journal publications, inventor on 18 patent (families) and PI on multiple international research projects in the field of surgical instrument waste processing, SMART implants, global instruments and Minimally Invasive Surgery. In 2016, Tim was awarded the Dutch royal engineer of the year award for his contributions to the healthcare sector. In 2018 and 2022 Tim was elected Tech Committee member of the European Association of Endoscopic Surgery, with a strong focus on sustainable surgical instruments and processes.

Preface

The climate discussion seems to divide the world into opposing parties. The discussions are increasingly dominated by emotions and opinions, rather than exploring the fundamental causes of climate change. Over the past years our focus has been on research and innovation in the field of sustainable design, reprocessing waste into raw materials and making new products from waste.

This gave us leave to stay in our shelter, as it where: a niche where everyone seemed enthusiastic about our ideas, and we did not have to take up a position in the climate discussion. We set up projects up in collaboration with hospitals, companies and universities; with people who were intrinsically interested in investing their valuable time, and sometimes even money, to reuse waste and test our sustainable designs. Our project felt like a magnet of enthusiasm, motivation and positivism.

This had a positive impact on our results. New possibilities and techniques emerged, where waste is seen as a raw material and circular principles are applied to new products and processes. After all, humans are more susceptible to positive developments than negative ones. The climate discussion often causes fear - fear of temperature rise, of floods, of drought. The very word “crisis”, used to direct discussions in a certain direction, is perhaps the biggest pitfall in the climate discussion.

Behavioral studies show that engagement is higher with positive framing than with negative and neutral framing. Positively framed messages create engagement and motivation. Perhaps this is the key to achieving climate goals. We operate in the special world of healthcare, and are aiming in particular to make healthcare more sustainable. The three authors of this book – which can be considered a follow-up to *Creating a Circular Healthcare* – each look at sustainable care from their own perspective: Bruno with his background as a lawyer, politician and administrator; Bart as a healthcare entrepreneur, researcher and manager, and Tim as a scientist, designer and health-tech valorization expert.

With this book we want to give the circular healthcare economy a platform for making adequate decisions and policies. We want to show the possibilities that are there, but also the contradictions and paradoxes. By combining our perspectives, we describe how making healthcare (and other sectors) more sustainable is not difficult at all. The ultimate goal is to ensure that we move towards a zero-waste society, making us independent of raw materials, and having a positive impact on the climate. The best thing is that this approach has the power to connect and motivate people to add their own contribution.

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We are also grateful to TU Delft staff, especially the team at the department of BioMechanical Engineering. We would like to thank our partners at the participating hospitals and the team members of GreenCycl and Van Straten Medical. We also extend thanks to Saskia Roselaar, the editor of this book, and Jacqueline van de Riet and the team at TU Delft Repository. Without you it would not have been possible to transform scientific knowledge into valuable new processes and products.

Quality check on recycled medical waste by XRF Fluorescence spectroscopy at the department of Materials Science, Faculty of Mechanical Engineering, TU Delft. Image courtesy of Ruud Hendrikx.

Authors' note

Our previous book *Creating a Circular Economy* highlighted design principles and methods. This book focusses on policies, vision and strategies and may be regarded as a guide to circular (healthcare) economy tactics, smart policy-making and design principles.

Why we wrote this book

To succeed in creating circular strategies which effectively reduce or even eliminate waste streams, the best way is to build expertise, gain knowledge and experience. In this book we offer examples of successful projects and describe pitfalls and solutions to conquer challenges which you will face on the path to sustainability. Important key elements are visualized through illustrations creating a comprehensive overview of circular economy concepts.

When starting out in order to make an organization more sustainable or to develop circular strategies, you might have many questions. Where do I want to start? What are the challenges? What knowledge do I need? How can I find, select and involve the right stakeholders and how can I motivate them to support the initiative? How much energy or CO_2 do I actually save with my actions? How do I measure the sustainability levels in my new product or process? How do I get my team on board and deal with resistance and opposing policies and guidelines?

In this book we want to address these questions by giving examples, describing different perspectives and explaining them.

We want to help you develop your own vision in the field of sustainability and the best way to translate this vision into a strategy to be implemented.

Your efforts are of great importance to make the world more sustainable and to become less dependent on raw materials from other countries. Only with willpower and a growing number of ambassadors can we make a difference.

Online course on circular strategies

As an additional source of information, we encourage you to follow the free online courses in the program 'Circular Strategies for Sustainable Healthcare' on the edX TU Delft online learning platform:
https://online-learning.tudelft.nl/programs/circular-strategies-for-sustainable-healthcare/

Book on circular strategies

Our previous book 'Creating a Circular Healthcare Economy' can be downloaded free of charge or ordered as a paperback via:
https://books.open.tudelft.nl/home/catalog/book/167

Feedback

As authors we realize that we cannot cover everything in this book, but also that insights can change as we learn more, so that some aspects might not be covered here or are outdated. Furthermore, we realize that the reader might find errors or inaccuracies that may have been missed during the editing process of this book. Please communicate this to us, so we can update the book in the next edition and provide an improved reading experience. We look forward to your feedback!

Outline of the book

Part I describes circular principles and policy tactics.

Chapter 1 deals with the essentials of sustainable healthcare and describes the paradoxes inherent in daily practices of sustainability and the circular economy.

In Chapter 2 the impact of leadership on policy is discussed, with examples of best practices. The legislation and infrastructural web, in which many stakeholders and circular economy initiatives are strangled, is described. Despite the fact that politicians and policymakers are motivated to encourage sustainability, the infrastructure is designed to discourage circular economy projects. This chapter shows examples of setting up intrinsically motivated teams of hospital staff, green teams, industry leaders and scientifically motivated research teams.

Chapter 3 discusses the legislation paradox. It describes how legislation should be redesigned to accomplish the goals set out in the green deal and climate legislation.

Part II has been written as a quick guide in creating a circular healthcare system.

In chapter 4 the reader is guided through the fundamentals of circular strategies by visualizing the circular economy.

Chapter 5 showcases successful design strategies for products and processes which contribute to a zero-waste society.

In chapter 6 we will explore (surgical) waste as input for new products. Recycled materials can and should be used more. This is a fundamental concept within circular design principles, but hardly used until now.

Part III explores circular economy design principles on basis of successful examples.

Chapter 7 is focuses on leading by design. Success stories of circular concepts which have effectively changed the market with circular products and services are described, and success stories of circular economy business models are presented.

Chapter 8 investigates how to measure the effectiveness and impact of circular economy products and processes. In particular, it discusses how reliable some facts are which are used to sell products or introduce new policies or legislation: how trustworthy is data from life cycle assessments (LCA's)? Circular Economy principles, sustainability and, in the broader sense, the climate discussion seem to trigger emotions. Using fundamental and reliable data is essential in order to be able to judge whether a product or process indeed reduces CO_2 emissions.

Chapter 9 focusses on the way universities can contribute to sustainable solutions by presenting cases studies which yielded results that were implemented in practice or are ready for upscaling.

The authors reflect on this book in the reflection part. A critical analysis is presented and the impact of this book on future developments and society is discussed.

Introduction

Part I

The world is dominated by geopolitical developments often resulting in conflicts. Behind these conflicts is often a desire for valuable raw materials. This is clearest in wars, but also when trade barriers and import duties are imposed. The dependence on raw materials creates limits that hinder human development. This is why the circular economy is so important and why sustainable policies can eventually create peace in the world. Part I discusses the importance of the circular economy and why we should consider waste as a raw material. We also discuss the importance and characteristics of leadership, legislation and policy in a sustainable world, as strong leadership is needed to make this vision a reality.

Part II

The transition to a circular economy is a fundamental shift from the traditional linear model of production and consumption. By focusing on design strategies that prioritize sustainability, policymakers, businesses and consumers can work together to create a zero-waste society. Visualizing this new economic model helps stakeholders understand the flow of materials, the impact of waste reduction, and the benefits of closing resource loops. Governments and industries must integrate circular principles in policies and regulations to promote sustainable manufacturing, efficient recycling systems and extended product life cycles.

A key component of circular design is rethinking how products are created, used and repurposed. By adopting innovative design strategies, companies can develop goods that are durable, repairable and recyclable, reducing the need for raw materials. Manufacturers must also consider modular and adaptable product designs, making it easier to replace or upgrade parts, rather than discard broken items. These changes not only minimize waste but also encourage businesses to shift towards service-based models, such as leasing or refurbishing products instead of selling disposable goods.

Recycled materials play a crucial role in closing the resource loop, turning waste into valuable raw materials for new products. Industries can leverage waste streams from various sectors, such as plastics, textiles and metals, to create high-quality, sustainable alternatives. By investing in advanced recycling technologies and infrastructure, society can increase material recovery and lower its environmental footprint, realizing economic growth while preserving natural resources.

Part III

Part III describes the assessment of the environmental impact of “green” products through Life Cycle Assessment (LCA) as a crucial method for evaluating sustainability. LCA methodologies analyze the entire life cycle of a product, from raw material extraction to disposal, identifying areas where environmental improvements can be made. This capability to map life cycle stages and quantify environmental impacts makes LCAs a powerful tool for informed decision-making, whether comparing the environmental impact of existing products for sustainable procurement or guiding eco-design for new products entering the market.

LCAs play a growing role in the surgical field for evaluating the environmental sustainability of surgical instruments. LCAs are valued for their ability to capture the full environmental footprint of products across their entire life cycle. Despite their value, LCAs applied in the surgical instrumentation sector often yield inconsistent and occasionally contradictory results, raising concerns about their accurate execution and reliability in this field. The reliability of LCA results depends on factors such as data quality, assumptions and system boundaries, leading to potential risk factors in decision-making.

The last chapter discusses the vital role that technical universities play in driving sustainability in hospitals by advancing LCA research, developing new eco-friendly materials, and training future professionals to implement sustainable healthcare solutions.

Part I

Circular Principles and Politics

1

The essentials of sustainable principles and the circular economy paradox

Who cares which choices you make? Can you, as an individual, come up with solutions that make the world more sustainable and circular? And how important are your actions in this? Can we achieve collective solutions with our choices, policies and initiatives? In the next chapters we will discuss how we can use policy and decision-making effectively to achieve a society in which we produce less waste.

Whether your individual choices create a circular and sustainable world depends on whether your behavior makes an impact. It's your actions that matter and these will be different for every person. The feeling that you are a tiny cog in the whole and that you cannot change the system creates insecurity and perhaps individualism and thus egoism. But through your behavior you can encourage others to act the same. Thus, you may create collective behavior that influences collective consciousness.

So, to make an impact through your actions, you must seek connection. After all, you can increase your influence by working together, carefully choosing who you work with. Because your actions can convince others to do the same. In a pioneering role, you can be an example for everyone, for your children, your environment, society. You can become a source of inspiration in many ways and thus you can certainly make a difference as an individual.

The question then arises: what is good behavior and how do we measure that? Are we pushing the right buttons or are we being misled by various interests and groups? That is why it is very important to remain critical and make your own choices, based on facts. Separate facts from emotions. Find a balance within yourself between being a dreamer and a practical decision-maker. And above all, keep your back straight and do not let others deviate you from your path.

1.1 Circular strategies in light of the climate discussion

A lot has been said and written about reducing carbon dioxide (CO_2) emissions. Sometimes it seems like the climate debate is about nothing else. Yet opinions differ widely; emotions run high and facts are often confused with opinions and assumptions. We must be in favor of protecting the climate, but if you ask people what the definition of “the climate”, they remain silent or give different answers. It is important in these types of discussions to stay close to fundamental questions. Furthermore, it is important to know what we are talking about.

Todorov[1] describes climate change as one of the most controversial and complex definitions in meteorology. What are objective criteria which define climate change? Werndl[2] attempts to find a definition of climate and climate change, as various definitions have been offered in climate science literature. She discusses five definitions and argues that these definitions should meet five criteria, including elements such as the application of the definition to the past, present and future, as well as being mathematically confirmed. According to Werndl, the definition “climate is the finite distribution over time under a certain regime of varying external conditions” meets all of the defined the criteria.

NASA describes climate as the average of all regional climates in the world and climate change as the change of average weather in a region or, on a broader scale, on Earth.[3] While weather is about short-term changes such as rain, sunshine and drought, climate is the average over many years.

Climate change is affected by several factors, such as the orbit of the Earth, the amount of energy coming from the sun, changes in the oceans and volcanic eruptions. These are all natural causes of climate change.[3]

1. Todorov, A. V. [1986]: ‘Reply’, Journal of Applied Climate and Meteorology, 25, pp. 258–9.

2. Werndl, C. (2016). On defining climate and climate change. The British Journal for the Philosophy of Science.

https://www.journals.uchicago.edu/doi/full/10.1093/bjps/axu048.

3. NASA (2011). What Are Climate and Climate Change? Retrieved from: https://www.nasa.gov/learning-resources/for-kids-and-students/what-are-climate-and-climate-change-grades-5-8/#:~:text=Earth's%20climate%20is%20the%20average,average%20annual%20rainfall%2C%20for%20example.

Climate change is not only caused by natural factors, but also by humans. This is called anthropogenic global warming and started around 1750 during the Industrial Revolution, with the burning of fossil fuels releasing CO_2 and other greenhouse gases. These gases are formed due to human activities such as burning coal, oil and gas related to the production and consumption of energy, deforestation, land use changes, livestock and other factors leading to the emission of heat-trapping gases such as CO_2.

According to NASA's climate scientist Peter Hildebrand, the current problem is that in the pre-industrial age, CO_2 levels responded to changes in temperature. If the temperature increased, CO_2 levels increased. If the temperature decreased, CO_2 levels also decreased. The reason for this was that if temperatures increased, the whole biosphere accelerated and started to emit CO_2, resulting in higher CO_2 levels in the atmosphere.[5]

In the post-industrial age a change occurred. Increasing CO_2 in the atmosphere led to increased temperature. While the temperature was driving CO_2 levels in pre-industrial times, CO_2 levels are driving temperature in the industrial era. This is an entirely different physical-biological process, meaning a fundamental change in the Earth's radiation balance. Although we have technology to combat the increase in the Earth's temperature, this is often not used for political reasons. Furthermore, climate change may not be the most urgent problem facing humanity, but the depletion of scarce natural resources is.[6] Scarcity of natural resources is the basis for many geopolitical conflicts. Countries with valuable raw materials can fall prey to other countries that want them, leading to conflicts, (trade) wars and trade barriers.

This requires our immediate attention, as human population growth will lead to increased consumption and production. Controlling this phenomenon should be the major focus and responsibility of political leaders.

4. Peter Hildebrand, Director of the Earth Science Division at NASA's Goddard Space Flight Center, USA.

5. Hildebrand, P. (2013). Ask A Climate Scientist - Lagging CO2. Nasa Scientific Visualization Studio. Retrieved from: https://svs.gsfc.nasa.gov/11362.

6. A. Nientker. De Klimaatklem. 2023. ISBN 978-94-648-9614-5.

1.2 Valuable resources and potential for geopolitical conflicts

Critical and Strategic Raw Materials (CRMs) have large economic importance and are essential to society. Yet, there is a high risk of disruptions in their supply, that is why they are called ‘critical’. These materials are concentrated in specific regions, as shown in Figure 1, making them vulnerable to exploitation by other powers.

The ice-free zone of Greenland is rich in strategic minerals and rare earth elements (REEs), which are critical for high-tech industries and the green energy transition, such as uranium, iron ore, nickel, lithium and cobalt, all critical for battery production.[7]

Ukraine is rich in critical and strategic minerals; it has the one of the largest deposits of ilmenite in Europe, a primary source of titanium. Ukraine has, furthermore, significant lithium reserves; other critical raw materials include beryllium and natural graphite. Given these reserves, Ukraine has gained interest from investors around the world and governments looking to secure these supplies,[8] making it potentially one of the wealthiest countries in Europe.[8] However, Russia’s invasion of Ukraine in 2022 was at least partially motivated by a desire to gain control over these reserves.

The Democratic Republic of Congo (DRC) houses a very large supply of strategic critical raw materials. The DRC extracts around 70% of the world’s cobalt.[9,10] High-tech industries around the world depend on the DRC,[9] especially since the increasing demand for EV batteries and renewable energy storage is driving global competition for cobalt. Most of the mines are controlled in the DRC by foreign firms and influenced by foreign states.[11] China has invested heavily in extraction and mines in the DRC. China and the DRC are at the opposite ends of the supply chain.[12]

In Sudan, different parties are in conflict, with one of the main reasons being gold. Gold from “gold-conflict” zones such as Darfur has led to the term “conflict minerals”.[13] Foreign investments and supplies of weapons are driven by ownership claims to the nation’s gold and uranium deposits and the supply of mercenaries to Darfur.[14] Where gold as a raw material should enrich the population, it instead appears to be the source of conflict.

Countries in the Middle East and North Africa are considered to be the most strategically regions for oil and gas. This region, representing only six percent of the global population, contains 59% of the world’s oil reserves and 45% of its gas reserves.[15]

7. Rosa, D., Kalvig, P., Stendal, H., & Keiding, J. K. (2023). Review of critical raw material resource potential in Greenland. MiMa rapport, 1, 124.

8. Rudko, H. I., Lytvyniuk, S. F., & Karly, V. E. (2021). Deposits of critical mineral raw materials of Ukraine. Condition and prospects. Innovative development of resource-saving technologies and sustainable use of natural resources, 97.

9. Soufi, Y. (2020). Strategic Raw Materials, International Mining Firms and the Democratic Republic of the Congo. International Mining Firms and the Democratic Republic of the Congo (February 15, 2020).

10. Gulley, A. L. (2022). One hundred years of cobalt production in the Democratic Republic of the Congo. Resources Policy, 79, 103007.

11. Anderson, P. (2023). Cobalt and corruption: The influence of multinational firms and foreign states on the Democratic Republic of the Congo. Journal for Global Business and Community, 14(1).

12. Deberdt, R., & DiCarlo, J. (2024). Pericentricity on the Congolese copperbelt: how the DRC shapes Chinese cobalt supply chains and the low-carbon transition. Globalizations, 21(8), 1496-1517.

13. Ille, E. (2016). Complications in the classification of conflict areas and conflicts actors for the identification of ‘conflict gold’from Sudan. The Extractive Industries and Society, 3(1), 193-203.

14. Afriyie, F. A. (2024). Sudan: Rethinking the Conflict Between Sudanese Armed Forces (SAF) and the Rapid Support Forces (RSF). India Quarterly, 80(3), 439-456.

15. Aoun, M. C. (2013). Oil and gas resources of the Middle East and North Africa: A curse or a blessing?. In The New Energy Crisis: Climate, Economics and Geopolitics (pp. 133-160). London: Palgrave Macmillan UK.

These are just a few of many examples of countries and regions where raw materials are the basis for conflicts and territorial claims by governments who seek domination over other countries for their valuable materials. Raw materials that are strategically crucial for industries and technologies but have a high risk of supply disruption due to scarcity, geopolitical dependence, or limited availability. These materials are essential for sectors such as defense industry, renewable energy, electronics, aerospace, and healthcare. The growing quest for critical raw materials and energy is likely to reach unsustainable levels, posing risks to global stability. A basis for potential change in world order by governments claiming independent territories. Valuable resources that are disposed or incinerated after use creating a further imbalance.

Many of these scarce materials are used in medical devices, making medical waste streams valuable and worthwhile to explore for reusability. Using waste streams as a source of raw material could have not only a positive impact on reducing emissions of greenhouse gases. It also means that less energy is needed to create new raw materials and that fewer materials end up in landfill or incinerators. It also reduces geopolitical pressure on natural resource-rich areas and reduces the risk of international conflict. However, there are further advantages which are often forgotten, such as the prevention of waste in the oceans, reducing their ability to absorb CO_2.

Fundamental in this context is the discussion on the production and consumption of minerals, which often seems ignored but is extremely important. Just as we use fossil fuels on a massive scale, our mass consumption of natural resources deserves attention. These supply of these resources in our Earth’s crust is decreasing at a disastrous pace. If we do anything for future generations, it must be to use these increasingly scarce raw materials sparingly and with more care.

The circular economy can protect us from these negative developments, which is why circular strategies are increasingly important for every individual, business and nation.

In this book we focus on the principles of the circular economy, in particular with the following purposes:

- Using waste as a raw material with the aim of reducing geopolitical interdependence;
- Reducing waste streams and, as a result,
- Create a positive impact on the climate.

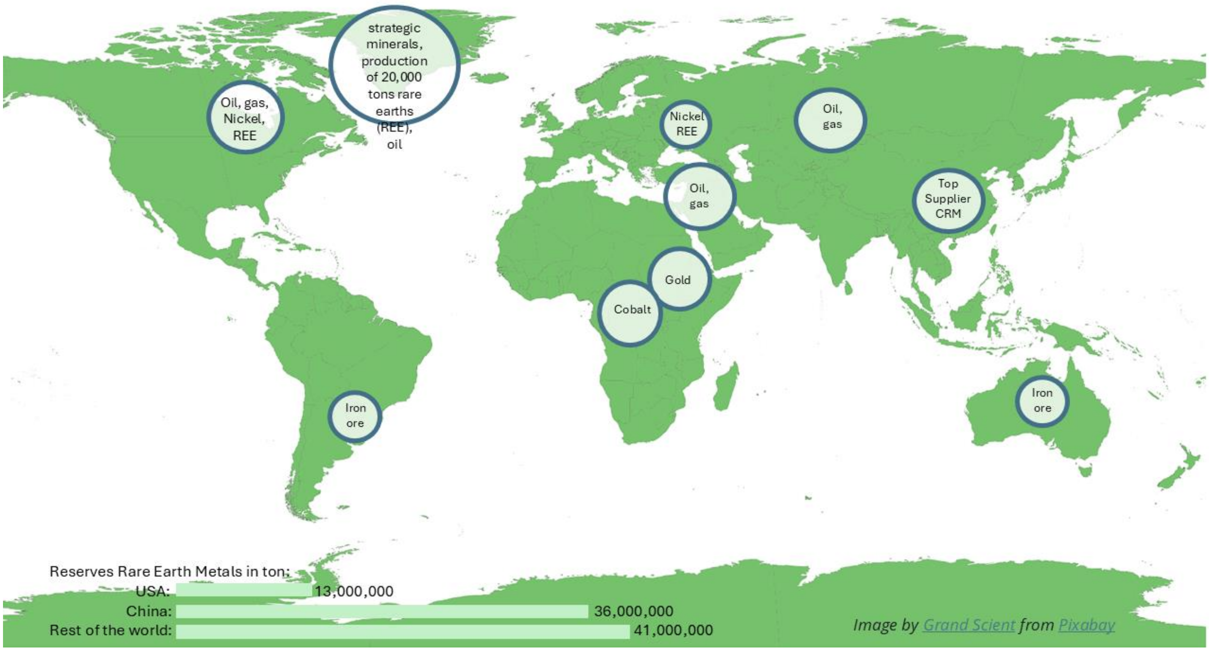

Figure 1. Examples of territories with critical and strategic raw materials

1.3 The essentials of a circular healthcare economy

In life there are only a few fundamental aspects - one of them is to create continuity. Our existence is about what we learn, how we adapt, and how we grow. One of our goals in our individual and collective life is to continue to evolve by learning. After decades of consumption and production of natural resources, we finally learn to understand how we can reuse materials instead of disposing them after use. Our consciousness has developed itself to become aware of the vulnerability of the Earth's natural environment.

The principles of the circular economy is an alternative to the traditional linear economy: the system based on make, use, dispose. The circular economy aims to achieve a 'zero-waste' society, which is no longer generates waste. It aims to keep resources in use again and again: make, use, reuse. The fundamental principal is to recover and regenerate products and materials at the end of each product life.

The circular healthcare economy is a derivative from the circular economy.[17] In healthcare, a circular economy is particularly necessary, as hospitals in the western world have become waste factories. The annual hospital waste production in the US exceeds five million tons per year,[16] or over 13.000 tons of waste every day.

16. Waste. Practice Greenhealth. Accessed on 01 June 2024. Retrieved from https://practicegreenhealth.org/topics/waste/waste-0

17. van Straten, B., Alvino, L., & Horeman, T. (2023). Creating a circular healthcare economy: Circular strategies for sustainable healthcare. Delft University of Technology.

Exploring the circular (healthcare) economy further, we can define its principles from a technical perspective as:

1. Designing products and processes for longevity and reusability

Healthcare is a product- and energy-intensive sector. The healthcare sector in the last decades saw a transformation from reusable devices to single-use devices, so-called disposables. Furthermore, operating rooms and central sterilization and services departments are built as clean room facilities, using large amounts of energy and water. It is necessary to rethink product design for both surgical devices as well as thermal washing machines and autoclaves, so their materials can be (re)used as long as possible, and so that they minimize or reuse waste such as energy or water, as these become increasingly scarce goods.

Essential in the circular healthcare economy is to design products or medical devices so that they have a longer life cycle, can withstand repeated use, and minimize waste. Furthermore, products or medical devices should be designed in a modular way to facilitate easy repair, upgrading, reuse, disassembly and recycling.

2. Resource efficiency of medical devices: efficient use of materials

One of the major problems for the next generations will be the availability of minerals: elements from the periodic table of which there are very few left in the Earth's crust.[6]

From a political point of view, more attention should be paid to this phenomenon if we want to protect coming generations from exhausting these resources.

Optimizing the use of materials to reduce waste and energy consumption during production or during the use phase of a product is therefore, an essential aspect of the circular healthcare economy. Exploring the possibility of using renewable resources and materials is essential.

3. Product life cycle extension

Maintenance and repair are powerful tools in the circular economy. Extending the product life cycle is not only more eco-friendly, it also decreases costs for hospitals.[18] Providing services for maintaining and repairing medical devices as part of standard policy creates a sustainable and cost-reducing organization.

Refurbishing and remanufacturing provide medical devices and equipment is rather difficult in the medical field due to the CE guidelines. Safety certification is expensive and takes a long time to organize. This is an area where policymakers can help to reduce waste by legislation to facilitate refurbishment and remanufacturing.

18. van Straten, B., Dankelman, J., Van der Eijk, A., & Horeman, T. (2021). A Circular Healthcare Economy; a feasibility study to reduce surgical stainless steel waste. Sustainable Production and Consumption, 27, 169-175.

4. Reuse and sharing products and equipment

In contrast to the market mechanisms of the linear economy, the sharing economy posits a change from the ownership of products to renting or leasing products. Product as a Service (PaaS) requires a different mindset; its success depends on the openness of suppliers, users, administrators and managers in hospitals.

5. Recycling and resource recovery

Effective recycling systems in healthcare ensure that medical waste is collected, decontaminated when needed, and recycled into usable materials.

In the healthcare sector, large quantities of waste can be saved from the waste pile or incinerator. Depending on the type of waste, recycling 1 kg of plastic reduces emissions by ca. 3 kg CO_2.[19] Recycling 1 kg of steel reduces emissions by ca. 2 kg CO_2. A positive side effect is that the negative ecological effects like water and air pollution associated with mining elements such as iron ore and oil are prevented.

Ideally, a closed-loop system would create a process where waste materials are reprocessed into new products. An example of such a product is the GO Jack instrument opener, that we made from recycled blue wrap and used in hospitals in the central sterilization and services department. The GO Jack (Figure 1) was made and CE certified as first product in the world made out of hospital waste.[20,21]

19. Pathak, Pankaj & Sharma, Susmita & Ramkrishna, Seeram. (2023). Circular Transformation in Plastic Management Lessen the Carbon Footprint of the Plastic Industry. Materials Today Sustainability. 10.1016/j.mtsust.2023.100365.

20. van Straten, B., van der Heiden, D. R., Robertson, D., Riekwel, C., Jansen, F. W., Van der Elst, M., & Horeman, T. (2021). Surgical waste reprocessing: Injection molding using recycled blue wrapping paper from the operating room. Journal of Cleaner Production, 322, 129121.

21. van Straten, B. (2022). From surgical waste to medical products. Delft University of Technology]. https://doi.org/10.4233/uuid:5fb99bbc-f0c2-4864-b9bf-f7c222631d59

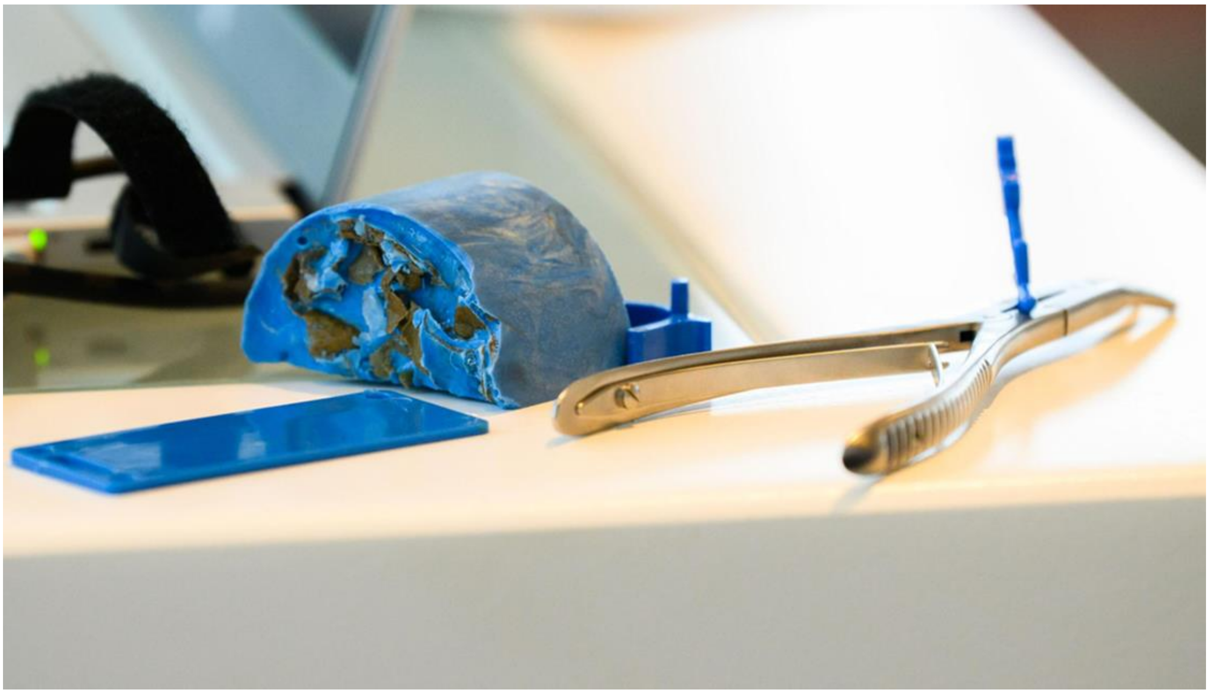

Figure 1. Closed Loop Recycling: GO Jack Instrument Opener made from recycled blue wrap hospital waste and reused as new product in the same hospital.


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6. Systemic perspective: a holistic approach

Systems thinking is an important aspect of the circular economy, not only for designers of new products but also for those who make policies or are active in procurement. This means that one sees the whole picture, holistically, from the beginning of the product life cycle to the end, and considers the entire life cycle of products and systems, recognizing the interconnectedness of economic, environmental and social factors.

Holistic thinking also means acting holistically, in collaboration with multiple stakeholders: designers, manufacturers, buyers, users, researchers and governments, in order to collectively drive circular practices.

7. Policy and regulation

There are few fields where policy is as important as in healthcare. Particularly because guidelines are not always clear about sustainability, reuse and recycling, the efforts of policymakers are necessary to achieve a zero-waste society. Supportive policies and regulations are needed that incentivize circular practices as well as certifications that promote circular economy principles.

8. User engagement and education

Finally, it is very important to properly educate all those involved, not only to implement best practices of the circular economy, but also to learn what is important to them and how to verify whether a product is sustainable.

On the one hand, we need to collect information to determine to what extent products are circular and contribute to reducing waste streams. On the other hand, we need to stimulate behavior that promotes sustainable initiatives and creates circular consumption patterns.

Implementing these essentials requires a comprehensive approach that integrates design innovation, business models, supply chain management and policy frameworks in order to transition towards a sustainable and resilient circular economic system.


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1.4 The circular economy paradox

We find paradoxes in all types of situations, including in claims about sustainability and the application of circular principles - claims made by suppliers and organizations, individuals and institutions. Not all of them will consciously provide incorrect or paradoxical information, although many engage in 'greenwashing': consciously pretending to be greener than one is. However, many people are not aware of the downside that such actions may bring.

Field study

To gain more insight into how businesses, management and policymakers arrive at their decisions – in the context of sustainability – we conducted a study. This was conducted in the form of a survey among healthcare executives, purchasing managers and senior management in the industry. Decision-making can be highly complex in organizational circumstances, as decision-makers are influenced by different, often contradictory interests such as financial limitations, political interests, ethical dilemmas, beliefs, social influences and cognitive factors. It was interesting to explore how sustainability and circular economy factors influence current board and management rooms.

A questionnaire regarding decision-making distributed among 275CEOs and senior managers of medium to large businesses and managers and board members of hospital organizations. The results shows that the following factors are most often considered when making decisions regarding sustainability: financial restrictions are for 43% of influence, organizational objectives 17% and personal interests 7% (Figure 2a).

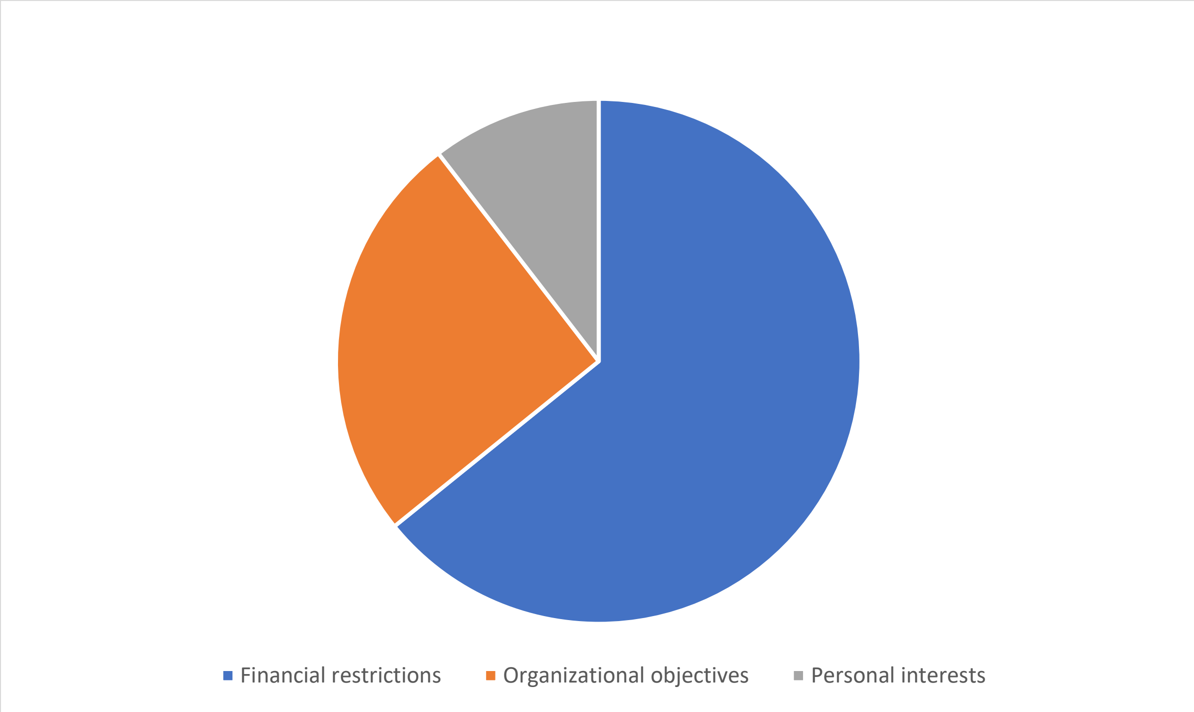

Figure 2a. Factors most considered when making decisions regarding sustainability.

In 60% of cases, organizational objectives appear have the most influence on decision-making in the board room. Personal values are relevant in 20% of cases. In 13% of cases, the expectations of stakeholders or shareholders play a role (Figure 2b). The respondents further reported that their decisions are based on financial results in 47% of the cases and for 53% on political influences and public opinions.

More than half (57%) admitted to have faced internal dilemmas between sustainability, personal values and financial returns. 53% admitted finding it difficult to guard against bias (ignore contrary evidence and seeking data that confirms ones existing beliefs) in decision-making when it comes to sustainability and circular economy principles.

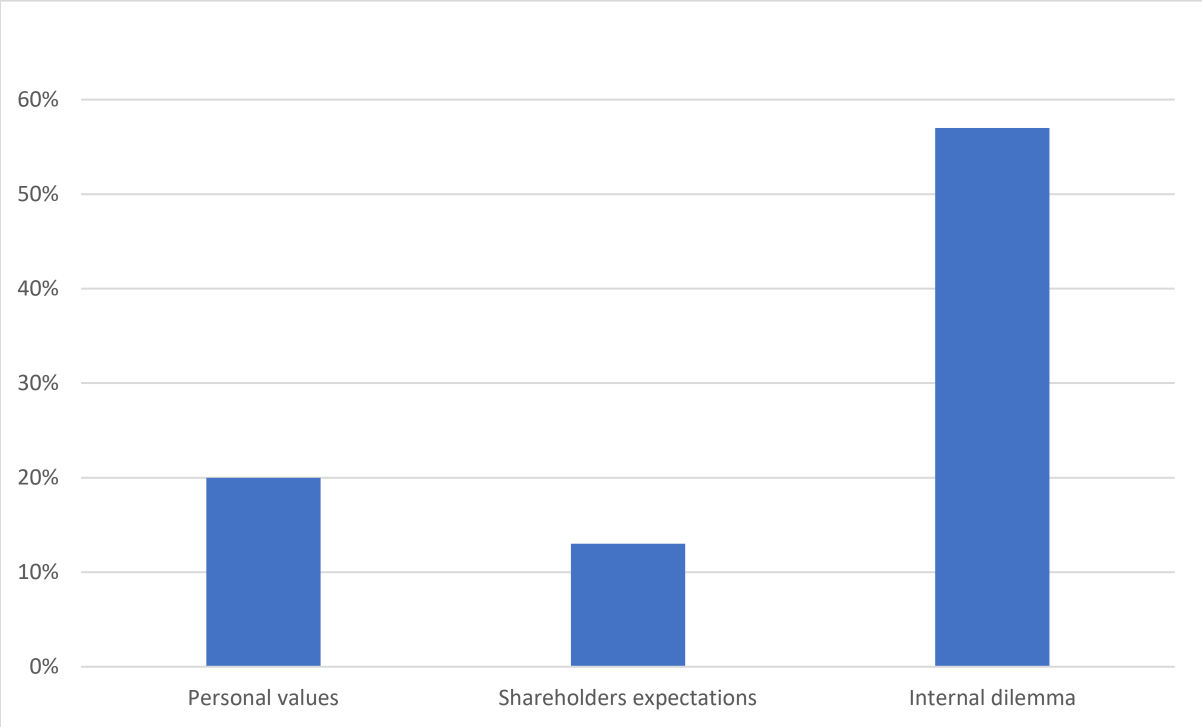

Figure 2b. Personal values, shareholders' expectations and internal dilemmas.

To prevent against bias, the respondents indicated that they ask the opinions of others as primary strategy, followed by gathering data and evaluating consequences in the long term. Conflicting interests are the biggest challenge for making sustainability decisions, due to time pressure; decision-makers often do not get enough time to thoroughly investigate all the options before the decide.

Thus, the important elements in the decision-making process are: financial results, organizational objectives, politics and public opinion. An important aspect is so-called 'confirmation bias'. This means that when we are convinced about a certain mindset, our mind searches for information supporting those beliefs, whether they are true or not.

This tendency to seek validation of our existing views can cloud our judgment, especially in complex fields like sustainability, where data can be interpreted in multiple ways. When such cognitive biases interact with real-world complexity, we often encounter situations that defy our expectations or logic. This brings us to the concept of a paradox—a seemingly contradictory phenomenon that challenges our assumptions and forces us to think more critically.

A paradox may be described as a phenomenon that appears to contradict itself. Paradoxes not only contradict themselves; they also challenge our intellectual capacities, as we realize that a situation is not as it seems or a specific outcome is contradictory to the outcome which is claimed.

Paradoxes in some scientific studies are referred to as revealing complexities, another truth or hidden messages in logical reasoning, language or reality. Although paradoxes intend to create confusion and mislead us, studying and unravelling them may result in increased philosophical knowledge and deeper understanding. Typically, paradoxes present a conflict between different reasons and objectives[22,23] and are defined as 'contradictory with interrelated elements'.[24]

For instance, it may seem sustainable to stimulate electric driving, as it has fewer emissions than fossil fuel cars. However, electric driving also leads to harmful cobalt and lithium mining, as these are needed for battery packs. This may in fact cause more human and ecological damage and increased CO_2 emissions, especially as these materials are shipped to China for further reprocessing. This creates an apparent paradox, which can only be solved by scientific research that shows which type of car is the most sustainable.

Within the medical field, Figure 3 shows a multi stapler which can be powered by hand (left) or by replaceable batterie packs (right). A manual stapler seems the best option to improve sustainability and is cheaper. However, surgeons suggested that the force needed to operate the manually-powered instrument can lead to fatigue and physical injury. Whether this is true or not, this argument keeps the less sustainable and more expensive option in the market. This mindset also hinders attempts to design better manually-operated staplers which need less force.

22. Olin, D. (2014). Paradox. Routledge. https://doi.org/10.4324/9781315710532

23. Hahn, T., Figge, F., Pinkse, J. et al. A Paradox Perspective on Corporate Sustainability: Descriptive, Instrumental, and Normative Aspects. J Bus Ethics 148, 235–248 (2018). https://doi.org/10.1007/s10551-017-3587-2

24. Smith, W. K., & Lewis, M. W. (2011). Toward a theory of paradox: A dynamic equilibrium model of organizing. Academy of management Review, 36(2), 381-403.

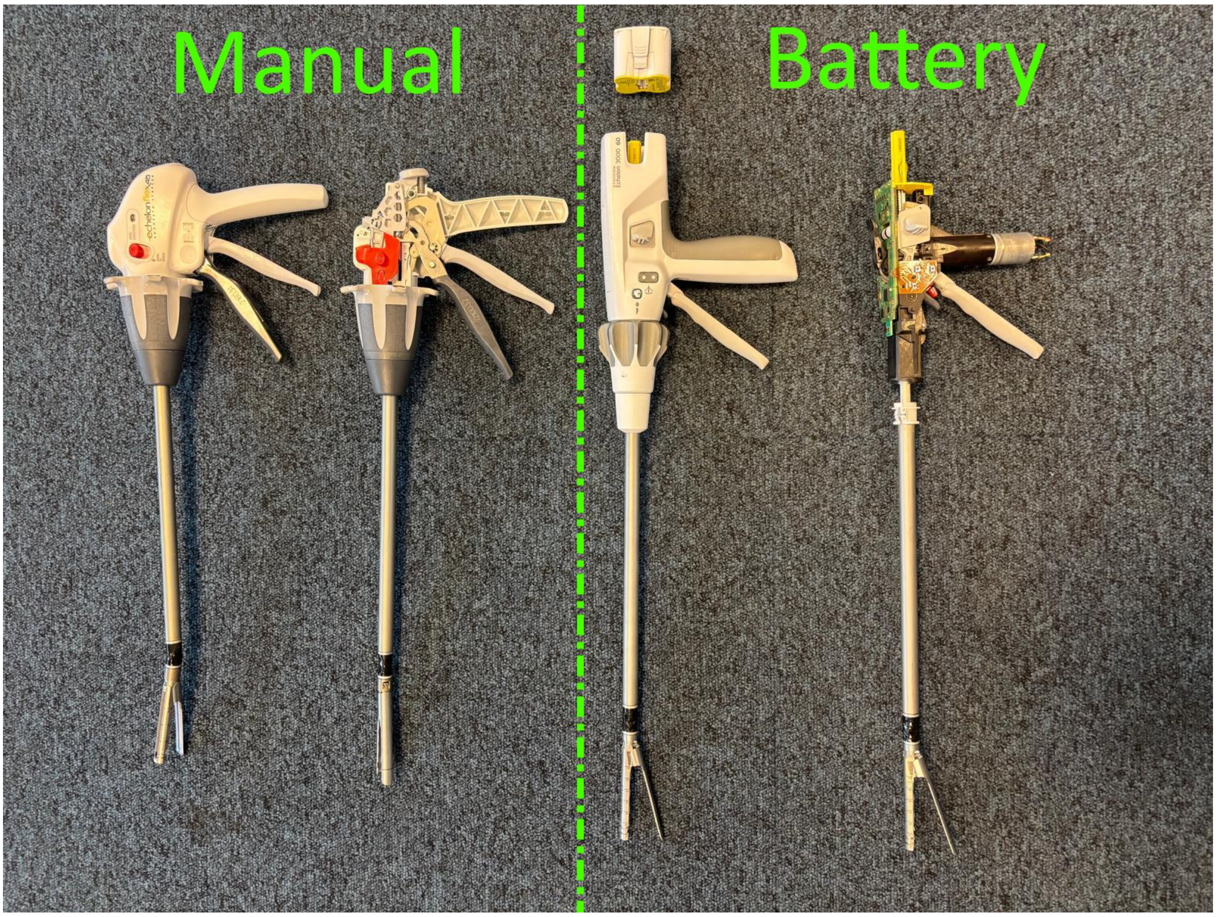

Figure 3. Multi-staplers, whether hand- (left) or battery-powered (right), cause great dilemmas when sustainability is added to the tender. Photo by Rob Dekker.

Therefore, the Circular Economy Paradox maybe regarded as a paradox where certain sustainability and circular economy actions lead to further pollution. This may lead to false conclusions with regard to how sustainable they are. In these cases, further evidence shows that the claim that they lower CO_2 emissions is false. Thus, the circular economy paradox means that specific change cannot be truthfully said to lead to increased sustainability, without leading to a contradiction. This can be explained by several examples.

From a manufacturer perspective

A circular economy business model aims to eliminate waste by designing products and processes which are based on principles such as repairability, reuse, refurbishment, remanufacturing and recycling. However, these principles are sometimes contradictory to a business model in which turnover is based on maximum quantities and low production costs.

Sacrifices have to be made in order to become sustainable and apply circular economy principles. Imagine a manufacturer making high-end, complex surgical instruments. These instruments used to be reusable 50 years ago, but due to product iterations and enhancements, these products have been transformed to single-use with a cost price varying between $500-1500. The manufacturer produces and sells 1 million of these devices annually. A redesign to a sustainable device based on circular principles would mean that the sales of these devices decreases to only 100.000 devices annually.

The paradox is that such an action would have the manufacturer increase its reputation for sustainability, potentially leading to increased customers, but still resulting in a decrease of sales. The paradox is that more demand for sustainable manufacture may lead to contradictive situations where the manufacturers or their shareholders realize that their earnings will decrease as a result of sustainable behavior and therefore actively stop sustainability programs. This paradox challenges our understanding of what it means for a manufacturer and its shareholders to be intrinsically motivated to develop sustainable programs using circular economy principles.

Hahn et al.[13] describe the paradox perspective for corporate sustainability. They conclude that sustainability actions that enable society and the environment to thrive, paradoxically necessitate relinquishing the absolute priority of profitability for businesses. This means that companies have to address the interconnected and often conflicting demands of achieving economic prosperity, environmental health and social equity.

From a material perspective

In pursuit of the green agenda, many initiatives are encouraged and subsidized, such as battery-powered devices and electric products, such as cars. The currently used types of battery, however, require scarce products such as lithium, cobalt, neodymium-iron-boron magnets, dysprosium and terbium. Many of these are mined mostly in the Democratic Republic of Congo using child labor and leading to major impacts on ecosystems. Rather than supporting initiatives to recycle cobalt from batteries, virgin cobalt is mined and sorted with bare hands, leading to potential toxicity effects.

Thus, paradoxically, to reach the ultimate goal of electrifying society, we pollute further by harvesting and consuming scarce rare earth materials. This paradox highlights potential contradictions in making sustainable policies. Which policies seem to stimulate sustainability and which ones create more pollution? Policymakers should therefore always question the final outcomes and end results of their policies. This requires holistic thinking and deep knowledge of all potential consequences of any decision.

From a user perspective

Imagine a hospital that wants to transition from single-use products to reusable products. It's very ambitious and starts a program to stop using disposable stainless steel instruments, disposable laryngoscope blades and disposable gynecology sets. In total 60.000, disposable products are changed to reusable devices. This hospital encounters the problem that more disinfection, cleaning and sterilization is required. This obviously costs more water and energy, but it also requires more capacity, meaning more thermal disinfection machines and autoclaves, as well as more personnel and/or longer working hours. Again, this example shows the paradox that actions to promote the circular economy may lead to less sustainable outcomes.

Thus, we might earn less, pollute more or use more energy even though we aim to follow circular economy principles. In the discussion of the circular economy paradox, we are left with no alternative than to conclude that our actions do matter; they may lead to increased waste, costs and use of energy and water in the short term, but in the long term we must pursue the progress that the circular economy brings. This is central to the philosophy of progressivism, which interprets progress as the set of advancements in technology, science and social organization efficiency. Progressivism is essential part we want to achieve a zero-waste society. Therefore, this paradox should not really be a paradox at all.

The circular economy paradox can be solved by having the correct knowledge and using the correct technology. We can prevent the paradox by gaining experience, gathering knowledge and inventing new technology that promotes circular applications.

An important phenomenon that we must guard against is greenwashing. Since some suppliers want to prevent a decline in their turnover, there will continue to be situations where companies pretend to be greener than they are. Understanding these greenwashing practices requires knowledge as well as a critical attitude.

Philosophically, paradoxes may be thought-provoking; they may reveal deeper truths and logics, forcing us to think more critically and creatively about the nature of reality and knowledge - in particular when judging and evaluating sustainability and circular economy concepts. From the perspective of philosophy, paradoxes help us to better evaluate if a policy, product, service or organization is indeed circular and contributes to lower CO_2 emissions.

A deeper look into the matter

In decision-making, don't take anything for granted. Anyone can tell you a story about sustainability, but is it evidence-based? Is the entire supply and production chain presented? Ask yourself: 'what are the facts and what do they indicate?'

Paradox thinking could be a good tool. First of all, paradoxes force us to critically examine and question our assumptions. They reveal inconsistencies and limitations in our thinking. Paradoxes are valuable tools to use to reveal deeper truths and increase our understanding of complex concepts such as circular economy principles. Secondly, they challenge our knowledge and help us to look differently at a specific concept or theory. They can even lead to a new concept or theory. Paradoxes come in many forms and appear in various fields such as philosophy, mathematics and everyday life. Paradoxes help us to raise questions about the nature of reality, leading to deeper exploration of the concept. Therefore, it is sensible to think about the paradoxes that may lie behind policy and purchasing choices, sustainable product development and circular strategies.

Being critical is important, even essential. On the contrary: not being critical can even be dangerous when it comes to alleged climate-improving products, services or initiatives. With policy choice, therefore, we must challenge our intuitions and force ourselves to revise our understanding of the logic of a specific sustainable action and meaning.

Be aware that paradoxes may lead to cognitive constraints; to a limitation in an individual's mental processes that affects the ability to think, learn, remember or interpret. Sometimes we are so focused on the desired result that we no longer want to see the disadvantages of a particular policy choice or circular product or service. The nature of truth and meaning is essential. Paradoxes challenge the notion of truth and falsehood, suggesting that some statements may be context-dependent or inherently self-contradictory.

Philosophical paradoxes

The philosophical meaning of sustainability and the circular economy involves deeper ethical, moral and existential considerations about how humans interact with the natural world and each other. These concepts challenge us to rethink our economic systems, consumption patterns and responsibilities toward future generations and the planet. Thus, paradoxes like electric cars needing cobalt, lithium and other rare earth materials, may lead us to explore ethical dilemmas and moral reasoning. They challenge our principles about right and wrong.

Sustainability in decision-making requires a holistic view, meaning that all components of a system are included rather than just its individual parts. For example, a company claims to a supply a circular product. We should ask where the basic material comes from, if recycled materials are used, how energy is generated during production, how the product is designed to prevent waste, how it is shipped, if the packaging is made from biobased materials, if the manufacturer will collect the product at the end of life, and how it will reuse the materials to make new products. These answers should be evidence-based: we want to see answers with substantiation, such as a list of composition of materials, also called a bill of materials (BOM), lists with the origin of materials and calculations of transport and CO_2 emissions, so that we can be sure that these products do not come at the expense of environmental degradation.

Sustainability and circular economy principles acknowledge the finite nature of Earth's resources. This should be at the core of every policy, product, service or strategy claiming to be sustainable and fulfilling the demands of the circular economy.

The circular economy challenges the linear 'take-make-dispose' model by promoting the idea that waste can be used as a resource. This philosophical shift encourages seeing materials as part of a continuous cycle. Materials should never be thrown away, but instead always remain in use. This requires a new philosophy in product design: the concept of designing products with infinite life cycles in mind, guaranteeing that they can be reused, repaired, refurbished, remanufactured or recycled at the end of their product life, thus minimizing environmental impact. We will explore this further in chapter 4 'Visualizing the circular economy', using the Butterfly Diagram.[25]

25. Ellen MacArthur Foundation. (2013). Towards the Circular Economy: Economic and business rationale for an accelerated transition. Retrieved from: www.werktrends.nl/app/uploads/2015/06/Rapport_McKinsey-Towards_A_Circular_Economy.pdf

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CIENCE IN WASTE

2

The impact of leadership on policy and best practices

2.1 A circular economy policy agenda

How worried should we be about climate change and its impact on our lives? The circular economy seems to be gaining in popularity. Why is it so prominent in corporate and governmental responses in a world where everything seems to revolve solely around the climate crisis?[12]

The rise in popularity of the circular economy may have several reasons, but these are certainly not universal. Everyone views the circular economy from their own perspective. These motives may not even be of a sustainable nature, but rather serve a revenue model.

An important reason for the growing support of the circular economy is the awareness that Earth's resources are finite. The traditional linear economy (make-use-dispose) depletes natural resources. Furthermore, the circular economy may have economic benefits, since circular economy principles reduce material costs and dependence on raw material imports. Thus, businesses may realize significant cost savings. Efficient use of resources and waste reduction can enhance profitability and competitiveness.

Reducing the amount of waste, less pollution and lower emissions are fundamental and intrinsic motivations for a circular economy. It does mean, however, that manufacturers and suppliers have to invest in eliminating waste through designing products for durability, reusability and recyclability. This reduces the environmental impact of waste disposal and pollution, but it implies redesign costs and lower volumes of sales by decreasing the number of products intended for single use.

A large reduction of greenhouse gas emissions is realized by minimizing resource extraction and processing. Raw materials produced from oil and gas (petrochemicals) form the basic materials for millions of products used on a daily basis. Data from 2021 show that 98% of single-use plastic products were made from fossil fuels and approximately 400 million tons of plastic waste were produced each year.[26]

Policymakers are needed to create a system where raw materials made out of recycled waste streams are cheaper than when they are made from natural resources. Reducing toxic and waste-generating plastics production should be high on their agenda. This means that investors, CEOs, politicians, policymakers, buyers and consumers must take action against current trends to change the vision of society and current (petrochemical) industrial interests.

26. Wakefield, F. (2022). Top 25 recycling facts and statistics for 2022, in. World Economic Forum. Retrieved from: https://www.weforum.org/agenda/2022/06/recycling-global-statistics-facts-plastic-paper/

The impact of leadership is significant and new policies are needed to turn the tide. Leadership helps to shape policy outcomes through vision, decisive decision-making, advocacy and support in the implementation of new policies.

As discussed in the previous chapter, paradoxes can play a significant role in decision-making by challenging assumptions, highlighting the complexities and contradictions of certain policies and situations. Paradoxes force leaders to question their assumptions and consider alternative viewpoints. This can lead to more robust and well-rounded decisions.

Several examples will highlight how leadership impacts policy and strategies positively:

2.2 From a vision to building alliances

1. Vision and direction

Setting priorities: Successful leaders tend to articulate a clear vision and set priorities that guide policy agendas. This vision often reflects their values, beliefs and goals.

Strategic planning: Effective leaders develop strategic plans that outline policy goals, timelines and actions needed to achieve desired outcomes.

2. Decision-making

Influencing choices: Leaders influence policy decisions by weighing options, evaluating evidence and considering the potential impact of different policy choices.

Crisis management: Strong leadership is crucial for making swift and effective policy decisions to address strategic issues.

3. Persuasion and consensus building

Building consensus: Leaders should be persuasive in order to create consensus between all stakeholders and get them to support policy initiatives.

It is best practice to communicate to stakeholders with strong messages to communicate policy ideas, mobilize support and shape the opinion of the public.

4. The power of implementation

Being able to implement: Effective leaders know how to focus on getting the job done. The should ensure that plans do not stay plans but that the necessary human, technical and financial resources are allocated and that there is continuous focus on the implementation.

It is of great importance to establish systems which monitor policy implementation, evaluate outcomes and make adjustments where needed.

5. Ethical and inclusive leadership

Social equity: Leaders committed to ethical principles and inclusivity ensure fair treatment to all, including to the environment, and are transparent about their decisions. This integrity helps to build trust.

6. Innovation

Encouraging innovation: Good leaders create a culture of innovation by encouraging new ideas, technologies and new approaches. This means that an attitude is needed where responses to changing circumstances are quick and are taken with flexibility and resilience.

7. Leadership styles

Be inspiring: Leaders should inspire and motivate, creating common goals based on their vision. A positive attitude can stimulate significant policy changes by fostering a sense of shared purpose and commitment.

8. Building alliances: Leaders who build strong alliances and networks can create more success. Networks provide leaders with access to diverse perspectives and information. Connections helps decision-makers to find additional resources and exchange ideas.

2.3 Balancing between intuition and facts

A good decision-maker finds a balance between intuition and facts. Effective decision-making may be regarded as an optimal mix between an intuitive and an analytical process. McCormack suggests to look around the fringes during decision-making. It's important to look at what the facts indicate about trends, biases, conflicts and opportunities.[27] Good decisions ought to be self-fulfilling: McCormack argues that if you second-guess a decision, you have most likely made a bad one. Not necessarily because it is the wrong decision, but because doubt undermines its success. Another pitfall is not making a decision at all or postponing it for so long that the decision is made too late.

27. McCormack, M. H. (1996). What They Don't Teach You at Harvard Business School about Executive Travel: Hit the Ground Running. NewStar Press.

2.4 Green policies realized in Singapore

An example of how leadership and policymaking can come to visible results can be seen in Singapore. Singapore has formulated and realized comprehensive policies and strategies to promote green architecture as part of its vision to implement a sustainability program. Singapore recognized the importance of sustainable development and implemented steps to realize construction and retrofitting of buildings that are environmentally friendly and energy-efficient. The launch of the BCA Green Mark scheme in Singapore in 2005 initiated Singapore's first Green Building Masterplan. This policy was set up to encourage and engage industry stakeholders to develop new green buildings.[28] In 2018 the Super Low Energy (SLE) Building program was launched in order to stimulate best-in-class in energy efficiency, including the use of renewable energy and intelligent energy management strategies. The target is to make at least 80% of all buildings in Singapore green by 2030.

The photo on the next page shows an example of how this is reflected in the street. Photo by B. van Straten, Singapore, 2023.

28. Singapore Gov. Agency. Green Building Masterplans. (2006). Accessed on 12 August 2024 via: https://www1.bca.gov.sg/buildsg/sustainability/green-building-masterplans


Upp Pickering St
ROYAL COLLECTION

Drawing by Bruno Bruins©, 2024, no further use allowed.

Drawing by Bruno Bruins suggesting that despite the bumpy road, green market approaches may recruit many followers.
no further use allowed

There is a clear connection between leadership and decision-making. Leaders create a vision and formulate strategic goals. Decision-making is the process through which this vision is turned into actionable steps, also called ‘setting direction’.

2.5 Evidence-based decision-making

Data-driven decision-making is the analytical part of decision-making, in which relevant information is gathered, analyzed and processed. This is of great importance in the field of sustainability and circular economy.

There are plenty of opportunities to test and validate decisions. The resources are there, so use them!

Some examples of analytical tools are:

- Life Cycle Assessment – Internationally accepted assessment of climate change impact;[29]
- SWOT analysis – A framework to indicate strengths, weaknesses, opportunities and threats;
- PEST analysis – A method to analyze external factors such as political, economic, social and technological factors;
- Risk assessments/Monte Carlo Simulation – A mathematical technique for modelling of complex situations with numerous variables to predict different outcomes in uncertain scenarios;
- Fishbone Diagram, Ishikawa or Cause and Effect Diagram – A visual tool used to identify, explore and display the possible causes of a specific problem, in order to identify root causes of issues;
- Scenario planning – A method used to create and analyze a set of possible future scenarios, in order to anticipate potential risks and opportunities by considering various possible futures;
- Root Cause Analysis (RCA) – A method of problem-solving used for identifying the root causes of faults or problems, which helps in developing effective solutions by addressing the underlying issues.

29. van Straten, B., Ligtelijn, S., Droog, L. et al. A life cycle assessment of reprocessing face masks during the Covid-19 pandemic. Sci Rep 11, 17680 (2021). https://doi.org/10.1038/s41598-021-97188-5.

Although decision-making is often a balance between intuition and analytics, we must realize that the analytical part is crucial. Evidence-based decision-making involves using data, facts and empirical evidence to steer our decisions, rather than relying solely on our intuition or anecdotal information without support. Taking into account that there are a lot of sustainability claims without factual substantiation such as thorough LCA studies or other calculations. This is especially important since there are paradoxical contradictions in what is sustainable and what is not, and because we are confronted with greenwashing. Using evidence-based decision-making ensures that decisions are more objective and rational, and more likely to lead to positive outcomes. In any case, using common sense is always useful so that we do not blindly rely on others or are seduced by beautiful brochures, but rather ask what substantiation there is to see how sustainability is achieved.

In conclusion, leadership plays a crucial role in shaping, advocating, and implementing policies. The effectiveness of policy outcomes often depends on the vision, decision-making capabilities and leadership styles of those in positions of power. Effective leaders can mobilize support, navigate complex systems, and drive forward policies that address pressing societal challenges.

2.6 Leadership in the context of strategic and critical raw materials

Strategic and critical raw materials, including rare earth metals, are the foundation of nearly all modern technologies—from medical devices and renewable energy systems to advanced electronics and defence and medical applications. Their limited availability, combined with growing geopolitical tensions, trade restrictions, and rising global demand, makes access to these materials not just a matter of resource management, but of strategic foresight and leadership. In a chapter about leadership, it is essential to address this topic because true strategic leadership involves anticipating future challenges, securing supply chains, and making long-term decisions that align with both innovation and sustainability goals. Leaders who understand the strategic importance of critical raw materials are better equipped to guide organizations, industries, or governments in developing resilient, circular strategies that reduce dependency on vulnerable supply chains and enable more sustainable innovation. Incorporating this awareness into leadership ensures that decisions are not only economically sound but also geopolitically and environmentally responsible.

The increased scarcity of resources will become one of the greatest challenges in the coming years. This an important aspect in the climate discussion, which must be included in decision-making. However, it is a very heatedly debated topic, especially because this discussion is ruled by opinions and biased statements; a twilight zone where fact and fiction are mixed up as a result of emotion. It is becoming increasingly difficult and expensive to mine and process raw materials, and it will cost more and more energy. Currently, 2% of all energy on Earth is used to process, crush, grind and separate raw materials in mines.[30]

This is a reason to choose circular principles in our policies, products and strategies. We will have to reuse products and materials; for geopolitical reasons, in order to reduce waste, to protect the Earth and to reduce climate impact.

Several raw materials are considered scarce, strategic or critical due to their limited availability, high demand, the degree of importance to a country, geopolitical factors or environmental concerns associated with their extraction and processing. Some examples of key materials that are currently facing availability issues that are also used in medical applications include:

30. Tim Napier-Munn, Is progress in energy-efficient comminution doomed?, Minerals Engineering, Volume 73, 2015, Pages 1-6, ISSN 0892-6875, https://doi.org/10.1016/j.mineng.2014.06.009. (https://www.sciencedirect.com/science/article/pii/S0892687514002076).

1. Rare Earth Elements (REEs)

Uses: Essential in electronics, renewable energy technologies, and various high-tech applications, as well as surgical applications.

Scarcity Factors: Limited sources, difficult extraction processes, and geopolitical concentration. China, as a raw material hub, controls a significant portion of the market.

2. Lithium

Uses: Critical for batteries, especially in electric vehicles (EVs) and portable electronics.

Scarcity factors: There is increasing demand from the EV market and limited sources. The environmental impacts of extraction are significant.

3. Cobalt

Uses: Used in batteries, particularly in the cathodes of lithium-ion batteries.

Scarcity factors: There is a concentrated supply from the Democratic Republic of the Congo, leading to ethical concerns over mining practices, while rising demand from the tech and automotive industries drives up scarcity.

4. Platinum (group)

Includes: Platinum, palladium, rhodium, ruthenium, iridium, osmium

Uses: Crucial in catalytic converters, electronics and various industrial applications.

Scarcity factors: Limited geographical distribution, high extraction costs, and increasing demand in the automotive sector for catalytic converters.

5. Nickel

Uses: Important for stainless steel production and batteries (especially in EVs).

Scarcity factors: Growing demand from the steel and battery industries. There are environmental concerns over mining practices.

6. Indium

Uses: Used in touchscreens, flat-panel displays and solar panels.

Scarcity factors: Indium is a limited by-product of zinc mining, while there is a high demand for electronic devices.

7. Tantalum

Uses: Used in electronics, particularly capacitors in smartphones and computers.

Scarcity factors: Limited sources; it is often associated with conflict minerals. There is high demand for electronic devices.

8. Tin

Uses: Key in electronics, particularly in solder.

Scarcity factors: Limited mining locations and concerns over sustainable mining practices. There is high demand for electronic devices.

9. Helium

Uses: Essential for medical imaging such as MRI machines, scientific research, and aerospace applications.

Scarcity factors: Limited availability; it is non-renewable and there are challenges in extraction and storage.

10. Phosphorus

Uses: Crucial for fertilizers and agriculture.

Scarcity factors: There are limited geological sources and it is non-renewable. It is essential for global food security.

11. Graphite

Uses: Important for batteries (particularly lithium-ion batteries) and various industrial applications.

Scarcity factors: There are limited high-quality natural sources, while there is growing demand from the battery industry.

12. Certain types of plastics such as polypropylene used for blue wrap for packaging of sterile surgical instruments, face masks, gowns. PET plastic used for packaging of medical devices, ABS plastic used for handles and hand grips of instruments. Although these raw materials are not always scarce, they are critical for medical applications. A period of limited availability such as in the corona period did result in imminent shortages of face masks and blue wrap.

To address the availability of these raw materials, several strategies can and should be employed. This is where sustainable leadership is needed.

The most important strategy in a circular economy is reuse and recycling, which can be applied by enhancing recycling technologies and processes to recover valuable materials from end-of-life products. For example, rare earth materials in surgical devices are hardly recycled; the majority is incinerated. Other strategies include:

- Substitution: developing alternative materials or technologies that can replace scarce materials.
- Efficient use: improving the efficiency of material use in manufacturing and product design.
- Sustainable mining practices: implementing and enforcing sustainable and ethical mining practices to reduce environmental and social impacts.
- Diversifying supply chains: reducing dependence on single-source materials by developing alternative supply sources and improving geopolitical strategies.

The development of such strategies will create a major disruption in the petrochemical industry and industrial sector, but will mitigate the risks associated with raw material scarcity and ensure a more sustainable and resilient supply chain for critical materials. It will reduce dependence on single countries as sources for these materials.

However, the development of new recycling technologies needs to be encouraged. Support by policymakers is needed to make virgin raw materials less attractive by making them more expensive. For instance, it would be helpful to decrease the prices of recycled materials, biomaterials and renewable energies such as hydrogen so they can compete with virgin materials and fossil fuels.

Industry leaders need to tackle the is of critical and strategic raw materials including plastics. Plastic waste streams furthermore, need global attention and should be managed at its root by reducing the global production of toxic and wasteful plastics. Instead, recycled materials should be used in new product designs. This means that sacrifices have to be made in the form of higher investments and engineering costs. While this benefits the environment and society, the initial investment needed to manufacture sustainable products can be a barrier. This is where leadership can make a difference. Thus, it is possible to overcome the paradox that a company wants to become more sustainable by selling products which generate less waste, but cannot afford it because this decreases sales volumes and increases costs.

Leadership, decision-making, experimental handling, and evidence-based working are deeply interconnected, driving innovation through research and collaboration. In this video, Bart van Straten and Tim Horeman demonstrate how these elements combined helped to transform hospital waste into a groundbreaking medical device. Scan the QR code to watch.

https://surfsharekit.nl/objectstore/97f60240-fc28-4af3-8ea5-cb9c609c2f74?utm_source=edusources.nl&utm_content=download


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Swimming against the current: legislation

3.1 A regulatory paradox

Green innovation efforts often encounter a great deal of opposition. Especially in the medical sector, there is legislation that hinders the development of sustainability and a circular healthcare economy.

The term "legislation paradox", also known as the "regulatory paradox" or "compliance paradox", refers to the phenomenon where the introduction of new laws and regulations aimed at addressing a particular issue can sometimes lead to unintended consequences that may exacerbate the original problem or create new issues.

Chen and Li concluded that "a regulatory paradox emerges where environmental policies produce counter-intuitive effects on manufacturers' innovation strategies".[31] Their study explores the paradoxical impact of environmental regulations on green innovation in the manufacturing of energy vehicles. Their findings show that environmental regulations should be calibrated according to the diffusion stages of green innovation, and misaligned stakeholder interests can lead to environmental regulations that inadvertently hinder, rather than promote green innovation efforts.

31. Chen Q, Li C. The Green Paradox in NEV Manufacturing: Regulatory Impacts on Innovation from a Stakeholder Perspective. Energies. 2024; 17(14):3508. https://doi.org/10.3390/en17143508.

Our experiences are consistent with those of Chen and Li. In 2019, the GreenCycl FieldLab was founded by the authors Bart van Straten and Tim Horeman (not Bruno Bruins) together with Joost van der Sijp, MD and Majid El Mortadi. The aim of this field lab was to make healthcare more sustainable. On 17 March 2020, at the outset of the COVID-19 pandemic, I, Bart van Straten, received a call from the director of the Franciscus hospital in Rotterdam and a medical microbiologist. At this time, at the start of the Covid pandemic, there were growing shortages of face masks in hospitals globally. The hospital had run out of protective face masks and there was great concern about sending healthcare professionals into the Covid wards without protection. The microbiologist suggested that the COVID virus possibly could be inactivated on used face masks if they were heated. So, the director of the hospital called us to ask whether we could find a way to heat or sterilize used face masks at a high temperature and test whether the face mask still filtered particles sufficiently.

We, as GreenCycl agreed to explore this and the same evening I drove to the hospital, where people dressed in protective suits and gloves put three large boxes of used face masks in my trunk. The face masks had been worn in the Covid department and the intensive care unit. I drove to the Field Lab where our researchers, also fully dressed in protective clothing, unpacked the boxes of face masks, gloves and hats to sterilize them using steam.

The masks were first heated at 134 degrees and then at 121 degrees. A test setup with particle counters was built in both the Field Lab and at TU Delft to test the face masks after sterilization. We wanted to know whether the face masks still filtered out the Covid virus after it had been sterilized at a high temperature. This way we could determine whether the face mask was still of good enough quality to be used again. We use the following days and nights to build the test setups and perform the tests. In this were helped by Renewi, a waste processing partner who collected medical waste under safe conditions from clinics and brought them to GreenCycl.

The results showed that certain types of face masks were best sterilized at 121 degrees, after which they could be reused five more times. Disposable FFP2 face masks could reprocessed using a method that could be applied in all hospitals, using their available equipment. Each face mask could, moreover, be reprocessed five times without losing filter quality.

We shared our data with the National Institute for Public Health, and published our data so that the rest of the world, also facing shortages, could adopt our methods.[32,33] Our research finding had major impacts, not only for the Franciscus hospital, but also for hospitals around the world who were able to reprocess and reuse their single-use face masks safely using our methods.

We felt we had done some good: protecting international public health by coming up with scientifically substantiated methods for reusing disposable face masks; coming up with new scientific insights. We had invented a method to reduce waste by facilitating reuse and thus achieving CO_2 reduction. We had provided a cost benefit to society because resterilization at the time of Covid was much cheaper than new, scarce face masks, if they were available at all - an apparent contradiction.

32. van Straten, B., Robertson, P. D., Oussoren, H., Espindola, S. P., Ghanbari, E., Dankelman, J., ... & Horeman, T. (2021). Can sterilization of disposable face masks be an alternative for imported face masks? A nationwide field study including 19 sterilization departments and 471 imported brand types during COVID-19 shortages. PLoS One, 16(9), e0257468.

33. De Man, P., van Straten, B., van den Dobbelsteen, J., Van Der Eijk, A., Horeman, T., & Koeleman, H. (2020). Sterilization of disposable face masks by means of standardized dry and steam sterilization processes; an alternative in the fight against mask shortages due to COVID-19. Journal of Hospital Infection, 105(2), 356-357.

3.2 Apparent contradiction: key aspects of the legislation paradox

Let's analyze our methods and actions in the light of legislation and in particular medical regulations.

In the EU there is legislation formulated for the collection, management and disposal of potentially contaminated medical waste from hospitals. The aim of this is to protect public health and the environment; potentially contaminated medical waste must be incinerated. We collected face masks which were used on the Covid and Intensive Care departments, meaning they were classified as hazardous waste. GreenCycl was co-founded by the authors to make healthcare more sustainable. We were surprised by the shortages of face masks during the Covid pandemic.

The Covid pandemic was a time of crisis. The consortium between GreenCycl, TU Delft and Franciscus hospital had only three days before the hospital was out of stock, meaning either their staff would be unable to enter the Covid and IC departments, or they would help patients while being exposed to Covid. In other words, there was no time to investigate which rules and regulations applied, such as the EU Waste Framework Directive (WFD)[34] and the Directive on Hazardous Waste (91/689/EEC).[35] This directive dictates requirements for the handling, storage and disposal of hazardous waste. There is also additional national legislation on Healthcare Waste Management, such as the regulations for the transport of dangerous goods by road (ADR).

The WFD provides rules for labelling, record keeping, monitoring and control obligations. This directive also forbids mixing hazardous waste with other categories of hazardous waste and with non-hazardous waste. On 17 March 2020, we loaded my trunk in the hospital parking lot with cardboard boxes full of used face masks and other items: mixed together, not labelled, no records. I drove my car with dangerous goods straight from the hospital to the Field Lab. In fact, we did everything the law prohibited. In part, this was because we were not aware what was in fact in the regulations and there was no time to check. Naturally, GreenCycl did not possess the relevant permits to reprocess and recycle potentially contaminated face masks, nor did we have an environmental permit.

34. Waste Framework Directive EU 2008/98/EC. (2024). European Commission. Accessed on 24 July 2024: https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en.

35. Council Directive 91/689/EEC of 12 December 1991 on hazardous waste. (1991). European Union. Accessed on 24 July 2024: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A31991L0689.

All these regulations are examples of legislation that serves to protect people, but now they turned out to be a danger to public health. If we had followed the law, we would not have been able to help the world during the Covid pandemic to reprocess face masks in a safe way and thus protect patients and healthcare providers.

This paradox that applies not only to face masks, but to climate goals in general. Because GreenCycl can be seen as an experimental lab, we have been able to gain experience in the context of research, but we have also experienced the obstacles to making healthcare more sustainable. The permit we applied for in 2021 to collect medical waste for recycling in our Field Lab ran up against the same legislation. It would take nine months before we were officially allowed to use medical waste and recycle it. Furthermore, a restriction was imposed on the volume, because experience first had to be gained with small volumes before expanding to larger amounts. Setting up sustainable and circular concepts remains a risky operation in the eyes of many: from legislators and enforcement agencies to banks and investors who think that financing recycling will yield low returns. Still, in our case the regional authorities and enforcement agencies were fully on our side and just as frustrated that the permit process hardly allowed us to set up circular economy activities.

The climate goals, which are anchored in European climate law,[36] require that we reduce greenhouse gas emissions by at least 55% in 2030 compared to 1990 and become climate neutral in 2025. With the current legislation, it is questionable whether these goals can be achieved at all.

36. European Climate Law. (2021). European Union. Accessed on 24 July 2024: https://climate.ec.europa.eu/eu-action/european-climate-law_en

3.3 The paradox

The outcome of these regulations was obviously not anticipated by lawmakers. Politicians, policymakers and legislators should anticipate circular principles and new technologies in order to prevent legislation from lagging behind the facts.

If we want to stimulate start-ups and organizations whose mission is creating a circular economy, we should bear in mind that the cost of compliance can be disproportionately high for smaller entities, potentially slowing down innovation and green initiatives. Although many policymakers do not like exemptions, it may be necessary for this category of businesses to get exemptions, since some regulations may be perceived as overly restrictive or unreasonable.

It is also good to realize that overregulation can lead to greenwashing and violation of the rules. As we previously discussed with regard to the circular economy with the financial paradox, the pressure to achieve financial returns in a commercial organization can sometimes be too great and thus drive managers to decisions that go against laws and regulations.

Take for instance the case of Volkswagen. Regulations to reduce emissions for cars should have led to the development of cleaner technologies. However, the Volkswagen emissions scandal showed that Volkswagen used software to cheat on emissions tests. It was revealed that Volkswagen had installed software in its diesel engines that could detect when the car was undergoing emissions testing and alter the engine's performance to meet regulatory standards; however, under normal driving conditions, the cars emitted up to 40 times the allowed levels of nitrogen oxides (NOx). This led to a major corporate scandal in September 2015, in which the US Environmental Protection Agency (EPA) issued a notice of violation of the Clean Air Act to the Volkswagen Group.

Here too, as in the previous chapter on leadership and decision-making, there is a balance between balanced regulations and law making versus a flexible climate where sustainability can flourish optimally.

Image on the next page by Alexa from Pixabay, VW Beetle, Volkswagen.

3.4 Addressing the legislation paradox: what to do in future decision-making?

It is also important for the legislator to adopt an evidence-based approach when formulating new legislation and regulations. Policymakers should base their decisions on robust data and analysis in order to anticipate potential unintended consequences and design regulations that are effective and efficient. Environmental and social impact assessments are needed to identify potential consequences and scenarios. This requires a holistic view of a complex environment. It also requires engagement with stakeholders, who can provide insights into the practical implications of regulations and help design more balanced and feasible rules.

It is necessary to create and design regulations with built-in flexibility. This allows for adjustments as circumstances change, as in the case of the face mask shortages during Covid. We did what we felt we had to do; we may not have got everything right, but we were driven to find a technical solution to the face mask problem by making it possible to reprocess them. An added benefit was that the particle counter testing method we used to test filter quality led us to simultaneously discover inferior new masks. Face masks were imported from other countries with all the necessary stamps and (CE) quality marks on the packaging, but sometimes it turned out that these new masks did not filter sufficiently and did not meet the Dutch norms. Without our test setup, we would not have discovered this, so that healthcare professionals would have felt they were protected while this was not the case. This also shows how failure to enforce or check imported products can directly damage public health.

With regard to flexibility, periodic reviews of regulations must take place in collaboration with experts from the field in order to re-evaluate legislation and regulations, to ensure that it remains relevant over time.

Conclusion

The development of the circular economy provides complexities and challenges for legislators. Flexibility is needed; some laws and regulations need to be revised in order to be able to reach the set goals of the current climate legislation. Creating effective policy and legislation involves systematic and evidence-based methods. Now more than ever, policymakers will have to collaborate with experts from the field and other stakeholders.

We have to create a vision to redesign society towards the circular economy and we must act from this vision. This means that industry, government, hospitals and universities have to work together to enable large-scale innovation and legal infrastructure to create a new, zero-waste system that can scale up fast.

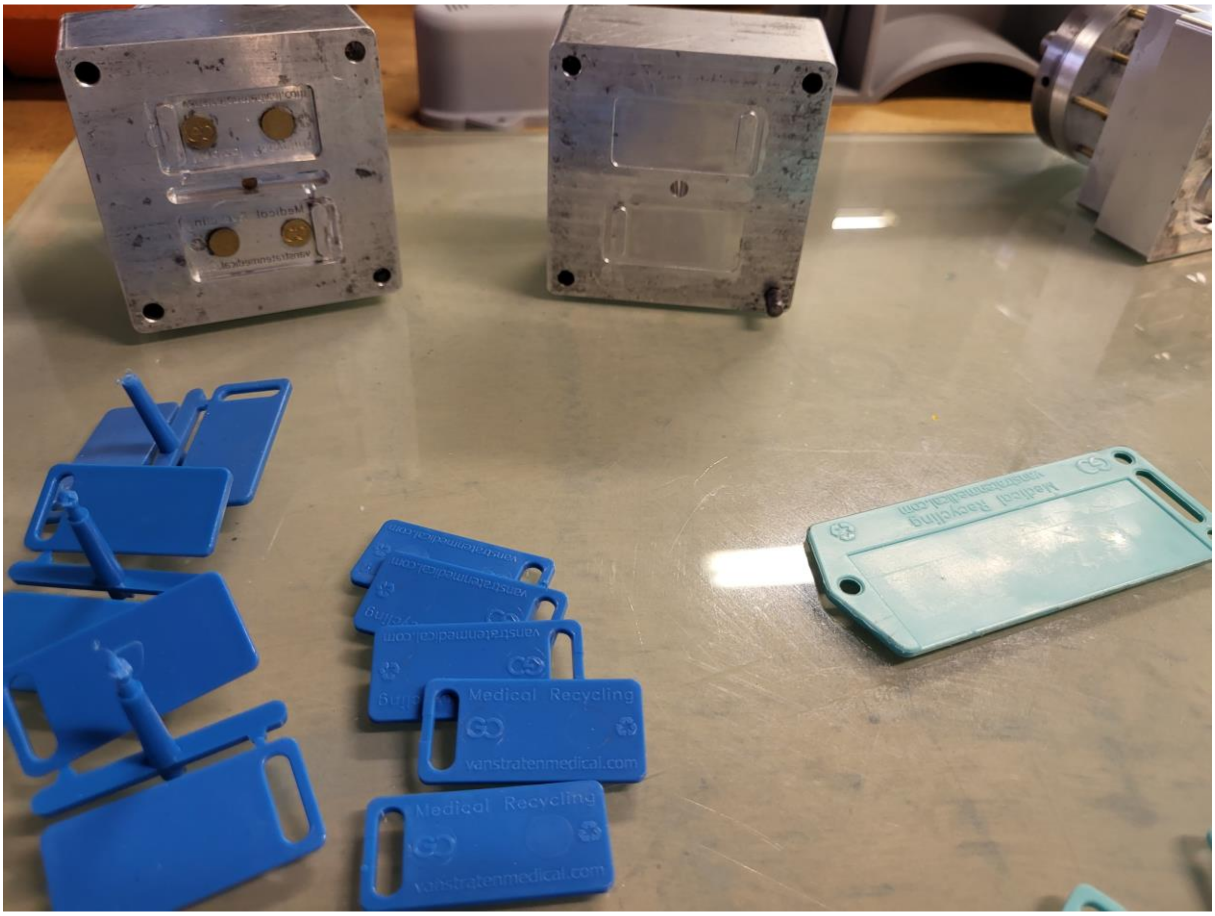
A new day, time for a new law!

Drawing by Bruno Bruins©, 2024, no further use allowed.

Scan the QR code below to watch a video in which Bruno Bruins emphasizes the importance of the circular economy. Therefore, an effective approach is needed from a policy point of view.

https://surfsharekit.nl/objectstore/5a3f1454-38b2-4b5f-bf4a-c9fea2304a81?utm_source=edusources.nl&utm_content=download

The pictures on the next two pages show medical device products which are made from recycled medical waste. Despite the high barrier to recycling medical waste and the testing and production costs for medical approvals to sell these products, it is necessary to take this path. Not only because it is surprisingly easy to come up with new technology that allows us to reuse and recycle more, but also because it makes us much more independent from external producers and suppliers of materials in other countries. Furthermore, apart from the positive impact on the climate, it is cheaper: waste flows are classified as raw materials and the costs of waste processing and rising raw material prices are no longer relevant.



Above: molds made for injection molding set labels out of hospital waste. Left: nail scrapers made out of implant packaging, thus reprocessing disposable packaging waste into reusable medical products. Next page: a collection of products made from various waste streams.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Political Vision as the Cornerstone of a Circular Economy

4.1 A political challenge

The transition to a circular economy is not merely a matter of technological innovation or entrepreneurial willpower—it is, above all, a political challenge. In an era defined by climate disruption, resource scarcity, and mounting waste streams, the urgency for a coherent and long-term political vision has never been greater. Policymakers hold the unique position—and responsibility—to create the legal, fiscal, and societal frameworks that can accelerate the shift from a linear to a circular model. Without their leadership, the system-wide change required to reach a zero-waste society will remain fragmented, slow, and insufficient.

This chapter explores the vision of politics in shaping the transition to circularity. It features the contributions of two politicians who, each in their own way, have placed sustainability and resource efficiency high on the agenda.

Vincent Karremans, who served as State Secretary for Sustainable Healthcare in the Netherlands at the time of writing, offers insight into how government can address the vast resource inefficiencies in the healthcare sector—a sector known both for its essential function and its substantial environmental footprint. His perspective illustrates how targeted policy can not only reduce waste but also safeguard access to critical raw materials and stimulate innovation.

From a European perspective, Wopke Hoekstra, as European Commissioner for Climate and Clean Growth, outlines how the EU's climate policies are increasingly intertwined with circular economy strategies. His vision stresses that climate goals cannot be reached without rethinking how we design, produce, use, and recover resources across all sectors of the economy.

Together, these contributions underscore a vital message: political will and direction are indispensable to overcoming structural barriers and enabling system change. A zero-waste society does not happen by chance—it requires deliberate choices, courageous leadership, and above all, a shared vision for a future in which economic prosperity is decoupled from resource depletion.

4.2 The political vision: a dialogue with Vincent Karremans, State Secretary for Sustainable Healthcare in the Netherlands

When writing this book, we were curious how the Dutch government as well as the European Committee views our methods and the circular economy as a whole. After all, we can only achieve a more sustainable world together, and the government is indispensable when it comes to policy and new technologies. After a visit by State Secretary Karremans to GreenCycl in December 2024, we asked him to give his vision on circular care in an interview followed by the vision of Wopke Hoekstra, as European Commissioner for Climate, Net Zero and Clean Growth in the second von der Leyen commission.

Photo Vincent Karremans by Arenda Oomen, Ministry of Health, Welfare and Sports, The Hague, the Netherlands, 2025. No further use allowed.

Vincent Karremans has been State Secretary responsible for Sustainable Care since 2 July 2024 in the Netherland. In a contribution, in the form of an interview, Vincent gives his vision on sustainable healthcare at a national level including the results he wants to achieve during his term of office?

Mr. Karremans, to my knowledge, 'sustainable healthcare' has never before been explicitly designated as a topic under the responsibility of a Minister of Health, Welfare, and Sport. Why is that?

"Unfortunately, I do not have the honor of being the first; that was Minister Ernst Kuipers. However, that does not matter. The explicit designation of this topic within a minister's portfolio underscores the importance that the government assigns to the issue. Rightly so: with its many buildings, high energy consumption and extensive material use, the healthcare sector has a significant ecological footprint and, therefore, a major responsibility. Healthcare accounts for 7% of all greenhouse gas emissions in the Netherlands and 13% of all waste. The sector recognizes this responsibility and acts accordingly. But as the government and the Ministry of Health, Welfare, and Sport, we must also take action. By focusing on sustainability and reducing waste, we contribute to the affordability of healthcare."

Circularity and sustainability are now crucial themes in policy documents across various departments, such as Infrastructure, Healthcare, and Climate & Green Growth. Is there a shared agenda or a common thread among you and your colleagues?

"Sustainability policy is indeed managed by multiple departments. For example, Minister Hermans (Climate and Green Growth) coordinates climate policy. However, as a cabinet, we are responsible for ensuring that each department contributes to the sustainability agenda.

The sustainable goals for healthcare are set out in the Green Deal Sustainable Healthcare 3.0. Regarding circularity, we are focusing on reusability over disposability and aim for at least a 75% reduction in residual waste by 2030. This is not just an isolated ambition; the Green Deal has been signed by multiple ministries, including Infrastructure and Water Management, Economic Affairs and Green Growth, and Health, Welfare and Sport. This serves as our joint foundation for making healthcare more sustainable.

When it comes to sustainability policies beyond my own department, I ensure that these policies take into account their effects on people's health and the healthcare system. That is my guiding principle."

It is tempting to ask: who really owns the topic of sustainability and circularity? Is it the responsibility of Europe, the national government, or local municipalities? You will probably say: it's all of us. But suppose I am an small or medium business looking to explore sustainability measures for my business operations. Who should I turn to first, and why?

"That depends on the type of company and the approach it wants to take toward sustainability.

If you are specifically aiming to bring sustainable medical products to market, then European regulations come into play. For example, rules regarding the approval of medicines and medical devices. If these products comply with European regulations, they are also permitted in the Netherlands."

As we conduct this interview, we quickly end up discussing responsibilities and regulations. That does not always inspire me. Our new book will be published on TU Delft's open platform and will therefore attract the attention of students. What would you say to students who consider sustainability and circularity important for their future careers?

"You are absolutely right. The disposables culture that has developed is not sustainable. To prevent shortages in healthcare, for example in medical products, we must stop wasting valuable resources. Creative ideas and products are urgently needed to ensure that healthcare remains available, safe and affordable without waste and pollution; also for future generations. So, continue to engage in this cause and challenge potential employers on their sustainability efforts."

And what would you say to students who think sustainability and circularity are just passing trends?

"The finiteness of fossil resources is a fact. We must transition to a society where resources are reusable or renewable. That is a major and far-reaching change. That is why the goals we set extend far into the future: 2030, 2040, 2050. But we must act now to achieve them.

In healthcare, sustainability and circularity are considered highly important, particularly by younger generations. The visibility of hospital waste plays a significant role in this. Hospitals that ignore sustainability already struggle to attract staff. And that makes sense: after all, you choose a career in healthcare to improve people's well-being. It is contradictory if providing care contributes to resource waste, pollution and climate damage that ultimately harm people's health.

Additionally, we see the emergence of Green Teams throughout the healthcare sector. These teams work on making their organizations more sustainable. The movement that has started is very powerful - it can no longer be stopped."

Can we afford this focus on circularity? Shouldn't our economy simply return to prioritizing profit? Healthcare costs in the Netherlands and in other countries continue to rise every year. Many argue that this is unsustainable. If you were to scale back sustainability ambitions, significant cost savings could be achieved, and the public might praise you for it. How do you see this?

"Precisely because of healthcare costs, we must also work on sustainability. Firstly, there is still much to gain in reducing waste within healthcare. This also saves costs. Energy, materials and medication can all be used more sparingly. Every entrepreneur knows that it is essential to critically examine processes and ways of working. There are now many examples and initiatives where healthcare providers analyze their care processes and find ways to make them more sustainable while saving money, and in some cases even labor time. This is a win-win-win situation.

Furthermore, sometimes new technologies and alternative 'sustainable' products are initially more expensive. This is often the case with innovations, as their developers invest considerable time and money. They are entitled to a return on that investment. However, in the long run, sustainability pays for itself.

Finally, we know that doing nothing will ultimately cost us even more - in terms of health, wealth, food and resource availability, and infrastructure. We cannot pass this burden onto future generations. Doing nothing is not an option."

Recently, you paid a working visit to GreenCycl in Utrecht, a company in which all three authors of this book are involved. We saw massive piles of hospital waste and realized that this was just a few days' worth of collection from only a handful of hospitals. You, too, were surprised by the enormous volume of hospital waste. What approach would you take to reduce these mountains of healthcare waste? How? Who should take the lead? What movement is needed, and how do you get this started?

"We all have a role to play in achieving circular healthcare. Within the healthcare sector, a great deal of work is already being done on the ground to make healthcare delivery more sustainable and to reduce waste. It helps when administrators provide their staff with the time and space to engage with this issue. Suppliers, hospitals and healthcare providers must and can tackle this challenge together. The government can provide an additional push.

In the Netherlands, we promote circularity through the National Circular Economy Program and, specifically for healthcare, through the Green Deal. Because the Dutch market is relatively small, we also rely on European collaboration. The Netherlands is actively involved at the European level to make healthcare more sustainable and more circular, with a focus on quality, safety, availability and affordability of care."

Policy, financing, regulation and innovation are key approaches to achieving a circular (healthcare) economy. Various measures can accelerate sustainable healthcare, such as setting a minimum recycling percentage for hospitals, requiring hospitals to procure biobased and circular products, reducing waste streams, expediting permits, and ensuring sufficient energy supply for circular initiatives. Do you believe these are initiatives that should be politically regulated, or do you see other priorities? If so, which ones? How can we demonstrate to the world that the Netherlands, just as with water management, is at the forefront of using technology and the latest insights to make hospital waste reusable?

"In the Green Deal, agreements have been made between all relevant parties. The Green Deal helps align everyone's efforts. As a government, our role within the Green Deal is primarily to facilitate: we subsidize research and innovation projects focused on sustainability, ensure the monitoring of progress and results, and promote knowledge exchange.

Additionally, I believe it is important for the government to create space within legislation and regulations to support sustainability. Since January 2025, for example, the rules on reprocessing single-use medical devices have been relaxed. This means that, under certain conditions, healthcare institutions themselves may now reprocess and reuse single-use medical devices. Previously, this was only allowed under the regulations applicable to manufacturers.

Where necessary, relaxed regulations can provide an extra push toward sustainability. Consider, for example, the proposed Extended Producer Responsibility for diapers and incontinence materials. This policy sets specific recycling targets for these products."

Suppose you were to outline a pathway for an impactful circularity initiative. What would it look like? Which stakeholders should be involved, and at what stage of the transition? What do you see as the responsibilities of the stakeholders, and what should not be their responsibility?

"That is a great question, and I have commissioned research on this topic. The conclusion was that diapers and incontinence products have the highest potential in a government strategy for circular healthcare. Washable incontinence products can significantly reduce healthcare-related waste, since disposable incontinence products generate 85 million kilos of waste annually. That is why I am funding a pilot project for washable incontinence products in healthcare institutions.

The most critical step comes later, when the initiative proves successful, and upscaling becomes the next challenge. Such a transition demands a great deal from an organization: incontinence products must be collected separately, washed and returned to the correct patient. Perhaps schedules for changing materials will need to be adjusted. In this phase, it is incredibly helpful if those involved in the initial pilot - ranging from suppliers to users - share their experiences with other interested parties. This is something we can facilitate."

The initiators of GreenCycl – and others – argue that universities in the Netherlands are not sufficiently involved in the transition to a more sustainable healthcare system. Yet these institutions possess the knowledge needed to develop and implement new processes and technologies. What is your stance on this?

"Knowledge and research play a crucial role in the transition to a more sustainable healthcare system. This is especially true because there is still much that we do not know: what are viable sustainable alternatives? Where are the opportunities for sustainability? Universities play an essential role in answering these questions. Through the Dutch Federation of University Medical Centers, the medical faculties of universities are already connected to the Green Deal. However, further collaboration between universities to make healthcare more sustainable is certainly desirable. The importance of innovation for sustainability is undeniable."

Naturally, we also ask ourselves how we can reduce the massive amounts of waste, not only in healthcare but in general. We see significant potential in reuse and, ideally, in using fewer materials altogether. At TU Delft, our courses frequently address responsible material usage. Experience shows that students are creative and embrace 'resource efficiency' as added value for future medical instruments. How, as State Secretary for Sustainable Healthcare, do you encourage tomorrow's students?

"This is a specific theme within the Green Deal: knowledge and awareness. I want to ensure that we collectively develop new ideas and knowledge about sustainability. We do this through the Knowledge and Innovation Covenant, which fosters collaboration between businesses and the government. Additionally, through Health Holland, we stimulate innovative research in the Dutch Life Sciences and Health sector.

We need all the expertise available in the Netherlands to transition to a more sustainable healthcare system while keeping care affordable for future generations. Cost-saving techniques are therefore highly welcome. TU Delft students will play a key role in making this possible."

As we review our notes from this conversation, we notice that the patient -the citizen - is somewhat absent from the discussion. Do citizens have a role or responsibility in promoting sustainable healthcare? If so, what role?

"Citizens have the right to affordable, high-quality healthcare. When you need care, you already have enough on your mind, and you may not always want or be able to consider whether the care you receive is sustainable. I do not expect people to take on that responsibility.

However, citizens can certainly contribute by thinking critically and asking questions, whether out of personal conviction or curiosity. They may see opportunities that a healthcare provider has not yet considered or question certain processes in ways that lead to improvements.

What I find important is that the healthcare system should enable people to make more sustainable choices if they wish to and where possible. At present, this is only an option in some cases. For example, asthma and COPD treatments can be administered with two types of inhalers: one that releases a high level of greenhouse gases and another that does not. From the patient's perspective, both function similarly. But making an informed choice requires substantial knowledge. That is why I believe it is essential for healthcare organizations and professionals to critically evaluate their processes and explore where sustainability improvements can be made."

We are conducting this interview at the beginning of 2025, the first year in which large companies are required to report on circularity and sustainability in their annual reports according to the EU directive Corporate Sustainability Reporting Directive (CSRD). This requirement includes a standardized reporting method, which makes sustainability progress more transparent. The number of companies subject to this reporting obligation will expand in the coming years. At your department, these annual reports will likely be reviewed, at least the sustainability sections. Do you plan to use this information for future policy? Do you foresee debates in Parliament about these reports?

"Foundations are exempt from the CSRD. As a result, this obligation currently applies to only about 45 hospitals, mental health institutions and nursing homes that operate as private limited companies in the Dutch healthcare sector. For foundations, reporting remains voluntary, as we want to limit the administrative burden on the sector.

I will read these reports with great interest. However, I cannot yet predict how they will influence policy, as this reporting requirement is still new and currently applies to only a small group of institutions."

Developments in circularity and sustainability are progressing rapidly. For that reason, we expect our book to require a new edition soon, incorporating the latest insights. If we were to interview you again for the next edition and ask what achievement you look back on with satisfaction and pride, what would your answer be?

"I would be satisfied if the healthcare sector would be on track to achieve the Green Deal targets - 75% less residual waste and 50% less primary raw material consumption by 2030, with a 25% reduction in residual waste by 2026.

The mountain of waste can and must be significantly reduced. I am convinced that achieving this goal would not only benefit the environment but also generate financial savings."


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4.3 The political vision: a dialogue with Wopke Hoekstra, EU Commissioner Climate, Net Zero and Clean Growth in the EU

For this book commissioner Hoekstra expressed his vision on sustainable healthcare. Wopke Hoekstra, European Commissioner for Climate, Net Zero and Clean Growth, plays a central role in shaping the European Union's policies aimed at achieving climate neutrality and strengthening sustainability across all sectors, including healthcare. By aligning sustainable healthcare initiatives with European climate policy, Hoekstra emphasizes the importance of systemic change in healthcare to reduce environmental impact, secure access to critical raw materials, and protect the health of future generations.

Wopke Hoekstra, ENVI meeting, European Parliament, Photographer: Philippe Buissin, EP 2025. No further use allowed.

Mr Hoekstra, you were previously Minister for Finance and Minister for Foreign Affairs in The Netherlands. Does your current position, as Commissioner for Climate, Net Zero and Clean Growth, rely more on funding or more on cooperation between EU countries? Why?

"From a European perspective, it is important for us to work well together and cooperate effectively. We rely on national governments and the private sector to drive investments in the clean transition, and we use our more limited financial resources to crowd in this money, often by providing guarantees and derisking.

Our Innovation Fund is a good example of how we try and make impactful investments in new technologies, using revenues from our emissions trading system. In this way we create a virtuous circle where polluters pay for the development of new technologies. Investment is truly at the heart of our current climate policy agenda. We need to help our industry deliver on our clean transition targets.

We have adopted the Clean Industrial Deal, which is our business plan to make this happen, and we have complemented it with a Savings and Investment Union Plan. The next big milestone will be our new long-term budget, known as the Multiannual Financial Framework. The Commission made a proposal for spendings from 2028 to 2034. The EU must maximise the impact of every euro it spends."

The growth of the EU economy is by no means a small matter. How do your colleagues look at your ambitious plans? Do they find your policy difficult or encouraging? Why?

"Economic growth is essential for the European Union. It pays for everything we want to have and find meaningful. We are all too aware that our slow economic growth, our dependencies and the fragmented market we still operate in are increasingly a problem, particularly against a backdrop of volatile geopolitics.

The Clean Industrial Deal is a game-changer for Europe's economy. It is a business plan to truly re-industrialise our European Union. It will drive competitiveness, boost our strategic independence and accelerate climate action. Ideally, it brings all those three elements closer together. I am confident that this is the way forward."

This question would also be addressed to your Dutch national: to whom belongs the topic of sustainability and circularity now? Is it a European matter or primarily a national one? Imagine, I am an SME in the Netherlands, and I want to focus on sustainability measures for my business. If so, do I first look at the authorities in NL or just about the EU? Why?

"In the EU, we have the potential to become world champion on circularity. It is a business and climate opportunity. The natural resources our continent has are wind, water and sun. Therefore, in the light of the current geopolitical unrest in the world, we need to become independent from foreign actors. And circularity can help with this.

The European single market is one of the greatest tools that our companies can benefit from, so I would encourage them to look across Europe for opportunities and partners. At the same time, businesses need to start local and understand the environmental impact and regulations which concern them at the local level, from permitting and safety rules to waste management and the sustainability of their premises. And then, we have a great track record of exporting our products and services around the world, so why stop at the European border? The Clean Industrial Deal aims to keep Europe as an attractive hub for traditional industries, accelerating new clean technologies and circular business models that can compete worldwide."

This interview is part of a book published on TU Delft's open platform. But expect many students to get this text in touch. What is your message for (these) students?

"We need the next generation. This is the generation that will experience more climate change than any other in human history. In the last few years, we have seen the physical and economic harm of extreme weather events in Europe and around the world. We need to build a society that can adapt and be resilient to these changes. When I say that we need the students reading this message, I mean that we need their creativity, their innovation, their skills, and their engagement. Every generation faces its own unique challenges. The generation that will emerge from our schools and universities in the next few years will have the challenge of building a completely new industrial and economic model in Europe. They will have a mission to decarbonise, to make better use of resources, and to make this new business model both profitable and exportable. It's a tough ask, but they can do it.

A significant proportion of the TU Delft students will choose a job in business or science. You are developing the Clean Industrial Deal and the Industrial Decarbonisation Accelerator Act. What you can tell about these developments – from the perspective of students preparing for the labour market.

The future is Europe. We have seen that the United States has been a magnet for entrepreneurs, researchers, investors and businesses. Part of that was about finance and risk-taking, but it was also about political stability, a commitment to science, and a desire to work openly with the rest of the world. Some of these pillars are being called into question across the Atlantic, but not here in Europe. That gives us an advantage. We welcome scientists with open arms. We are the safe choice for many innovators and investors now. We need to double down on innovation and on the Capital Market Union.

We are investing in innovative clean technologies, and the decarbonisation of older heavy industries. Your students will find a world of opportunities in front of them if they can develop the skills to thrive in this clean economy that we are building."

If we ask you whether climate and green growth are a "hype" in international public policy or a "stayer", you probably choose the latter. But can we afford this focus on green growth, should we not focus on European manufacturing? And give that the top priority?

"For too long, we've been one dimensional in how we approached the climate question. We're now in a different world. And to go forward, we're going all in on decarbonisation, using it as a strategic opportunity to cut emissions while growing our GDP.

As we accelerate our climate efforts, it's essential that we bring European businesses along with us. Given the uncertainties and challenges we are facing globally, it is natural to feel like we could be standing at a crossroads. But for Europe, the path ahead is clear. We will re-industrialise our economy and we will do so in the European way. We will be investing in the technologies and energies that will power a cleaner, more competitive and self-sufficient future."

The authors of the book where this interview appears are involved in a company recycling hospital waste. Care is responsible for a huge amount of waste. Do you see any reason to use certain sectors at European level, such as health care, to contribute to climate action?

"We are entering a phase in the transition where everybody will have a role to play. It is fair to say that in the first years of our climate action we have been tackling some of the 'low hanging fruit' and reducing emissions where it was 'easier' to do so – for example replacing fossil fuels with renewable energy in our power systems, improving energy efficiency in products and industrial processes, or starting the shift towards electric vehicles.

But to reach climate neutrality by 2050 every sector of our economy will need to contribute, and healthcare is no exception. Waste is a critical area. We are doing quite well in terms of the 'end of life' part, with more and more awareness that we need to separate waste for recycling and disposal. What we need to focus on more is the upstream part – and designing products which are better able to be re-used, repaired or recycled. For health and safety reasons there are of course a lot of single use products in healthcare, but there is definitely scope for more innovation and circularity."

Your mission, as formulated on the EU website, focuses on policy measures. Citizens/voters/consumers do not appear in the contract. That cannot be the intention? What can people do themselves?

"My Mission Letter, which is a sophisticated version of a to-do list if you will, is very clear: citizens are at the heart of our work. It says that "we will respond to the real and legitimate concerns and expectations that Europeans expressed at the last elections. We will be closer to people and businesses where it really matters". We are committed to be more present 'on the ground' across all EU regions, giving more visibility to EU projects, and engaging in a deeper and more regular dialogue with citizens, in particular young people.

I have already held my first 'Youth Dialogue' to discuss my policy priorities. There is of course plenty of scope for people to adopt more sustainable practices in their daily lives too, whether it is at home, at school or university, or in the workplace. We all have a role to play, but we also need systemic change. We are all part of the solution, but we need the framework, choices and tools to act."

What do you think of the fact that instruments such as CSRD reporting contain very many regulations, and that this is not conducive to raising the level of business enthusiasm for sustainability?

"This Commission is making it simpler to do business in Europe because complexity and red tape are serious obstacles to innovation and progress. Our goal is to help companies reduce their carbon footprint without putting them at a competitive disadvantage. The Commission's recent proposals to simplify the CSRD will reduce complexity of EU requirements for all businesses, notably small and medium enterprises (SMEs) and small mid-caps (SMCs). They will focus our regulatory framework on the largest companies which are likely to have a bigger impact on the climate and the environment, while still enabling companies to access sustainable finance for their clean transition.

Finally, a look in the future. If we create a new edition of our book in a few years, what success of your policy would you like to have appointed? Of course, we hope for an answer that will help our students to work.

It's essential for our industry to achieve decarbonization without sacrificing economic growth. I hope for a cleaner and more prosperous Europe—a place where we want to live and that we can proudly pass on to current and future students who read this book."

Part II

Circular design principles

5

Visualizing the Circular Economy

Visualizing helps us to learn to understand complex theories and concepts. It transforms information into visuals to give us an instant overview to understand and remember particular theories and approaches. Tools such as infographics, charts, diagrams, graphs and drawings may show relationships, inputs, outputs and other variables which our brain finds easier to process in this way. Visual tools may also be regarded as storytelling, since they guide us through the information - like a basic roadmap that you can apply to different situations. As discussed earlier, it is important not only to be able to think analytically but also to have the necessary flexibility, especially in the case of complex developments such as the circular economy. Innovation, new developments and trends, technology, changing legislation and public opinions make this a complex environment. In this chapter we discuss visualizations and models that you apply to various scenarios and use for problem-solving. For example, we will discuss the Butterfly Diagram,[15] in which the loops of the model can be interpreted as strategies: strategies that can be applied in circular product design, vision and strategy formulation, policy design and the design of services that help keep materials in use instead of taking them to landfill or incinerating them.

5.1 A visual representation of the circular economy

Visualization of the circular economy might be helpful to guide our brains into understanding and rationalize the theory with the help of visual tools.

A visual representation is therefore, to be found on the next page.


Resource extraction
Waste is minimized and resources are used again and again.
Production
Consumption
Waste collection
Recycling
re-use

5.2 The linear economy

To understand and visualize the circular economy, we first need to discuss the linear economy. The linear and circular economy models represent two fundamentally different views on production and consumption. The global growth of human population in combination with the rise of single-use products, also called disposables, has led to a dramatic increase in production and consumption of natural resources. In the period after the Second World War, the world faced a growing global market with increased business opportunities. Businesses flourished and saw their sales growing as market demand was increasing rapidly. Manufacturers focused on mass production. Product designers engineered their products in such a way that they could be manufactured in large numbers. Low-income countries with low-cost labor were used to manufacture products at lower costs and in greater volumes. The linear economy emerged, which be characterized by a linear process: extracting raw natural resources, making products, using them and disposing them after use (take, make, use, dispose). This economy caused globalization and was characterized by significant economic growth and growth of waste production. It also led to the era of trade liberalization, technological advancements, the rise of multinational corporations and global financial institutions, the emergence of new economic powers, the expansion of natural resource extraction and interdependence of countries.

5.3 The circular economy

The circular economy is a completely opposite system. It aims to design out waste, instead focusing on the continual use of resources and renewable energy. This economy is based on the fundamental philosophy of designing circular products, using and re-using them. The circular economy may be regarded as a closed-loop system in which products, materials and resources are maintained in the economy for as long as possible, extracting the maximum value from them. Products and materials are recovered and regenerated after use in order to bring them back into circulation as new products.

Thus, it is based on three fundamental principles: reduce, reuse, recycle, known as the three R's. These three powerful and well-known words go back to the 1970s. They remain the key strategy in promoting sustainable living, waste reduction and resource conservation, and remain highly relevant in the context of the circular economy. This economy pursues a 'zero-waste society'. On the next page, a photo shows the mantra of the circular economy painted on a wall in Bali, Indonesia. The circular economy is especially relevant in Indonesia, as the country is struggling with massive waste shipments from the western world which are dumped locally.


ampah
3R
Reduce
Reuse
Recycle

Figure 4 shows a graphical representation of the linear versus the circular economy. Depicted on the left is the linear economy, in which depreciation of products and materials takes place as the column moves downwards. After throwing them away, there is no value left. This is in contrast to the circular economy, in which products and materials are used again and again to prevent waste. Their value is retained and CO_2 emissions are reduced, compared to the linear economy.

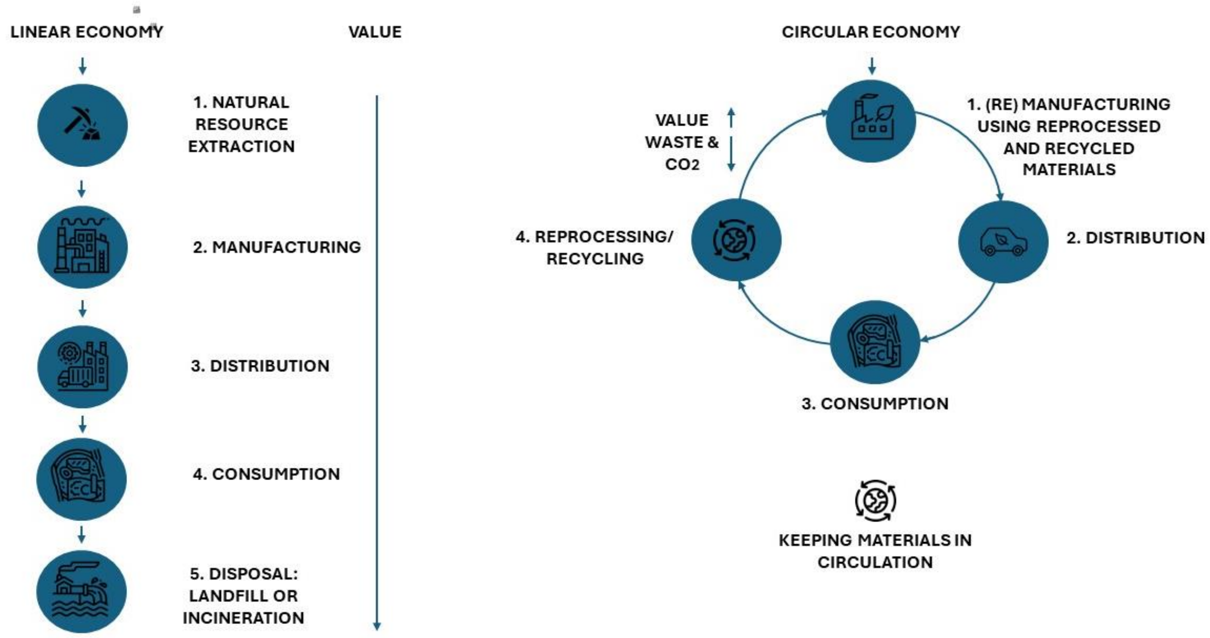


Figure 4. Linear economy with waste disposal versus circular economy where waste is prevented by keeping materials in circulation. Illustration by B. van Straten.

In the circular economy, after consumption, the product is collected and returned to the system through various strategies and options, such as biological regeneration, repair, maintenance, reuse of materials, refurbishment, remanufacturing or recycling.

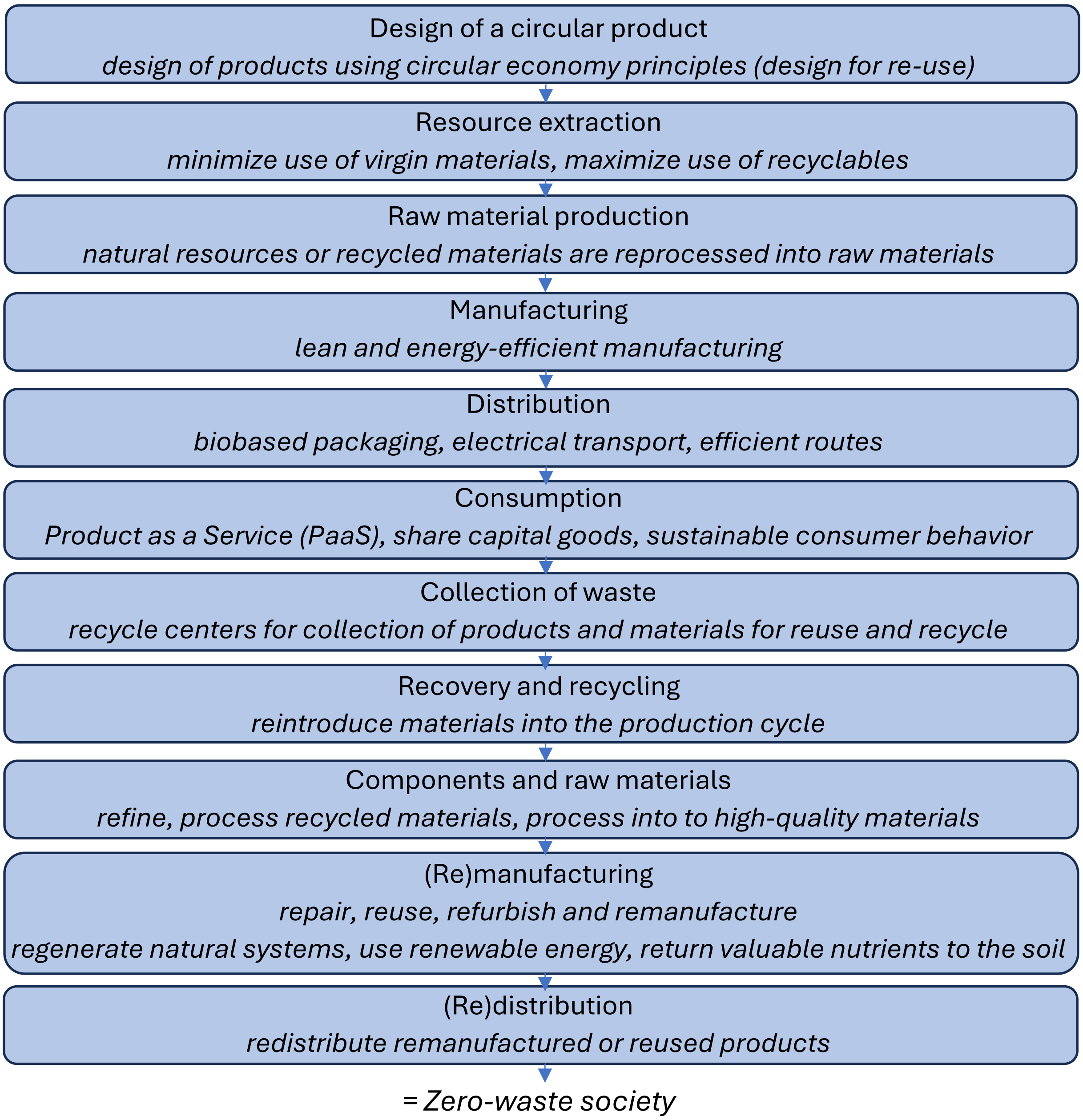
The visual on the next page shows used surgical instruments which have been repaired to ‘newly manufactured condition’. A large hospital usually has more than 100.000 instruments in circulation, which are used on a daily basis under harsh conditions. Replacing an instrument after it becomes blunt, bent or broken means high replacement costs. It also requires new surgical steel, made out of alloys consisting of multiple metals, some of which are getting scarcer. Repair is a circular strategy which lowers costs, reduces waste streams of broken instruments and relieves pressure on the Earth’s natural resources.


LAWTON 30-0060

The image below shows surgical instruments which are disposable. This means that they are made out of surgical steel and intended to be used only once, after which they are disposed of and incinerated. Scarce raw materials are burned in this way, while the quality of the steel would have allowed many uses. Some hospitals are known to through away over 50.000 surgical steel instruments per year after only one time of use. The costs of continuously buying single-use steel instruments is enormous, as are the waste processing costs. The cost of the greenhouse gas emissions and the effect on the well-being of those living near incineration facilities cannot be calculated.

5.4 The flow of materials and resources

The circular economy can be visualized by illustrating the flow of materials and resources through a system that prioritizes the reduce – reuse – recycle model over the traditional linear economy model. Below, a flow chart illustrates the circular economy.



5.5 The Ellen MacArthur Foundation

The Ellen MacArthur Foundation[37] published its model for visualizing the circular economy in 2019.[25] This model of the circular economy system diagram, known as the butterfly diagram and perhaps to be considered as a successor to Braungart & McDonough's Cradle 2 Cradle model (Figure 4), as it illustrates the continuous flow of materials in the circular economy.[38,39] There are two main cycles: the technical cycle and the biological cycle. In the technical cycle, products and materials are kept in circulation through processes such as reuse, repair, remanufacture and recycling. In the biological cycle, the nutrients from biodegradable materials are returned to the Earth to regenerate nature.

37. Visualising the Circular Economy. (2019). Ellen MacArthur Foundation. Accessed on 25 July 2024: https://www.ellenmacarthurfoundation.org/circular-economy-diagram.

38. McDonough, W., Braungart, M., Anastas, P. T., & Zimmerman, J. B. (2003). Applying the principles of green engineering to cradle-to-cradle design. Environmental science & technology, 37(23), 434A-441A.

39. Braungart, M., & McDonough, W. (2009). Cradle to cradle. Random House. Accessed on 25 July 2024: https://books.google.nl/books?hl=nl&lr=&id=13hfHzBstcEC&oi=fnd&pg=PT2&dq=Cradle+2+Cradle.+Braungart+%26+McDonough+&ots=IeoVaOuOZC&sig=erLMlgYxZew3q5e_HxsSuXlS5Ss.

5.6 The Butterfly Diagram

We have already discussed this diagram in detail in our previous book *Creating a Circular Healthcare*,[17] where we discussed the circular principles can be applied to policy choices, strategy formation and product design choices. We will briefly discuss this diagram in Figure 5 here.

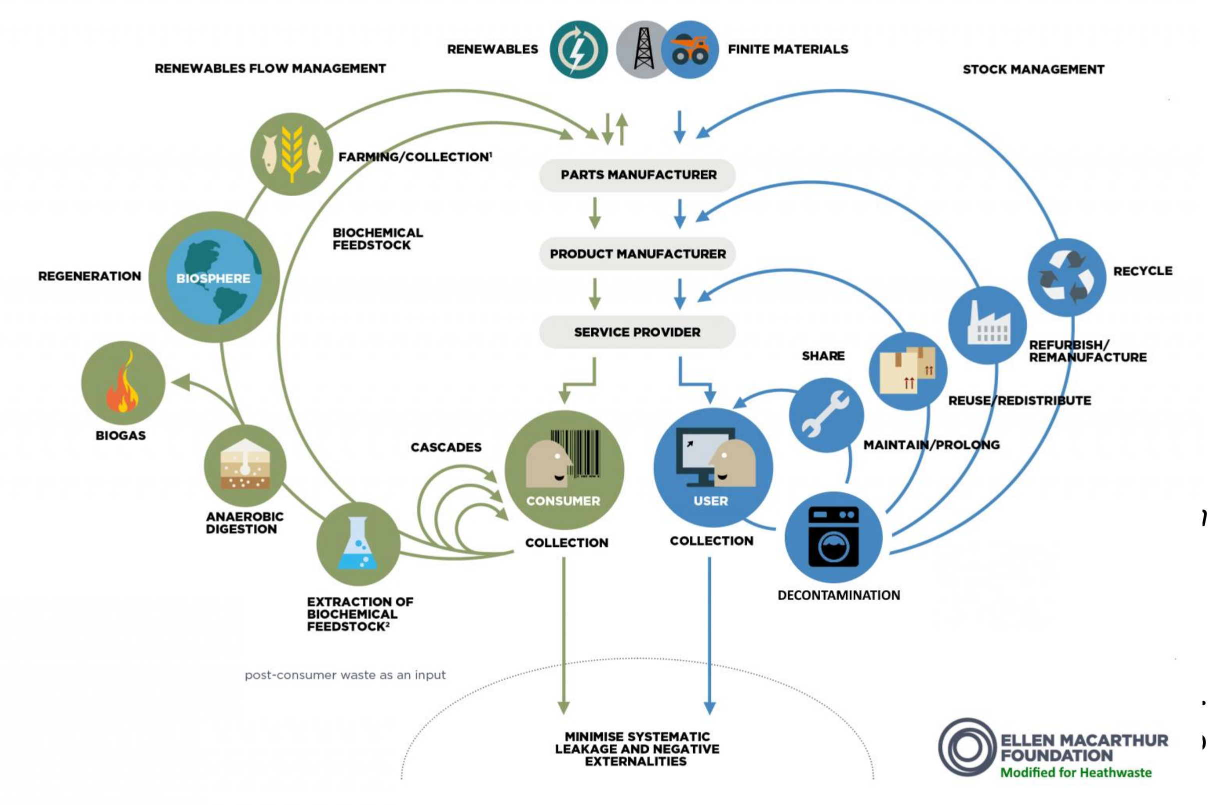


Figure 5. Butterfly Diagram showing the circular strategies, by the Ellen MacArthur Foundation modified by B. van Straten and T. Horeman with a decontamination step for healthcare. No further use is allowed without prior permission of the Ellen MacArthur Foundation: https://ellenmacarthurfoundation.org/circular-economy-diagram.

5.7 The technical loops in the diagram

In healthcare, one extra step should take place: decontamination. With potentially contaminated healthcare waste, decontamination is needed before we can safely reprocess materials and components. For example, if we want to remove precious metals, valuable parts or printed circuit boards from used robotic instruments or cardiac catheters, we want to be sure that the instrument is clean after use in the operating room before we touch it.

On the right side of the butterfly diagram as shown in Figure 6, the technical cycle is shown, which applies to products and materials.

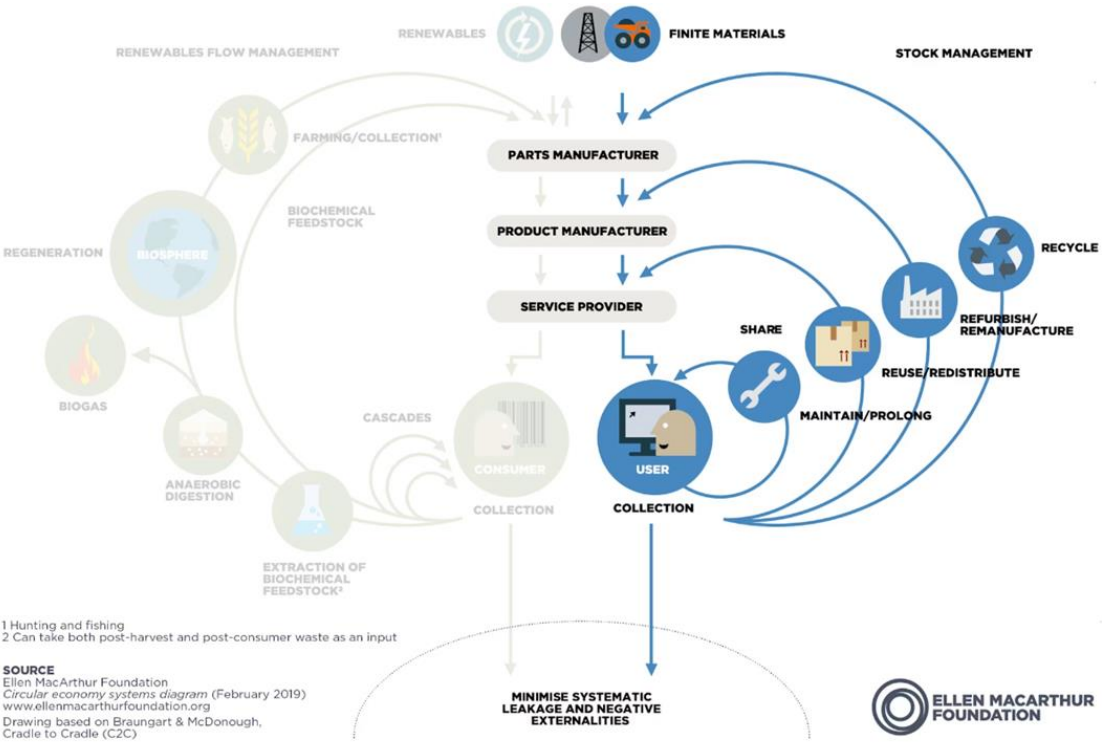


Figure 6. Right-hand side of the Butterfly Diagram, representing the technical cycle. © Ellen MacArthur Foundation. No further use is allowed without prior permission of the Ellen MacArthur Foundation: https://ellenmacarthurfoundation.org/circular-economy-diagram

The diagram shifts from smaller to larger loops. The inner, smaller loops require less energy to keep the materials in circulation, as compared to the loops to the outside. Maintenance, repair and reuse consume less energy than refurbishing, remanufacturing and recycling. These loops also represent cost savings for consumers, as these products and materials are already in circulation. Reusing them is cheaper than the investments needed for making them new. Although recycling requires a lot of energy, it is still significantly less than extracting natural resources to process them into raw materials and products.

5.8 The biological loops of the diagram

On the left side of the butterfly diagram, there is the biological cycle as shown in Figure 7.

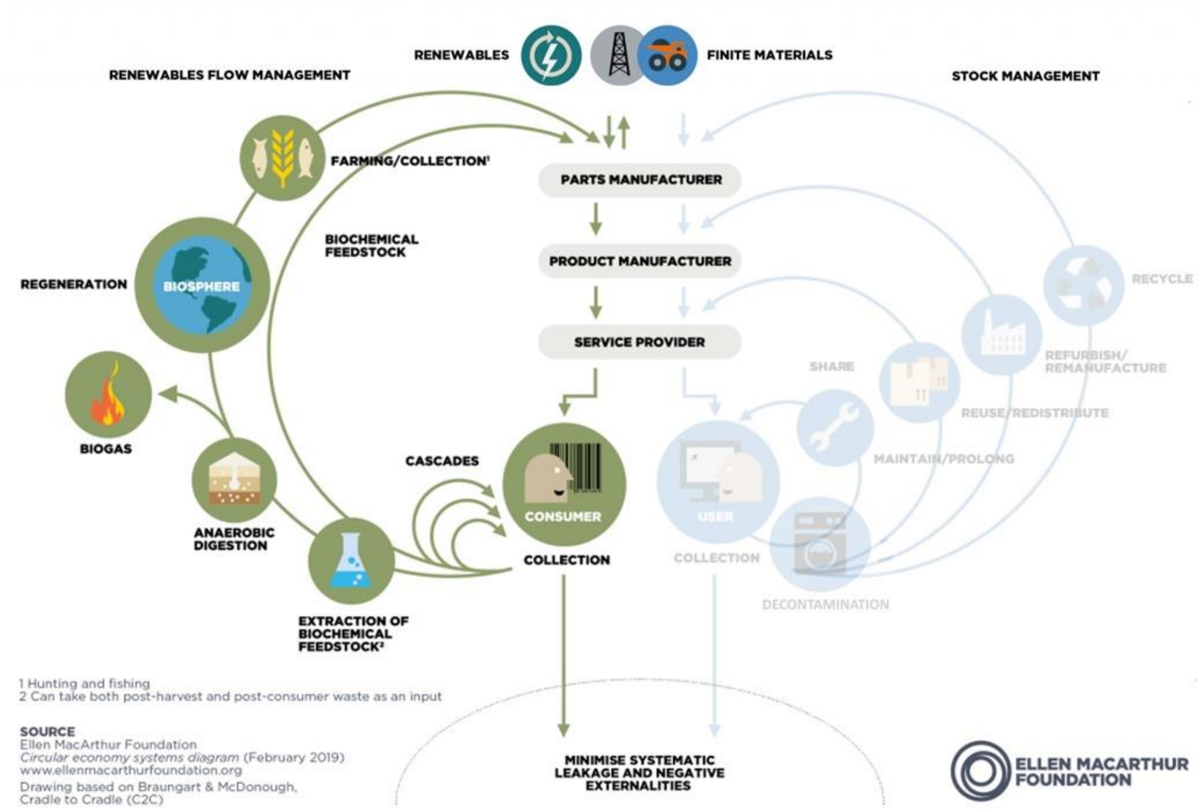


Figure 7. Left-hand side of the Butterfly Diagram, representing the biological cycle. © Ellen MacArthur Foundation. No further use is allowed without prior permission of the Ellen MacArthur Foundation:

https://ellenmacarthurfoundation.org/circular-economy-diagram

After consumption these products are returned to the Earth. Some examples of this are:

Composting

The aim of composting is to minimize organic waste by means of biological reprocessing, for products that can biodegrade and be returned to the Earth. The Ellen MacArthur Foundation describes the process of composting as "Composting is the microbial breakdown of organic matter in the presence of oxygen".[40] Composting turns biodegradable materials into compost, after which it can be used, e.g. as fertilizer.

In product design, incorporating composting and biological reuse means to design products that can either be decomposed or reused in natural cycles at the end of their product life. This approach is aligned with the left-hand side of the butterfly diagram, representing the biological cycle (Figure 6).

The cascade loops of the Butterfly Diagram include strategies where food-like waste is used to make other products. Orange peels, for instance, are used more and more to make appliance cleaners, cleaning sprays and air fresheners. As mentioned before, the carton boxes of the GO Jack instrument opener[20] were made from grass fibers and the plastics bags from sugar cane.

Biobased plastics is another popular application. These are plastics made out of renewable raw materials and can be biodegradable. Nowadays, natural biopolymers are used in plastics processing. Materials used include bio-based Polyamide, commonly called nylon, a semi crystalline thermoplastic (PA) using cellulosic fibers, potato starch, vegetable oils and other components.[41] Product designers, manufacturers and suppliers aiming for a sustainable strategy should investigate the use of bio-based polymers and bio-based plastics in their products and packaging.

40. Ellen MacArthur Foundation. The biological cycle of the butterfly diagram. (2022). Accessed on 24 July 2024: https://www.ellenmacarthurfoundation.org/articles/the-biological-cycle-of-the-butterfly-diagram

41. Maik Feldmann, Johannes Fuchs, 5 - Injection Molding of Bio-Based Plastics, Polymers, and Composites, Editor(s): Hans-Peter Heim, Specialized Injection Molding Techniques, William Andrew Publishing, 2016, Pages 211-237, ISBN 9780323341004, https://doi.org/10.1016/B978-0-323-34100-4.00005-5.

In policy, policymakers can implement a range of measures that encourage the collection, processing, regeneration and use of organic materials. Incentives to stimulate biological reprocessing are grants, subsidies, loans, tax reductions, notifications of preferred supplier preferences, the creation of special infrastructure (collection programs of organic waste in separate bins) and support for concepts such as regeneration, (local) composting programs, anaerobic digestion, and other forms of organic waste recycling. Mandatory organic waste separation or restrictions on the disposal of organic waste as landfill could also be implemented. From the perspective of policymakers and procurement managers, it should be mandated that government agencies purchase compost and products derived from biological reprocessing. Furthermore, user awareness campaigns for these principles can be set up to stimulate the circular economy.

5.9 Circular principles in policy formation

Reducing waste, costs, dependence on other countries and CO_2 emissions make these circular strategies extremely attractive for policy formulation and future decision-making. In other words, the following components could be included in policy formulation and strategies:

- Biological recycling
- Maintenance and repair of products
- Sharing and reuse
- Refurbishment and remanufacturing
- Recycling of materials.

However, this means that we must design products and processes so that they can easily be maintained, repaired, shared, refurbished, remanufactured and recycled.

This includes stimulating modular design so components can be replaced and remanufactured, or designing products with fewer mixed materials or with materials that can easily be separated for recycling. Circular design also means that design is aimed at processing through multiple loops, for instance a repairable product made from recyclable materials which can be shared by multiple users, supplied in biodegradable packaging.

Visualizing these circular strategies can help to illustrate how we can use these in decision-making and policies in order to realize environmental, social and economic sustainability. In particular in the field of healthcare as this is sector is energy intensive, high in resource management and generation large amounts of waste. Applying circular strategies on board, management and department level may help to reduce costs, decrease waste streams and lower the amount of CO_2 emissions. A visual representation of key circular strategies is shown in Figure 8:

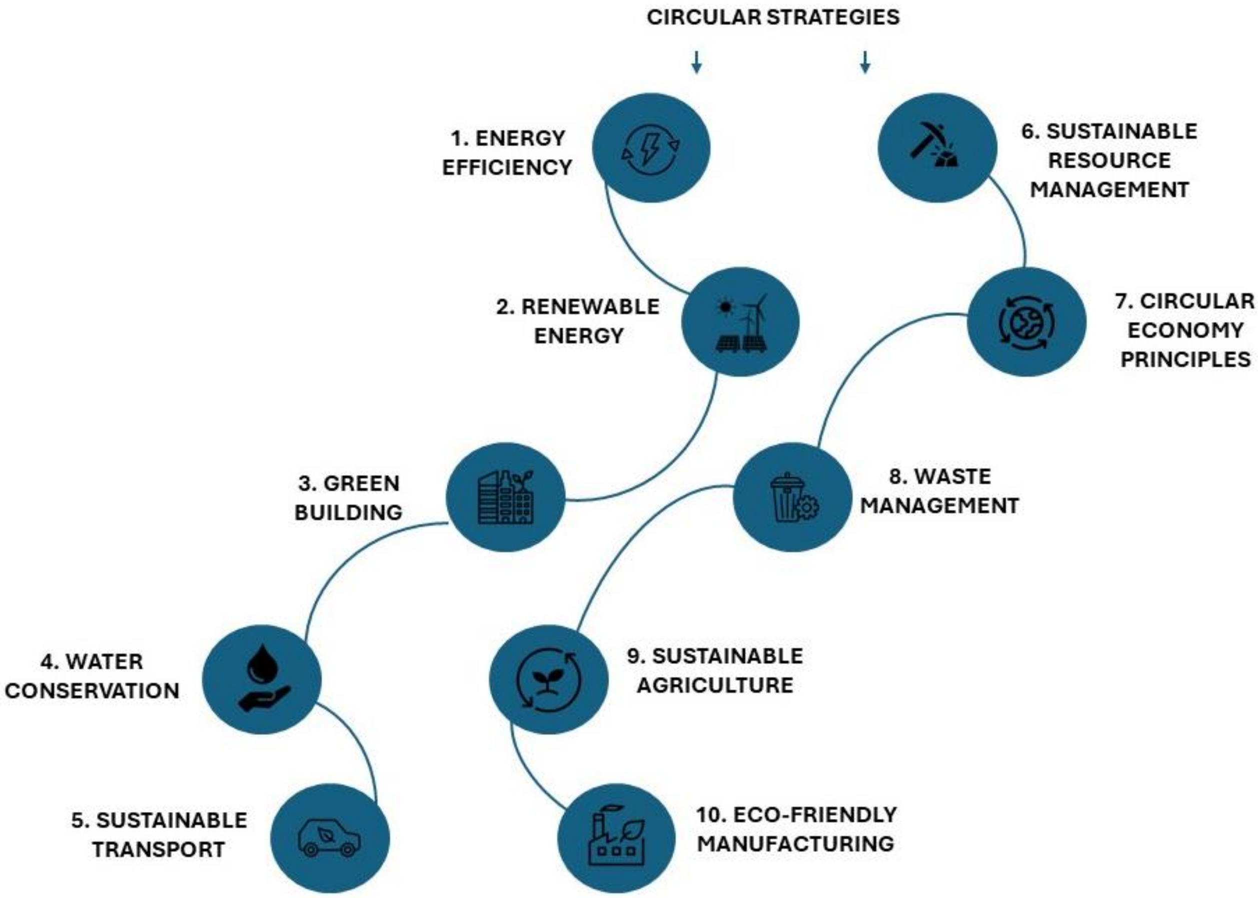


Figure 8. Circular strategy visualization by B. van Straten, based on several key sources.[42-46]

42. Pomare, C. (2019). United Nations (UN) Sustainable Development Goals (SDG) and accountability framework. Encyclopedia of the UN Sustainable Development Goals: Partnerships for the Goals.

43. Ellen MacArthur Foundation. The butterfly diagram: visualising the circular economy. (2019). Accessed on 24 July 2024: https://www.ellenmacarthurfoundation.org/circular-economy-diagram.

44. World Resources Institute. Resilience in a Warmer World: The Future of Extreme Heat. (2024). Accessed on 24 July 2024: www.wri.org.

45. Braungart, M., & McDonough, W. (2009). Cradle to cradle. Random House.

46. ISO. ISO 14001:2015 Environmental Management Systems. (2015). Accessed on 24 July 2024: https://www.iso.org/standard/60857.html.

By integrating these circular design principles, the diagram provides a comprehensive overview of how different strategies can work together to achieve sustainability, create a zero-waste society and reduce greenhouse gas emissions. Each layer can serve as a basis for the foundation of a new circular policy:

1. Energy efficiency

Define steps and policies which mean using less energy to perform the same tasks.

2. Renewable energy

Define steps and policies which stimulate the generation of energy from natural sources such as solar, wind, hydroelectric and geothermal power.

3. Green building

Design and construct buildings that are environmentally responsible and resource-efficient. This includes using sustainable materials, incorporating energy- and water-efficient systems, and optimizing indoor environmental quality.

4. Water conservation

Define strategies that use water resources more efficiently.

Examples of this include low-flow fixtures, rainwater harvesting and water recycling.

5. Sustainable transport

Stimulate transportation methods that have a lower environmental impact, such as public transit, cycling, electric vehicles and car-sharing programs.

6. Sustainable resource management

Stimulate the efficient use and management of resources to reduce waste and negative environmental impacts, such as sustainable forestry, fishing and mining practices.

7. Circular economy

Support an economic system aimed at eliminating waste by stimulating measures that continually reuse resources which would otherwise be regarded as waste. This includes stimulating maintenance, repair, reuse, refurbishment, remanufacturing and recycling of products and materials. Recycling one kg of (medical) plastic leads to about 3 kg of CO_2 reduction.[10] For stainless steel this is 2 kg of CO_2 savings for every kg of steel that is recycled.

8. Waste management

Efficiently manage waste to reduce its impact on the environment. This includes recycling programs, composting and waste-to-energy technology.

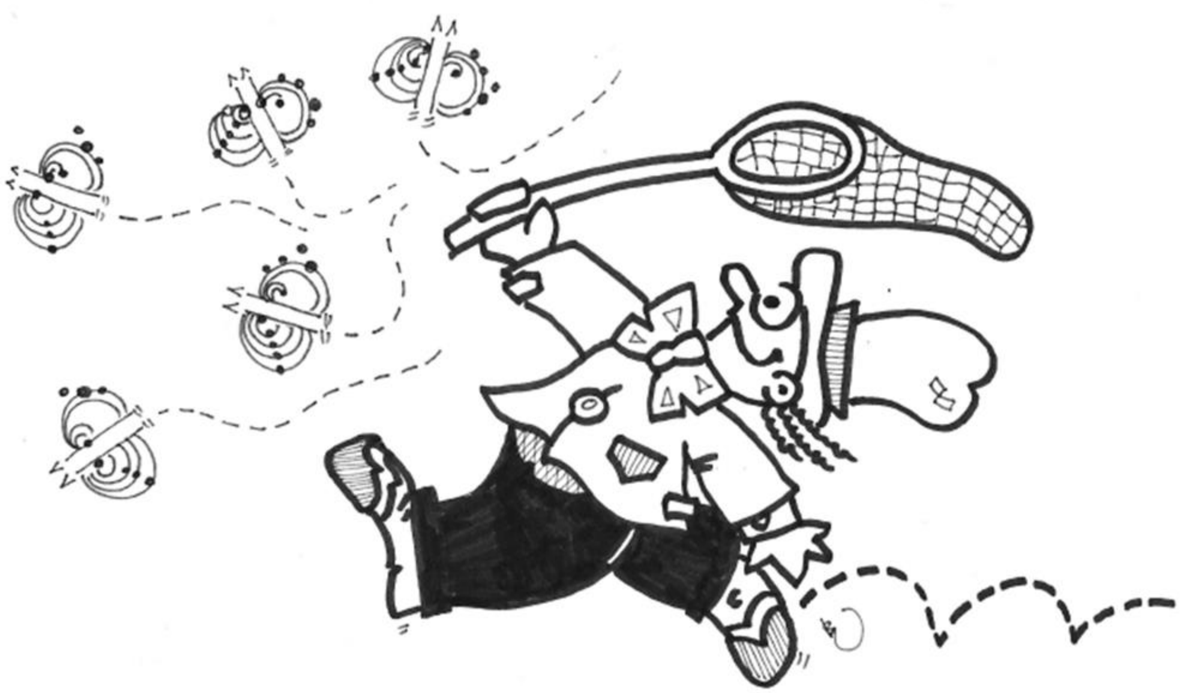
9. Sustainable agriculture

Stimulate farming practices that protect the environment, public health and animal welfare. Examples are organic farming, crop rotation and integrated pest management. This enhances soil health, reduces chemical use and supports biodiversity.

10. Eco-friendly manufacturing

This means producing goods in a way that minimizes environmental impact by using sustainable materials, reducing waste and improving energy efficiency.

Visualizing these sustainable strategies helps to understand how the various approaches interact and creates a holistic overview of all aspects in the chain. Each strategy contributes to reducing environmental impact, conserving resources and promoting long-term ecological balance. By implementing these strategies, businesses, governments and individuals can work towards a more sustainable and resilient circular future.



Catch the butterfly diagrams

Drawing by Bruno Bruins©, 2024, no further use allowed.

Watch the video through the QR code below to visualize the circular economy in the medical sector.

https://surfsharekit.nl/objectstore/09bcc10b-7ef1-4ad4-8e4d-dafdafef2b05?utm_source=edusources.nl&utm_content=download

6

Design strategies for policies, products and processes in a zero-waste society

6.1 Life on our planet

Our Earth and its life are unique. The arrangement of atoms and molecules on Earth allow life to exist. Atoms and molecules are organized in complex and organized structures and systems to support life. The essential atoms for life include carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P) and sulfur (S). These atoms form the basis of organic molecules. For life to exist, we need essential molecules such as water (H_2O) and carbon dioxide (CO_2), which is used by plants in photosynthesis to produce organic molecules. Many more molecules and structures make our existence possible. From the atomic level to the level of entire complex organisms, these organized structures and systems are fundamental to life on Earth. The precise and intricate organization of these components underscores the complexity and wonder of biological systems.

Until now, life on Earth is the only known life in the universe. This uniqueness not only inspires, it should make us realize that we need to be more careful with our planet. And not use up natural resources so that the next generations will not have any use for them. Using waste as a resource for new products can help with this. Achieving a circular economy in which we no longer create waste is essential. That's why we should want to come up with zero-waste strategies.

Zero-waste strategies are aimed to minimize or even eliminate waste streams. The circular economy has been variously defined. The definition by Geissdoerfer et al. (2017) is spot on: "An economic system in which waste is prevented, minimized or even completely reused".[47]

47. M. Geissdoerfer, P. Savaget, N.M.P. Bocken, EJ. Hultink. The Circular Economy – A new sustainability paradigm? Journal of Cleaner Production., 143 (2017), pp. 757-768. https://doi:10.1016/j.jclepro.2016.12.048.

To achieve this, we need to start "rethinking" our policies, processes and product designs by creating zero-waste strategies. These strategies emphasize reducing, repairing, reusing, remanufacturing and recycling to achieve a circular economy where waste is eliminated and resources are continuously reused.

6.2 Zero-waste strategies

Writing an effective strategy involves a structured approach that clearly outlines goals, identifies the means to achieve them, and details the steps necessary for implementation. It is written based on a vision – an inspiring, desired outlook for the long term – answering the question "What do we want to achieve in the future?" In this case, the vision is achieving zero waste in a specific production process. A strategy should be formulated broadly, with long-term aims, and be aligned with your mission to accomplish the vision defined. Formulate the strategy according to the 'SMART' principles:

- Specific: Clearly defined.
- Measurable: Quantifiable.
- Achievable: Realistic.
- Relevant: Aligned with the vision.
- Time-specific: With clear deadlines.

Creating a circular economy strategy means writing a plan to enable the transition from a linear "make-use-dispose" model to a circular "(re)make-use-reuse" economy. Aspects that could be included are:

- Design for longevity by stimulating products that are durable, repairable and upgradable.
- Promoting reuse and refurbishment.
- Formulate measures that extend the life of products through reuse, repair and refurbishment.
- Facilitate recycling and composting.
- Utilize renewable resources.
- Switch to biodegradable materials where possible.

6.3 The R-ladder

In the 1970s, the R-ladder, or R-strategy, emerged from the concept of waste hierarchy, which aimed to organize waste management approaches by their environmental impact and sustainability. This framework first became prominent with the 3R model - reduce, reuse, recycle - which gained popularity through environmental campaigns focused on reducing pollution and waste. Over time, the model has expanded to encompass additional steps, creating versions with new R's such as Recover, Refuse, Repair and Repurpose. This broader hierarchy is now often referred to as the waste management hierarchy or circular economy hierarchy, aligning with global sustainability efforts.

There are multiple R-ladders and R-frameworks promoting R-strategies. One ladder describes ten strategies in hierarchical order: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, reover.[11,12] The concept is built on the idea of prioritizing actions that reduce environmental impact, inspired by the principles of circular economy and sustainable development.

The R-ladder with the levels of circularity, the 10 R's,[13] is a commonly used hierarchy, as shown in Figure 6, representing different strategies for sustainable materials and waste management. The classic 10-R ladder shows a linear progression in which the R-strategies are placed from top to bottom, suggesting that some (such as Refuse or Reduce) are always superior to others (such as Recycle or Recover). Recycling, for example is often considered less favorable compared to strategies such as Refuse, Reduce and Reuse. Recycling is low on the ladder because it still requires energy and raw materials to process materials, while the higher steps focus on preventing waste production.

However, this can lead to an underestimation of the value of certain circular strategies, depending on the context. There are arguments why all R-steps are equally important and why recycling should be ranked higher. An example of this is the increasing focus on closed-loop recycling, where materials are reused with minimal loss of quality and material costs. This ensures that recycling is a crucial link in the circular economy, especially when the demand for recycled materials is high and technological innovations ensure more efficient recycling processes.

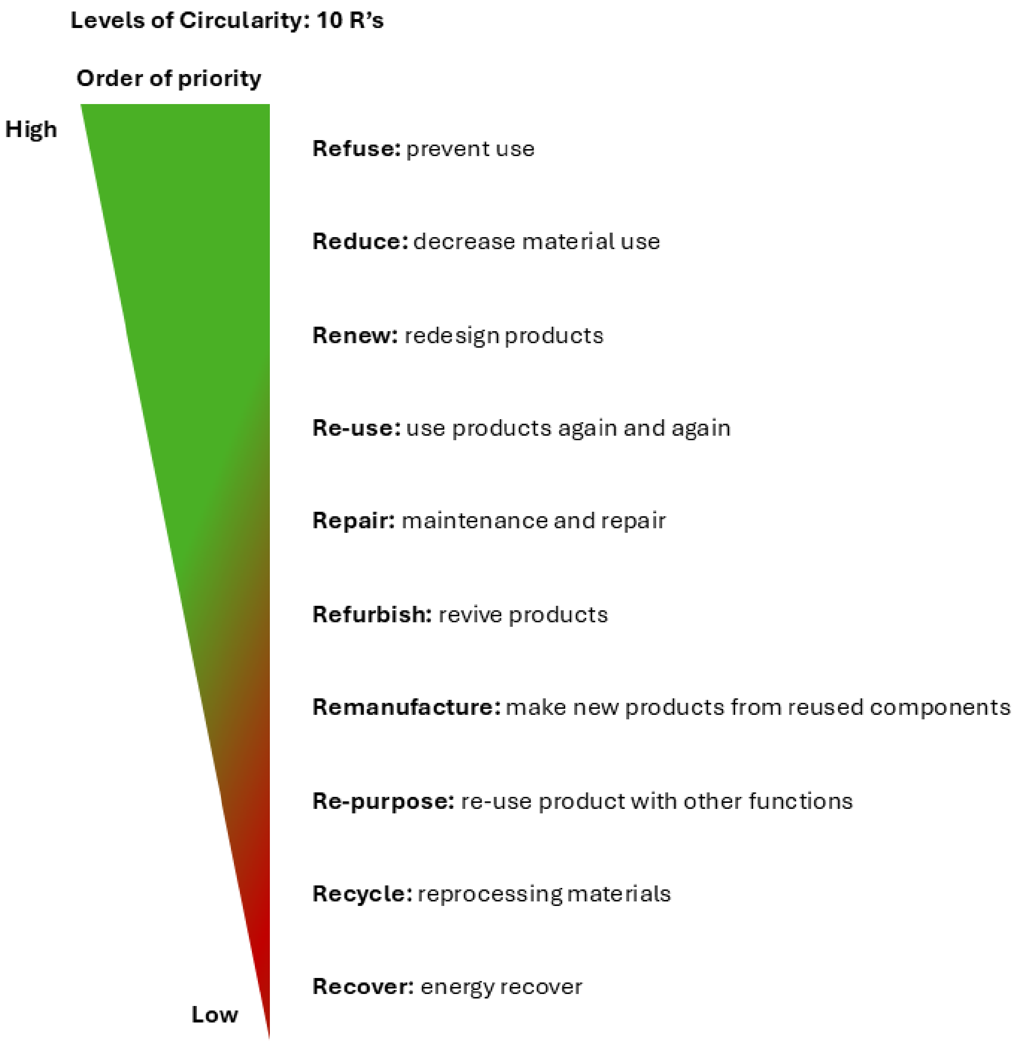


Figure 6. Hierarchical order of R-strategies.[13]

We believe that all processes that can be applied to prevent waste are equally valuable. Therefore, we present a revised version – as shown in figure 2 - of the classic R-ladder, the 10-R circularity disc.[14] This visualization encourages a more balanced approach to all stages, rather than focusing only on specific R-strategies. A circular approach emphasizes that every R-strategy is important; the effectiveness of a strategy depends on the specific situation.

If we consider recycling of materials from the operation room, one should consider that the mass flow of material can become very large and when a dedicated recycling plant is optimized for a mono stream like “blue wrap” the processing speed can be lowered towards a single minute. Especially when the end product (pellets) are used as a direct replacement for imported plastics, the impact of recycling on the environment compared to other R strategies is much higher than visualized. Regarding the R strategy “Energy recovery”, we see something similar. For example when we consider energy exchange from conditioned air and water use within sterilization departments, we see that placement of re-circulation ducts and heat exchangers that boost the energy recovery towards 60 percent [48] have a huge impact on energy loss and actual savings for a hospital that cannot be reached easily with other strategies. Therefore, if actual mass/material flows are considered per strategy, we opt for a more balanced visualization order of strategies versus impact.

48. Moreno, G. S. B., Calcedo, J. G. S., González, A. G., & Salgado, D. R. (2019). Sustainable solutions for thermal energy saving in hospital operating theatres. In E3S Web of Conferences (Vol. 85, p. 01002). EDP Sciences.

6.4 The circularity disc, the modified R-ladder

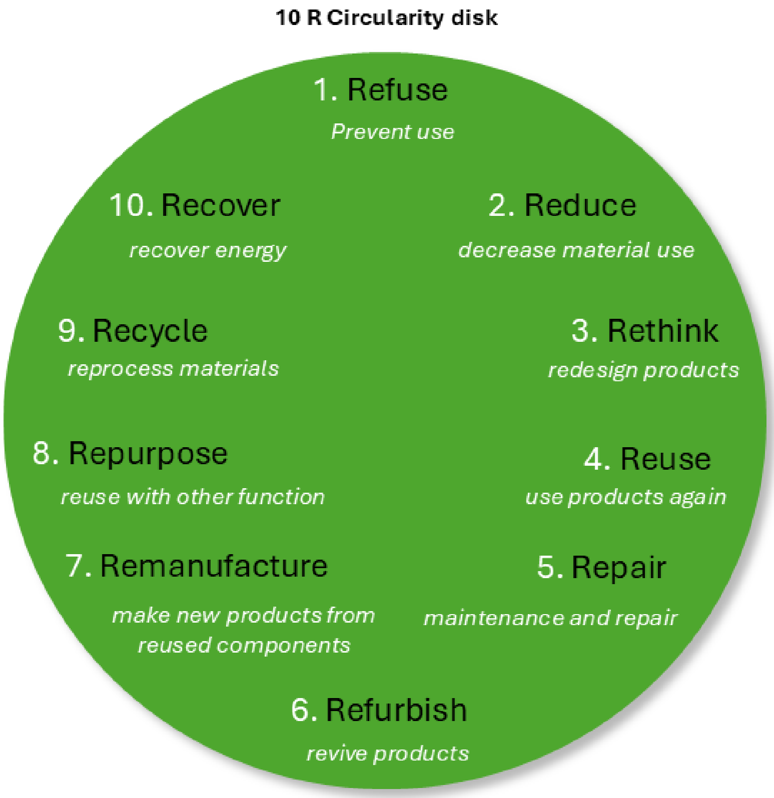


Figure 7. B. van Straten (2024). 10-R circularity disc: Revised version of the classic R-ladder with a circular and balanced approach to all R-stages. http://dx.doi.org/10.13140/RG.2.2.32538.45763

The objective of the 10-R circularity disc , as opposed to a linear ladder, is to make all R-strategies inclusive without discrimination or prioritizing the one over the other. In some cases, products or processes certain R-strategies might me more or less valuable than others. And we increasingly see that a combination of different R-strategies is much more powerful than selecting or prioritizing one strategy over another. In the case of R-strategies in healthcare, we will discuss a number of those that can be applied frequently:

Reduce

It is necessary to design strategies that minimize consumption of products, energy and materials. These strategies will contribute to reducing waste streams. There are various methods to do so.

In product design, defining a strategy that reduces waste involves incorporating circular design principles of from the very beginning of the design process. These strategies focus on designing products with fewer (different) materials, with modular design - reducing complexity and increasing flexibility - and minimize the use of parts, additives and adhesives. The aim to use recycled materials, as this means less energy is required to make the product.

In packaging, it’s necessary to reduce the amount of packaging where possible. For example, it’s possible to print on the product instead of using labels, and to use QR codes instead of paper for instruction manuals. It’s also recommended to use biobased or recycled materials for packaging. For instance, for the GO Jack instrument opener[20] we used carton packaging made from grass fibers and biobased plastic bags made from sugar cane.

In policy, integrating the Reduce principle implies creating regulations and initiatives that minimize resource consumption, waste generation and environmental impact. For instance, this can be done by introducing tax incentives, grants or subsidies for initiatives, products or companies that minimize waste or implement resource-efficient practices. Another important aspect for policy-making is to stimulate awareness of sustainable consumption and to teach consumers about the benefits of reducing consumption and choosing sustainable products. For purchasing policies, it’s a useful strategy to implement the Reduce principle in tenders, so that projects are awarded according to a new standard, namely to companies that work with biobased or circular materials in their products and packaging. It is also necessary to choose suppliers that promote sustainable design and manufacturing and collect their packaging and products at end-of-life for recycling.

Reuse

In product design, the Reuse principle can be incorporated by designing products to have long lifespans. Products designed according circular economy principles can be easily repaired, refurbished or remanufactured. Strategies for these kinds of products allow easy access to parts; they facilitate easy disassembly and have a modular design, so that individual components can be replaced. The components, moreover, are designed to be reused. These products are designed to have high-quality parts and components, which guarantees a long-life span.

Strategies which focus on Reuse should also incorporate reusable packaging. Reusable packaging is a key component of sustainable product design and circular economy practices. Examples are refillable bottles, refilling options for cleaning products such as shampoo and body wash, returning glass bottles and coffee and tea cups, reusable shopping bags and reusable gowns.

In policy, authorities could use Reuse in their policy formulation to prescribe the use of reusable packaging; for instance by placing taxes on single-use plastics, or by offering incentives for re-usable packaging. In procurement, this strategy can be effectively enforced by formulating so-called ‘knock-out’ criteria in purchasing processes for single-use products or packaging in tenders or purchasing policy. This keeps suppliers and therefore product designers alert to increasingly focus on sustainable solutions. In this way, an entire sector can be pushed in the right direction.

Recycle

In product design, it is always good to choose recycled materials for any product design that lends itself to this. In the design process, the fact that the product should be recycled can be taken into account from the very beginning when choosing materials and further design. But suppliers can even go one step further by designing collection systems for their products, as well as comprehensive recycling programs. This also immediately gives the supplier an advantage over others, because many consumers will choose their product because of its sustainability and their "take-back" programs. A fundamental aspect in eco-design is to model products with a holistic view, meaning designing with the entire life cycle in mind: from using recycled materials to design for disassembly, collection and recycling, including eco-packaging.

In policy and procurement, strategies for recycling and the use of recycled products can be stimulated by encouraging product designers and as well as users. Various policy measures, incentives and educational initiatives can be formulated to stimulate recycling, such as deposit-refund systems, tax incentives, charges for non-recyclable waste volumes, minimum recycling targets, supplier responsibility for taking back broken products for recycling, bans on certain products and bans on designing products that will end up in landfill. Authorities can further stimulate recycling by co-funding and facilitating this, e.g. via loans, recycling facilities, collection bins, stimulating recycling technology, education and awareness campaigns. By formulating a combination of these and others measures in policy or tenders, a robust recycling strategy can be designed.

On the next page, a photo is shown of the GreenCycl FieldLab, where hospital packaging and other waste is collected. The image shows polypropylene blue wrap waste; blue wrap functions as sterilization paper for surgical instrument sets and is disposed of after use. In the Netherlands alone, an estimated 1.3 million kg is thrown away every year. GreenCycl melts this blue wrap into high-quality medical grade polypropylene, which can be used to produce new medical products, such as the GO Jack instrument opener.[11] These instruments are distributed to the same hospitals who handed in their polypropylene waste for recycling.

The next page shows a picture of flower fields in the Dutch Bollenstreek region, particularly famous for its vibrant tulip displays, a breathtaking sight each spring (photo by B. van Straten). Compost made from organic waste can be used as fertilizer in floriculture. Compost is rich in nutrients and organic matter, making it an excellent soil amendment that can improve soil structure, enhance water retention, and provide essential nutrients for plant growth. In a growing number of places such as the Bollenstreek, compost made from organic waste is used, such as vegetable, fruit and garden waste (GFT), is increasingly used. This compost is often used in bulb cultivation and ornamental horticulture as a soil improver. Composting organic waste and reusing it in agriculture and horticulture contributes to a circular economy.

Drawing by Bruno Bruins©, 2024, no further use allowed.

Zero-waste policies are aimed to reduce waste generation, promote the reuse of materials, and ensure that any waste produced is recycled or composted. Sending waste to landfills or incinerators is discouraged.

Creating effective policies, procurement strategies, and product or corporate decisions is not easy when aiming to comply with circular economy principles by realizing zero-waste as output.

Product designers should create products with modular parts that can be easily repaired or upgraded instead of replaced. Furthermore, products should be designed so they can be reused; a good example are refill systems, where consumers can refill containers instead of buying new ones. Recycling should be incorporated into product concepts, so that materials can be recycled back into the same product. This means that products maintain their value and fewer raw materials are needed. Packaging should be also redesigned to use less material. Where possible, biological and composting principles should be used to create compostable packaging, or packaging made from biodegradable materials that decompose naturally.

By choosing products that are reusable, durable and made from recyclable or biodegradable materials, consumers contribute to reducing waste and promoting a more sustainable future. The positive and lasting impact of policies, procurement and management decisions is significant. These decisions affect all aspects of our lives and are needed to make the transfer to a circular economy.

In this video, Tim Horeman explains how manufacturers can be motivated to reuse materials in new products. Scan the QR code to delve deeper into the topic.

https://surfsharekit.nl/objectstore/5b3de17c-5847-491d-bae8-7d3bb84bcd65?utm_source=edusources.nl&utm_content=download

7

Recycled materials: using waste as input for new products

Earth has paid a high price for global economic growth. As economies grew since the Second World War, governments and consumers seemed paralyzed to counteract the negative effects of depleting the Earth's natural resources. Despite decades of scientific evidence, it is remarkable how few projects were funded and have actually worked to counteract the depletion. And still it seems that political agendas do not focus on limiting ecological damage, despite the fact that the quest for natural resources dominates geopolitical developments. The current world order seems to be around the dependence of oil and gas reserves, rare metals and precious materials. This dependence leads to geopolitical tensions and conflicts and will only intensify as raw materials become scarcer. Creating a vision to reduce this dependence on scarce resources by reusing materials should be on the radar of every world leader. Territorial claims, trade wars and disputes over valuable raw materials will be less necessary when we harvest them from our own waste streams which could lead to a more stable world order. Instead of focusing on other countries in order to secure these materials.

Utilizing recycled materials is a key component of the circular economy. By integrating recycled materials into production processes, companies can contribute to the circular economy, reduce their ecological footprint, and meet the growing demand for sustainable products - meaning recycling also offers commercial benefits.

7.1 The benefits of recycling

Using materials again and again is a fundamental element of the circular economy. Using recycled materials in production and manufacturing offers numerous environmental, economic and social benefits:

Environmental benefits

Recycling materials diverts waste from landfills, reducing the strain on these sites and decreasing the amount of waste that contributes to soil and water pollution.

Conserves natural resources

Using recycled materials reduces the need for virgin resources, such as timber, water, minerals and fossil fuels. This helps preserve natural ecosystems and biodiversity.

Reduces greenhouse gas emissions

Manufacturing products from recycled materials typically requires less energy than producing them from raw materials, leading to lower carbon emissions. For example, recycling aluminum saves 95% of the energy needed to make new aluminum from bauxite ore.

Preventing pollution

Recycling processes reduce the amount of air and water pollution associated with extracting, refining and processing raw materials. This includes reducing toxic emissions from mining activities and industrial processes.

Cost savings

Manufacturing with recycled materials can be more cost-effective than using virgin materials, due to lower raw material costs and reduced energy consumption.

Job creation

The recycling industry creates jobs in the collection, processing and manufacturing sectors.

Market opportunities

Growing consumer demand for sustainable products drives innovation and market opportunities in developing and selling goods made from recycled materials.

Public health

Reducing waste and pollution through recycling can lead to improved public health by minimizing exposure to harmful chemicals and pollutants.

Community engagement

Recycling programs can engage communities in environmental stewardship and awareness, fostering a culture of sustainability and responsibility.

Education and awareness

The use of recycled materials promotes awareness of environmental issues and encourages responsible consumer behavior and sustainable practices.

Supply chain security

Recycling provides an alternative source of raw materials, which can be more reliable and less volatile than sourcing virgin materials, particularly during times of resource scarcity or geopolitical instability.

Compliance and the Corporate Social Reporting Directive (CSRD)

The CSRD is European Union legislation, from January 2023, that necessitates EU businesses to make known their environmental and social impacts, and how their environmental, social and governance (ESG) actions affect their business.

Using recycled materials can help companies meet environmental regulations.

7.2 Mineral scarcity

One of the great challenges for future generations will be mineral scarcity. If we continue to consume these minerals as we do now the next generations will face the consequences. It is remarkable that this is so little emphasized in the political agenda. Politicians, policymakers, companies and the public should and could make more efforts to prevent this challenge for instance by stopping incineration of valuable waste streams and stimulate recycling with incentives instead of subsidizing virgin oil and virgin iron ore initiatives. In any case, we have to stop depleting the Earth.

It is of the utmost importance that rare, strategic and critical materials do not end up in landfill or the incinerator.

An important way to do so is to start using waste as raw material for new products. Not only for the standard, easy forms of recycling such as glass, metal and paper, but also for rare minerals such as cobalt, iridium, molybdenum and lithium. Many of these rare earth minerals are infinitely recyclable - we only need to find a way to get it done at the same costs as traditional mining.

7.3 Examples of recycled waste as input for new products

Some examples of how waste can be used to make new products include:

- Recycled PET plastic can be used in sound-absorbing panels.
- Recycled plastic from bottles, e.g. polyester waste, can be used in clothing.
- Recycled ocean plastic, e.g. polyester waste, can be used for making shoes, as is done by Adidas.
- Organic agricultural waste materials can be used to produce biodegradable plastics.
- Plant-based waste can be used to make plant-based plastics for Coca-Cola bottles.[49]
- Food waste can be used reprocessed into biogas for compost or fertilizer for agricultural purposes.
- Urban mining can yield precious metals, as in the case of the GreenCycl initiative to harvest iridium and platinum from cardiac catheters.
- Medical blue wrap waste can be used for polypropylene raw material to make the GO Jack instrument opener.[20]
- Sugarcane can be used to make plastic packaging and transport bags.[20]
- Fairphone utilizes recycled materials in the production of modular smartphones.
- Electronic waste can be used to make new electronics and phones.[50]
- Hemp hurd and mycelium can be used as input for protective packaging.[51]
- Computer waste plastics can be used for new computer cases, for example Dell's closed-loop recycling program.[52]
- Disposed Zamak laryngoscopic blades can be used for new turning wheels.[53]

49. Coca Cola Company. 100% plant-based. (2023). Accessed on 24 July 2024 via: https://www.coca-colacompany.com/media-center/100-percent-plant-based-plastic-bottle.

50. Fairphone. Recycle your old phone(s). (2024). Accessed on 8 August 2024 via: https://shop.fairphone.com/recycle.

51. Ellen MacArthur Foundation. Packaging from 'mushroom plastic': Ecovative. (2021). Accessed on 8 August via: https://www.ellenmacarthurfoundation.org/circular-examples/packaging-from-mushroom-plastic-ecovative.

52. Dell. Design for Environment. (2024). Accessed on 8 August 2024 via: https://www.dell.com/learn/vg/en/vgcorp1/corp-comm/closed-loop-recycled-content.

53. Bart van Straten.... Tim Horeman, et al. Reprocessing Zamak laryngoscope blades into new instrument parts; an 'all-in-one' experimental study, Heliyon, Volume 8, Issue 11, 2022, ISSN 2405-8440, https://doi.org/10.1016/j.heliyon.2022.e11711. (https://www.sciencedirect.com/science/article/pii/S2405844022029991).

These are just a few examples illustrating the potential of using waste as valuable raw material to make new products. By adopting these practices, businesses and industries can significantly reduce their environmental impact, conserve natural resources, and make a difference by contributing to a more sustainable and circular economy.

7.4 Using waste as input for new products in healthcare

At the GreenCycl Field Lab, we started to experiment with melting plastic and metal waste in 2019. Now, we recycle different kinds of medical waste streams into high quality raw materials. The following waste streams are relatively easy to collect from hospitals and can be 100% recycled into raw materials of good quality.

Plastics

- Implants and instrument packaging made from PET.
- Blue wrap, cups and liquid collectors made from polypropylene.
- Instrument handles and complex surgical instruments made from ABS.
- Bags, foils and packaging made from polyethylene.

Metal-based waste

- Instrument mesh baskets, furniture and OR equipment made from stainless steel 304.
- Disposable instruments made from stainless steel 304.
- Reusable medical instruments made from stainless steel 316.
- Equipment for the hospital central sterilization dpt. (CSSD), discarded cleaning equipment and autoclaves made from steel.

Figure 8 shows a visualization of the production line at GreenCycl where hospital waste is recycled into high-grade raw material in an energy-efficient manner.

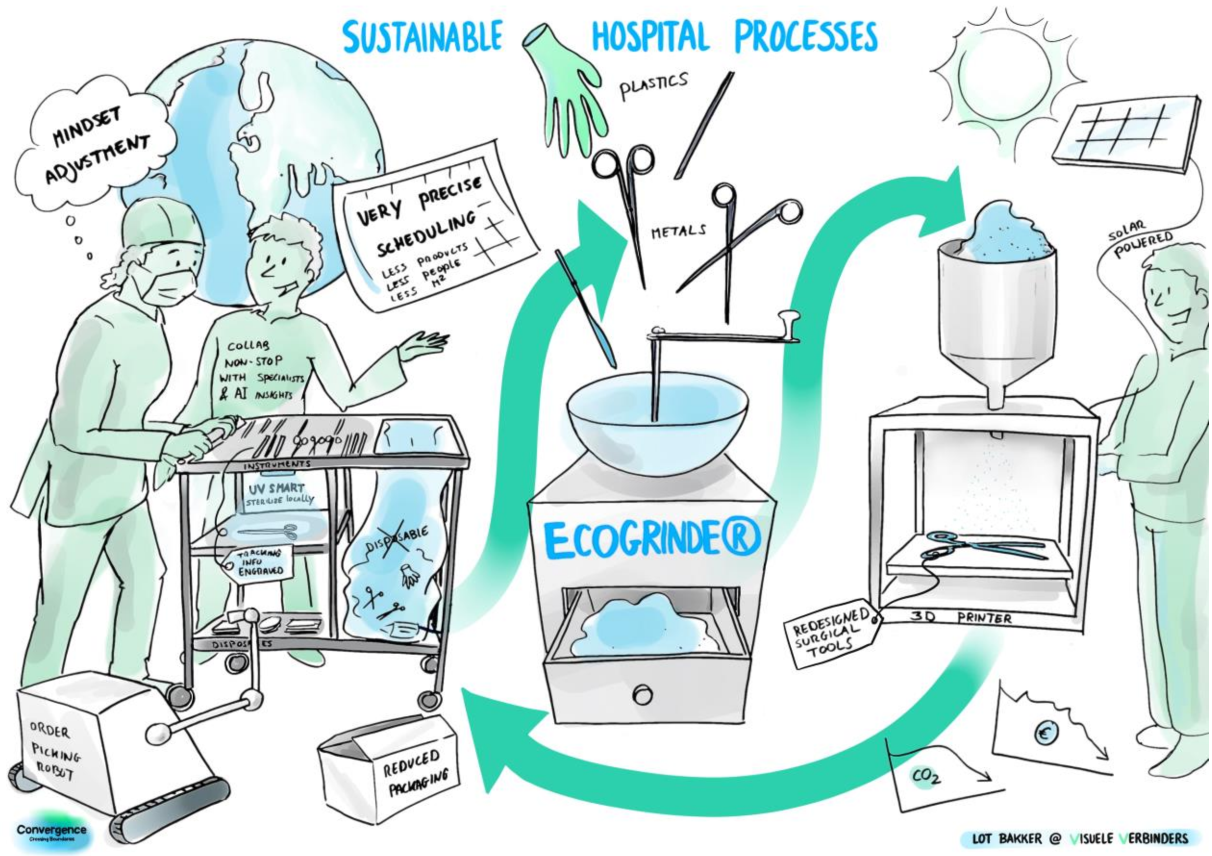


Figure 8. Reprocessing surgical waste into new raw materials by GreenCycl. Illustration made by Lot Bakker for Visuele Verbinders (www.visueleverbinders.nl). This figure may not be used without permission.

The above visualization shows some key aspects in implementing a circular economy process in healthcare. It starts with changing the behavior – the mindset of the users in the hospital towards sustainable solutions. Once the hospital is on board with recycling waste, the waste streams must be collected, such as plastics and steel instruments. After collection, these waste streams are ground in a special grinding mill. The ground material can be used in various ways to make new products. This drawing shows the process of 3D printing of new instruments. 3D printing has the advantage that no molds need to be made, which saves costs. It is a good method to make new products and in a sustainable way. Solar energy should be used to generate energy for 3D printing. After the safety certification process, the products can be reused in the hospital. Thus, the hospital is the supplier of its own raw materials. An important aspect of the process is to use less material for both the product and the packaging.

The key aspects:

- Stimulating change of behavior through education.
- Creating legislation and policies for collection, recycling and certification.
- Constructing infrastructure and technology.
- Using circular product principles and eco-design.
- Provide incentives such as grants, subsidies and tax reliefs.
- Share stories of success with communities and stimulate copy behavior.
- Apply a holistic approach to realize the Reduce – reuse – recycle principle.

Figure 9 below shows a bag of high-quality GC rPP raw material made out of used blue wrapping paper, which would otherwise have been made out of oil. As shown in figure 7, this is a type of urban mining, i.e., mining materials from urban areas. Waste is collected from hospitals, cleaned, melted it into a solid material and ground it into usable granules.

Figure 9. High-grade medical GC rPP raw material pellets made by GreenCycl out of used blue wrapping paper. Photo by B. van Straten.

Drawing by Bruno Bruins©, 2024, no further use allowed.


GETINGE

In this video Tim Horeman explains how waste can be used as source of raw material to make new products. Scan the QR code to delve deeper into the topic.

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Part III

Quick guide to creating a circular healthcare system

8

How to assess “green” products with LCAs: LCA methodology and reliability risk factors

This chapter gives an introduction into Life Cycle Assessment (LCA) methodology and its applicability to the healthcare sector, as well as its possible contributions to a circular economy in healthcare.

First, a general description of the general LCA methodology is provided, including its inherent limitations. Special emphasis is placed on the surgical field by identifying key risk factors that may contribute to inconsistent or even contradictory results in LCAs of surgical instruments, thereby jeopardizing the reliability of findings in this area. Additionally, best practices and strategies to mitigate these risk factors are explored. Next, to further understand the issues impacting the reliability of LCA findings in the surgical field and to investigate potential solutions, stakeholders’ perspectives and experiences regarding LCA practices within this field will be examined through a survey targeting members of the EAES.

8.1 Definition of Life Cycle Assessment

LCAs are one of several environmental management tools, including risk assessments, environmental performance evaluations and environmental audits, aimed at supporting environmental decision-making. Unlike these other methods, which focus on specific aspects related to environmental management, such as risk, performance or compliance, LCAs provide a comprehensive evaluation of the environmental impacts associated with every stage of a product’s life cycle, from raw material extraction to disposal. This ‘cradle-to-grave’ approach ensures that all environmental burdens are considered and helps prevent the shifting of impacts between different life cycle stages or impact categories. These burdens can include a wide range of issues, including energy consumption and the emission of hazardous pollutants.

The methodology of LCAs is systematically outlined by the ISO 14040 and 14044 standards and encompasses four main phases:

1) Goal and scope definition,

2) Life Cycle Inventory (LCI),

3) Life Cycle Impact Assessment (LCIA),

4) Interpretation.

This framework assists practitioners through a structured and iterative evaluation process, promoting consistency and transparency while encouraging continuous review and refinement of the LCA process. Supplementary tools, such as the International Reference Life Cycle Data System (ILCD), offer further detailed guidance aligned with the ISO 14040 and 14044[44] standards to enhance the quality of LCA practices. A visual representation of the general LCA methodology is provided in Figure 10. Additionally, for a summary of the identified risk factors and corresponding mitigation strategies, please refer to Table 1. The methodology and key risk factors for each phase are further discussed in the following sections.

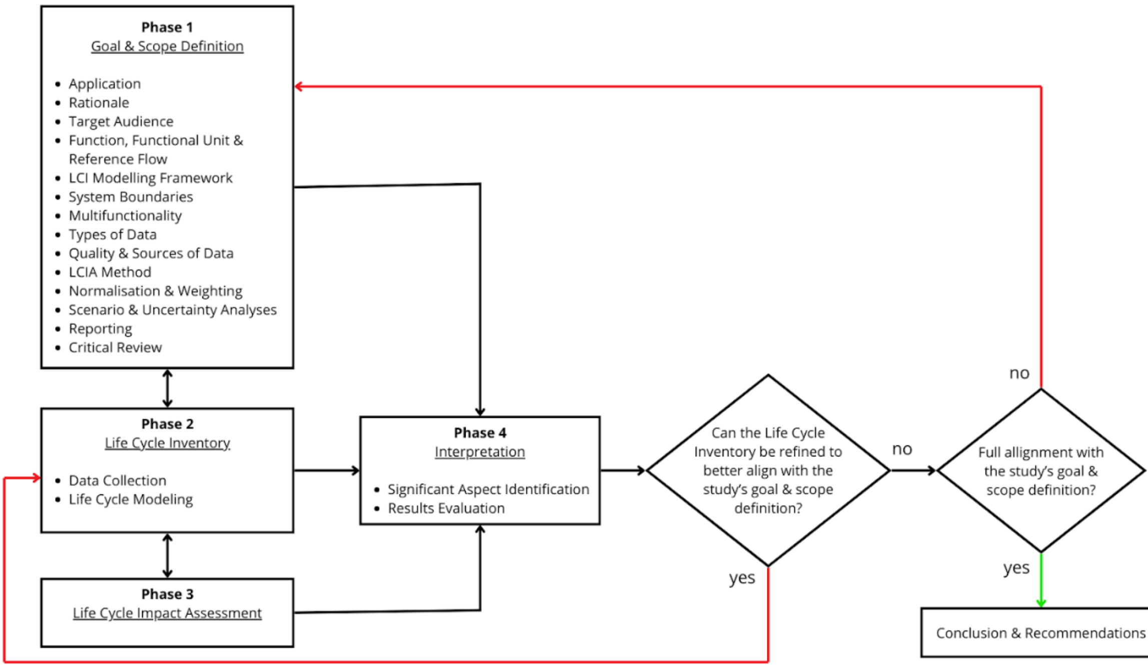


Figure 10: The general LCA methodology. The arrows represent the flow of data and information. Specifically, the red arrows indicate the iterative refinement process of the LCA, ensuring that the study aligns with the defined goal and scope while maintaining methodological appropriateness and high data quality. In cases where data limitations cannot be adequately resolved, adjustments to the initial goal and scope definition may be required.

Phase 1: Goal and scope definition

The goal and scope definition phase of an LCA is essential for establishing the framework of the study. The goal encompasses defining the study's applications, rationale and target audience, while the scope involves specifying the product under investigation and establishing the modelling methodologies, quality standards, reporting requirements and review processes necessary to align the LCA with its intended uses and audience. Early definition of these specifications is vital for maintaining the credibility and reproducibility of results. As the LCA progresses, initial scope definitions may require adjustments based on new data or insights to ensure the LCA remains relevant and accurate. The iterative nature of this process underscores the importance of documenting any changes for transparency throughout the study.

Application

LCA applications are varied, encompassing product comparisons, improvements in product design, the creation of environmental product declarations, and policy development through impact assessments. Each application comes with specific ISO 14040 and 14044:2006[54] requirements regarding data sets, reporting and review, which can result in variations in methodological approaches. In the surgical field, LCAs provide a structured framework for evaluating the environmental impacts of various surgical instruments, from reusable instruments that require energy-intensive cleaning processes to disposable options that consume significant materials and generate substantial waste. In this context, LCA applications include, for example, comparing the environmental impacts of functionally identical surgical devices and evaluating a single surgical device to analyze the differences in environmental impact among various design options.

54. International Organization for Standardization (ISO). (2006). ISO 14040:2006 – Environmental management – Life cycle assessment – Principles and framework. ISO.

Rationale

Understanding the motivations for conducting the LCA and the specific decision-making context helps to shape the LCA to meet its unique needs, ensuring that the results are relevant to the identified target audience. In the surgical field, LCA results assist instrument manufacturers in making eco-design decisions prior to market entry, helping them secure eco-friendly certifications or distinguishing their products. Additionally, LCA results can support healthcare institutions in making informed choices about sustainable procurement practices. It's important to note that not all LCAs are intended for decision support; some are purely descriptive, focusing on documenting the environmental aspects of the product being analyzed.

However, LCA practitioners themselves may have specific interests in the study outcomes, which can result in biased decisions during the LCA process, ultimately affecting the results and compromising reliability. Therefore, it is essential to clearly document the reasons for undertaking the LCA, particularly within a specific decision-making context, along with the entities commissioning the study from the start. Additionally, since studies are often funded by stakeholders with particular interests, transparency in identifying any co-financing parties is crucial for maintaining the study's credibility.

For instance, while reusable surgical instruments typically provide environmental advantages over disposables, a study by Leiden et al. found that a reusable lumbar fusion instrument set was nearly seven times more climate-polluting than its single-use counterpart. It was later revealed that the study was funded by the manufacturer of the single-use set, raising concerns about the reliability of its findings.

Target audience

The target audience, whether internal or external, technical or non-technical, influences the level of detail and confidentiality required in the reporting and should therefore be clearly specified from the start. LCAs involving comparative statements for public disclosure must adhere to additional requirements outlined in ISO 14040 and 14044:2006, due to the potential wider implications of their findings.

Function, functional unit and reference flow

The function of a product refers to the specific services or performance it offers, while the functional unit quantifies this function in detail, including aspects such as quantity, quality and duration of use. This unit serves as a standard reference against which impacts are evaluated, ensuring that LCA results are meaningful, comparable and applicable to real-world decision-making. The reference flow then defines the quantity of the product needed to fulfil the specified functional unit.

Literature reviews reveal significant variations in functional units across LCAs involving reusable surgical instruments, ranging from 'one use', which distributes the impacts of reusable instruments over their number of uses in their life cycle, to functional units based on the overall lifespan of these instruments. Since environmental impacts are evaluated based on the defined functional unit, different functional units can lead to varying results among LCA studies examining similar instruments. For instance, the study by Donahue et al. used a functional unit of 20 uses to compare a reusable stainless steel vaginal speculum with an assumed lifespan of 20 uses of 20 single-use acrylic specula.

In contrast, Rodriguez and Hicks employed a functional unit of 5,000 uses, comparing 100 stainless steel reusable specula, each with an assumed lifespan of 50 uses, against 5000 single-use acrylic specula. Although both studies reported lower carbon footprints for reusable specula compared to the single-use versions, Rodriguez and Hicks' study reported significantly higher climate change impacts due to the larger functional unit used, compared to Donahue et al.'s findings.

However, the different assumptions regarding the lifespan of the reusable stainless steel vaginal speculum (50 uses in the study by Rodriguez and Hicks compared to 20 uses in Donahue et al.) highlight the challenges of standardizing functional units in LCAs involving reusable surgical instruments, which may lead to varying LCA results. Although the functional unit is typically based on the overall lifespan of the instruments under study, the actual lifespan of a specific reusable instrument is often not fixed and can vary between facilities due to several factors.

These include the complexity of procedures (as instruments employed in more invasive procedures may degrade more quickly), the frequency and quality of maintenance (with poor maintenance leading to premature wear and damage), and storage conditions (instruments should be stored in a dry, clean and well-organized manner to avoid physical damage).

Scenario analyses from various studies illustrate how modifications to functional units, based on different assumptions about an instrument's lifespan, can alter a study's findings.

For example, in the baseline scenario by Boberg et al.[55], a functional unit of 500 procedures was based on an assumed lifespan of 500 uses for a mixed trocar system that includes both single-use and reusable components. In this case, no significant differences were found for resource use and ecosystem impacts when comparing the mixed trocar system to 500 single-use counterparts. However, when the functional unit was adjusted to 750 procedures based on an assumed lifespan of 750 uses for the mixed system, the 750 single-use systems displayed a greater impact on both resource use and ecosystem health. Conversely, reducing the mixed system's lifespan and functional unit to 250 procedures made the single-use systems appear more favorable.

55. Boberg, L., Singh, J., Montgomery, A., & Bentzer, P. (2022). Environmental impact of single-use, reusable, and mixed trocar systems used for laparoscopic cholecystectomies. PLoS One, 17(7), e0271601.

By conducting a break-even analysis, the study by Rodriguez and Hicks further highlights how differences between the assumed lifespan of a reusable instrument and its actual number of uses can lead to misleading conclusions if not carefully considered. They found that the disposable speculum breaks even with the reusable speculum around the 40th use regarding the ecotoxicity impact category, which assesses harmful effects on the environment and organisms.

With a functional unit of 50 uses, based on an assumed lifespan of 50 uses for the reusable speculum, their findings indicate that the reusable option is more environmentally favorable for this specific impact category.

However, if the speculum were actually used only 20 times, as assumed in the study by Donahue et al.,[56] and the functional unit adjusted to 20 uses, the disposable speculum would be preferred based on its ecotoxicity impact results. Therefore, they conclude that, given this uncertainty, no instrument outperforms the other in terms of ecotoxicity impact.

56. Donahue, L. M., Hilton, S., Bell, S. G., Williams, B. C., & Keoleian, G. A. (2020). A comparative carbon footprint analysis of disposable and reusable vaginal specula. American journal of obstetrics and gynecology, 223(2), 225-e1.

To accurately quantify the functional unit and ensure reliable assessments across instruments that serve similar functions, a profound technical understanding of the analyzed instrument, along with LCA expertise, is essential.

Functional units should reflect typical or average usage scenarios based on standard practices that are well-supported and agreed upon by stakeholders familiar with the practical application of the instrument. Moreover, performing a break-even analysis is essential to address uncertainties related to an instrument's actual lifespan, preventing incorrect conclusions from being drawn due to potentially inaccurate assumptions. Additionally, providing detailed descriptions, photographs and technical specifications can enhance clarity regarding the product being studied.

Phase 2: Life Cycle Inventory

8.2 Life Cycle Inventory

During the Life Cycle Inventory (LCI) phase of an LCA, the actual data collection and modelling of the product system are performed in line with the goals and specifications set in the scope phase. It not only provides the necessary data for the subsequent LCIA phase but also provides insights for refining scope settings based on new insights or data to better reflect actual conditions. The LCI phase typically is the most resource-intensive part of an LCA.

Life Cycle Inventory modelling framework

The choice of Life Cycle Inventory (LCI) modelling framework, either attributional or consequential, affects which processes are included in the assessment of the product's life cycle, how they are integrated into the LCI model, and the types of inventory data and additional information required. Attributional modelling focuses on quantifying the environmental impacts directly linked to a product system, covering all unit processes throughout its lifecycle. This framework is particularly effective for documenting the product supply chain as it stands, specifying the share of global environmental impacts associated with the product without considering broader market or environmental changes resulting from product-related decisions.

In contrast, consequential modelling examines how hypothetical product-related decisions can lead to changes in market behavior and, consequently, alterations in environmental flows. This dynamic approach makes consequential modelling suitable for assessing the broader environmental impacts of new products or policies.

System boundaries

Defining system boundaries is crucial for distinguishing the analyzed product system from the broader technological sphere, as it clearly specifies which life cycle stages and processes are necessary to achieve the system's functional unit. In cradle-to-grave LCAs the entire life cycle is covered, from raw material acquisition to disposal, whereas cradle-to-gate LCAs focus on the initial stages, from raw material acquisition up to the point where the product is ready for distribution, excluding its use and disposal.

By establishing precise system boundaries according to the chosen LCI modelling framework, all significant environmental interactions that cross the boundary between the system and the ecosphere are considered, allowing less relevant processes to be excluded or simplified. For transparency, these boundaries should be visually represented in a semi-schematic diagram to show included and excluded life cycle stages and processes. However, accurately defining system boundaries can be challenging, particularly for LCAs of surgical instruments, due to the complexity of the instruments and their life cycles. These instruments, particularly the complex ones, typically consist of various materials and components and undergo specialized processes, such as component manufacturing, assembly, reprocessing for reuse and waste treatment, each with variables that vary by location or facility.

In comparative LCAs of surgical instruments, certain processes are often excluded to simplify the analysis, especially when these processes are not directly related to the product life cycles or are assumed to be comparable for both products. This is particularly common for elements related to the use phase, such as capital goods and hospital infrastructure.

However, although the impacts associated with the production and disposal of capital goods used for instrument reprocessing, such as washing machines and autoclaves, are typically excluded due to the assumption that these impacts are not directly connected to the instrument's life cycle, their operational use is generally included. While the long lifespan of these machines makes the production and disposal impacts negligible for a single device, their operational use can contribute significantly to the environmental footprint of a reusable instrument.

Despite efforts to simplify the analysis by excluding less relevant processes, LCA practitioners often face difficulties in capturing all relevant processes, as detailed operational data is often unavailable. This forces them to make trade-offs: they can either include additional elements and processes to expand the scope of the assessment, which may risk compromising data quality, or exclude them to preserve data quality, potentially limiting the comprehensiveness of the analysis. Such inconsistencies in defining system boundaries can lead to significant variations in reported environmental impacts and may result in inconsistent findings.

This issue is particularly evident in studies where different decisions have been made regarding the inclusion or exclusion of components or processes related to instrument reprocessing, as can be seen in the studies by Donahue et al.[56] and Rodriguez and Hicks. After adjusting for functional units, Donahue et al.[56] reported a global warming potential for a stainless-steel reusable vaginal speculum that was more than double that reported by Rodriguez and Hicks. This variation was primarily attributed to Donahue et al.'s[56] inclusion of sterilization pouches, which were excluded in the analysis by Rodriguez and Hicks.[57]

Furthermore, while many LCAs of surgical instruments aim to cover the full life cycle of the instrument, determining its end-of-life fate can be challenging due to limitations in data and time. As a result, simplified assumptions are often made about the end-of-life phase, which in turn influence decisions about which processes and elements are included or excluded from the system boundaries. For instance, in LCAs that assume recycling, material recovery is typically factored into the system boundaries, leading to reduced waste and decreased demand for virgin materials.

This approach is often applied to metal instruments, such as stainless steel scissors or specula, where recycling is feasible because these metals retain their properties and reprocessing them poses minimal biological risks. In contrast, in LCAs that assume landfilling as the end-of-life treatment, future material recovery is not accounted for, as no materials are recovered. Since landfilling is generally viewed as a less sustainable option, it is typically only applied to instruments made from materials that cannot be recycled or incinerated, such as certain composites or polymers.

57. Morris, M. I. R., & Hicks, A. (2022). Life cycle assessment of stainless-steel reusable speculums versus disposable acrylic speculums in a university clinic setting: a case study. Environmental Research Communications, 4(2), 025002.

Even in studies that assume similar end-of-life pathways, system boundaries can still vary. This is particularly evident in LCA studies that consider the disposal of instruments as waste followed by incineration.

For instance, single-use instruments made from plastics or composites, such as plastic surgical scissors or laryngeal mask airways, which are often difficult to recycle due to infection risks, are typically treated as waste and incinerated. Similarly, complex devices like single-lung ventilation systems, composed of multiple parts and materials, complicate the separation of reusable components, leading to their classification as waste and subsequent incineration.

Some LCAs include energy recovery from the heat produced during incineration within the system boundaries, subtracting this recovered energy from the device's overall lifecycle energy consumption. However, other studies do not account for this energy recovery, leading to variations in reported LCA outcomes.

Extending the lifespan of surgical instruments through repair or remanufacturing processes has significant potential to reduce their environmental footprint, as demonstrated in studies by Rizan et al.[58] and Schulte et al. For example, Rizan et al. showed that repairing a reusable stainless steel scissor is more environmentally advantageous than producing a new one, while Schulte et al. found that remanufacturing a disposable catheter offers greater environmental benefits than manufacturing entirely new devices.

Despite these potential benefits, repair and remanufacturing remain underexplored and are not yet widely adopted. The primary challenge lies in the lack of detailed data needed to account for all related processes and impacts, which complicates their inclusion in the system boundaries of LCAs for surgical instruments. This issue is especially prominent for the repair or remanufacturing of more complex instruments, which consist of various materials and components, so that their repair or remanufacturing requires specialized equipment and techniques, for which little data is available.

58. Rizan, C., Steinbach, I., Nicholson, R., Lillywhite, R., Reed, M., & Bhutta, M. F. (2020). The carbon footprint of surgical operations: a systematic review. Annals of surgery, 272(6), 986-995.

Additionally, determining which parts can be reused and estimating their potential lifespan demands extensive research, often beyond the scope of standard LCA assessments. Schulte et al. addressed this challenge by incorporating a circularity metric into their LCA, accounting for the reuse of parts and materials over multiple product cycles. While remanufacturing was found to be more advantageous when multiple life cycles were considered, the overall environmental impacts were higher compared to focusing on a single life cycle, underscoring how LCA results can vary based on how end-of-life pathways are integrated into system boundaries.

In some LCA studies, uncertainties about an instrument's actual end-of-life pathway and material recovery rates have led to the decision to omit the end-of-life phase altogether. However, while certain processes or entire phases might be deliberately excluded due to data limitations, others might be unintentionally overlooked, despite their potential to contribute significantly to the overall environmental impact.

Given this, it is critical to carefully assess and justify which processes or elements are excluded from the system boundaries, based on the study's goals and the data available. With reprocessing activities playing a major role in the environmental impacts of surgical instruments, particularly for these activities, system boundary decisions should be made carefully.

Drawing insights from high-quality studies of similar products is suggested, and any exclusions should be supported by quantitative reasoning rather than based purely on the type of activity or component. To improve understanding and ensure transparency and completeness, a detailed overview of all processes and aspects excluded from the system boundaries, along with their potential environmental contributions, is highly recommended.

8.3 Multifunctionality

To effectively capture the complexities of a product system, it is essential to decide already during the scope definition how to manage the multifunctionality of processes that yield multiple products or functions. The ISO 14044:2006 standard provides a hierarchy of approaches to effectively isolate the inventory associated with the specific product or function of interest. Subdivision is the preferred method when possible, as it breaks down multifunctional processes into simpler, single-function processes, thereby eliminating the need for allocation calculations.

System expansion and substitution tackle multifunctionality by extending the system to incorporate additional functions or by replacing unnecessary functions with alternatives, which allows for crediting of avoided burdens and adjusting life cycle inputs and outputs accordingly. In contrast, allocation requires careful calculations to quantify total functional output and distribute environmental burdens among the various products or functions based on shared characteristics such as mass, energy content or economic value.

The selection of these methods largely depends on the LCI modelling framework adopted and the unique characteristics of the product system being analyzed. While attributional modelling typically uses allocation, consequential modelling aims to minimize allocation by utilizing system expansion and substitution instead, when direct subdivision is not feasible.

In the life cycle of reusable surgical instruments, reprocessing practices are a key example of multifunctional processes, as multiple instruments are often reprocessed simultaneously in sterilization and washing machines.

In LCAs that involve reusable instruments and utilize attributional modelling, allocation is typically based on the mass load of instruments in washing or sterilization machines. However, as these mass loads can vary between facilities and even between reprocessing cycles, accurately isolating the proportional impact of each instrument per session can be quite challenging. Variations in assumptions regarding loading efficiencies can result in different environmental outcomes for reprocessing practices, influencing the findings of LCA studies focused on reusable instruments.

For instance, Unger et al. found that their baseline scenario of reusing a dental bur 30 times results in lower environmental impacts across all considered categories compared to using it once, assuming the machines are fully loaded. However, in scenarios with suboptimal loading, the environmental benefits diminish, and when assuming a worst-case scenario where machines are only one-third full, reusing the bur 30 times can even lead to more adverse impacts than using it just once.

Additionally, Sørensen and Grüttner[59] observed that reusable bronchoscopes had a higher climate change impact than single-use options in their baseline scenario, where only one bronchoscope was cleaned per operation. However, if more than two bronchoscopes were cleaned simultaneously, the climate change impact significantly decreased, making reusable options more environmentally favorable.

59. Sørensen, B. L., & Grüttner, H. (2018). Comparative study on environmental impacts of reusable and single-use bronchoscopes. American Journal of Environmental Protection, 7(4), 55-62.

Variations in how reprocessing multifunctionality is managed have even resulted in contradictory findings across different LCA studies in the surgical field. For example, while Friedericy et al.[60] found that using an aluminum rigid sterilization container (RSC) for sterilizing instrument sets was more environmentally beneficial than single-use blue wrap, Rizan et al. reached the opposite conclusion. In their analysis, Rizan et al. assigned the environmental impacts of sterilization to the instruments themselves rather than to the packaging systems. Therefore, they only considered the washing of RSCs, which demands significant energy and water consumption, whereas single-use blue wrap does not suffer such washing impacts.

60. Friedericy, H. J., van Egmond, C. W., Vogtländer, J. G., van der Eijk, A. C., & Jansen, F. W. (2021). Reducing the environmental impact of sterilization packaging for surgical instruments in the operating room: a comparative life cycle assessment of disposable versus reusable systems. Sustainability, 14(1), 430.

Considering these examples of how LCA findings can be affected by the management of multifunctionality in reprocessing practices, it is crucial that the approach aligns with the selected LCI modelling framework and the unique characteristics of the instrument being studied.

In particular, for LCAs employing attributional modelling, allocations should represent typical or average loading scenarios based on standard practices that are recognized and agreed upon by stakeholders familiar with instrument reprocessing. Ideally, a reference hospital should be selected as a basis for gathering accurate data on reprocessing practices, with the chosen loading scenarios then customized to match the conditions at this reference facility.

8.4 Types of data

It is advised to prepare a detailed overview of the types of data and information required for the modelling of the life cycle inventory of the product system, covering for example raw inventory data, use patterns and end-of-life data. Attributional modelling uses historical data to represent the processes as they currently are or are expected to be, preferring specific, directly measured data where possible and only using extrapolated average data when needed.

Consequential modelling, on the other hand, should include marginal data related to the production of inputs, particularly when the product under study only has a relatively small impact on total production volume. Marginal data capture the changes in environmental burdens relative to production adjustments as linear approximations, meaning that the environmental impact per unit of production increase remains approximately constant.

8.5 Quality and sources of data

The availability of high-quality data sets, defined by their accuracy, precision and completeness, is crucial for obtaining reliable LCA results and should therefore already be established during the goal and scope definition phase of the assessment. While accuracy ensures that the data accurately reflects the true characteristics of the system being analyzed in terms of technological, geographical, and temporal representativeness, precision measures the uncertainty within the collected or modelled data, and completeness evaluates whether all relevant processes and environmental interventions are included in the inventory. Identifying and selecting reliable data sources early on, such as well-documented and externally verified databases, can improve data quality and significantly simplify the review process.

Data collection

The data collection process involves gathering quantitative information on all relevant inputs and outputs associated with the product's life cycle, based on the system boundaries defined during the scope phase. This includes product flows, waste flows and elementary flows, which are obtained through measurements, interviews, literature reviews and database searches.

For processes specific to the product system, primary data, collected directly from product producers or process operators, is preferred. When necessary, this primary data can be supplemented with secondary data from sources like patents, existing databases, literature or other projects. In instances where data is also lacking from these sources, expert judgement may be applied. For processes not specific to the product system, it is common to rely on secondary data from databases and research groups.

One of the main challenges in conducting LCAs is the lack of primary data on the specialized life cycle processes specific to the surgical instrument under study. Hospitals and manufacturers often fail to track or report critical information related to material flows, energy use and waste generation, which is essential for assessing environmental impacts.

This primary data gap is further widened by the different priorities of stakeholders who may possess this valuable data but vary in their willingness to engage in the LCA process, influencing both the level of detail and type of data they provide. This results not only in a lack of primary data, but the data that is provided is often limited and inconsistent in quality.

For instance, suppliers of semi-finished products and raw materials, as well as instrument manufacturers themselves, may be reluctant to share data due to fears of competitive disadvantage. Additionally, instrument manufacturers often lack comprehensive information about the composition and manufacturing processes of standard ‘off-the-shelf’ components, such as screws, fasteners, electronic components and connectors, as these components are typically sourced from external suppliers rather than produced in-house.

Furthermore, with the limited number of potential suppliers in the surgical instrument market, it is crucial that good relationships between manufacturers and suppliers are maintained, which can further restrict data availability.

On the healthcare provider side, preferences for specific instruments can result in adjustments to usage data, either being overly optimistic or pessimistic depending on their preferred options, or the manufacturers or suppliers may choose not to disclose any usage data at all.

Therefore, the successful execution of LCAs for surgical instruments depends significantly on the cooperation of stakeholders involved in the instrument’s life cycle. To improve the reliability of LCAs in the surgical field, practitioners must actively encourage stakeholder participation by emphasizing the importance and urgency of the study.

It is essential for practitioners to secure stakeholders’ commitment to the process and uphold any agreements made. In cases where variations in the level of detail in primary data are observed, practitioners should consider utilizing secondary data to maintain more consistent data quality.

To fill the gaps in primary data concerning the manufacturing phase of an instrument, LCA practitioners often rely on secondary data from comprehensive LCI databases that offer detailed information at the unit process level for various materials and manufacturing processes.

The same approach applies to data collection for an instrument's end-of-life phase, where simplified assumptions are often made, relying on secondary data from databases, to fill in the gaps of primary data on its actual end-of-life pathway. Thus, the data collection process is further constrained by a frequent lack of specific and up-to-date secondary data needed to address the gaps in primary data on an instrument's specialized life cycle processes.

Due to the frequent unavailability or difficulty in obtaining specific data, the secondary data usually relies on averages. For instance, these databases offer insights into common materials and manufacturing processes for standard components, such as off-the-shelf items lacking primary data, or market processes reflecting the average consumption mix of a material. While the use of averages helps fill data gaps, it may limit the accuracy of representing the actual conditions for the instruments under study, potentially compromising the quality of the data. Furthermore, there are many different databases available, each varying in content and reliability. Some are recognized for their comprehensiveness and transparency, such as the ecoinvent database which contains over 10,000 datasets, while others may provide incomplete or outdated information. As a result, the choice of database can significantly affect data quality, and using multiple databases may lead to data quality inconsistencies.

In contrast to the numerous comprehensive databases that provide information on a wide range of materials and manufacturing processes as well as potential end-of-life pathways, detailed databases specifically focusing on the usage practices of surgical instruments are not readily available. As a result, practitioners often have to rely on existing literature or prior studies to obtain secondary data that fill the gaps in primary data concerning the use phase of an instrument. However, usage practices can vary significantly across countries, regions, or even individual hospitals, which affects the usability and transferability of the information and data found in the literature.

As a result, secondary data on usage practices sourced from existing literature may not accurately represent the actual conditions of the instruments being examined. Inaccuracies in assumptions related to reprocessing variables, such as reuse frequency and loading efficiencies, can lead to biased findings, as the environmental impact of an instrument's use phase is heavily influenced by these assumptions. Scenario analyses from various LCA studies have shown that by extending the assumed lifespan of reusable instruments, thereby increasing their reuse frequency, and by improving the assumed loading efficiencies, reusable instruments can become more environmentally favorable than single-use counterparts, even when the baseline scenario initially suggested otherwise.

As mentioned earlier, in order to produce reasonably reliable results in the absence of primary data, it is essential that information on reprocessing procedures drawn from literature or previous studies reflects typical or average scenarios based on standard practices. Ideally, this data should be representative of the specific facility conditions, with assumptions validated by experts familiar with instrument reprocessing.

To ensure data quality, it is essential that secondary data for the manufacturing and end-of-life phase is sourced from well-documented, externally verified databases, and that it reasonably reflects actual conditions. Moreover, relying on a single database can help practitioners maintain methodological and data quality consistency.

Moreover, the environmental impact of reprocessing a surgical instrument is greatly influenced by the assumed reprocessing technique. Lalman et al. note that ethylene oxide (ETO) gas sterilization, a chemical method, consumes substantial energy due to long sterilization cycles and the need for additional detoxification to handle ETO residue toxicity. For conventional surgical instruments, this generally makes it a much less environmentally favorable technique compared to conventional steam sterilization, which uses heat.

However, as highlighted by Samenjo et al.,[61] complex surgical instruments often include heat-sensitive plastics, necessitating chemical sterilization methods over steam sterilization to maintain their durability which can result in lower environmental impacts per use of these instruments, as the total impact is distributed over a greater number of uses. Nonetheless, Lalman et al.[62] found that reusing a heat-sensitive electrophysiological catheter five times with ETO had much greater environmental impacts than using five catheters once.

Their scenario analysis, however, indicates that hydrogen peroxide sterilization, another chemical technique, reduces the overall environmental impacts of reusing the catheter by nearly 20 times compared to ETO, though it remains slightly less favorable than single-use.

In contrast, Unger and Landis[63] found that reusing seven conventional surgical instruments with ETO gas sterilization reduced global warming impacts compared to single-use, but significantly increased human health impacts.

These findings highlight that significant impact differences can be found depending on the specific reprocessing technique used, and the actual impacts vary per instrument based on their complexity. It is not a simple matter of one reprocessing technique being universally recognized as the most environmentally favorable for all instruments, highlighting the importance of establishing the true scenario for each specific surgical instrument under study.

61. Samenjo, K. T., Ramanathan, A., Gwer, S. O., Bailey, R. C., Otieno, F. O., Koksal, E., ... & Diehl, J. C. (2023). Design of a syringe extension device (Chloe SED®) for low-resource settings in sub-Saharan Africa: a circular economy approach. Frontiers in Medical Technology, 5, 1183179.

62. Lalman, C., Karunathilake, H., & Ruparathna, R. (2023). To dispose or to reuse? Analyzing the life cycle impacts and costs of disposal, sterilization, and reuse of electrophysiological catheters. Sustainability, 15(6), 5363.

63. Unger, S., & Landis, A. (2016). Assessing the environmental, human health, and economic impacts of reprocessed medical devices in a Phoenix hospital's supply chain. Journal of Cleaner Production, 112, 1995-2003.

Studies by Hogan et al.[64] and Kemble et al. furthermore illustrate how different assumptions about energy sources for sterilization can result in conflicting outcomes. Hogan et al. determined that the climate change impact of a reusable flexible cystoscope was greater than its single-use counterpart, as they assumed the use of Australian coal-based (high-carbon) energy. In contrast, Kemble et al. concluded that a reusable flexible cystoscope was environmentally beneficial when reprocessing involved lower power consumption.

Similarly, McGain et al.[65] showed that reusable anesthetic equipment had climate change impacts comparable to single-use alternatives when relying on coal-based energy, while their scenario analysis indicated that switching to renewable or natural gas-based electricity for reprocessing could significantly reduce impacts, making reusable anesthetic equipment more environmentally favorable compared to single-use options.

Additionally, scenario analyses should be conducted to assess how variations in reprocessing and end-of-life assumptions influence outcomes, ensuring the robustness of LCA findings and broader applicability in practical situations.

64. Hogan, D., Rauf, H., Kinnear, N., & Hennessey, D. B. (2022). The carbon footprint of single-use flexible cystoscopes compared with reusable cystoscopes. Journal of Endourology, 36(11), 1460-1464.

65. McGain, F., & McAlister, S. (2023). Reusable versus single-use ICU equipment: what’s the environmental footprint?. Intensive Care Medicine, 49(12), 1523-1525.

8.6 Problems with life cycle modelling

The life cycle model is constructed by connecting and appropriately scaling all data sets to accurately represent the product system's functional unit. This involves managing multifunctionality within the system to ensure precise attribution of processes to their respective inputs and outputs. The final life cycle model should aggregate the correctly scaled inventories of all processes within the defined system boundary, including only the reference flow and elementary flows such as emissions, energy consumption and material flows. It is advisable to present the inventory results in a table that clearly outlines all inputs and outputs of the product system, enhancing transparency and understanding of the environmental impacts. To protect sensitive information, any confidential or proprietary details should be aggregated.

In many cases, LCA software tools like SimaPro, which rely on databases such as ecoinvent, are used to calculate a product's environmental footprint based on its life cycle model. However, aligning inventoried data with predefined materials and processes from these databases can be challenging, especially for LCAs of complex surgical instruments that involve specialized components and materials not commonly used in other industries.

These databases often offer predefined processes for modelling off-the-shelf components, but these may not always be expressed in mass units, limiting their applicability in LCA modelling. Additionally, the specific materials or processes required may not always be available. When specific inventory data is unavailable, practitioners should select alternative materials or predefined processes that best approximate the required data, drawing from common practices for similar applications in the literature. In cases where multiple suitable alternatives exist, it is recommended to assess the environmental differences between potential substitutes. Particularly regarding material selection, practitioners may face challenges in selecting the most appropriate alternatives from an array of suitable options, as databases often provide several variations of certain materials, each with slight differences in treatment or condition.

For example, in a study by Samenjo et al., when modelling the manufacturing phase of a reusable syringe extension device in SimaPro, the necessary materials and processes were missing from the ecoinvent database. Therefore, the researchers substituted granulated polypropylene (PP) for homopolymer PP, wrought aluminum alloy for aluminum 6061 grade, and chose extrusion techniques instead of injection molding.

While these substitutions might approximate the environmental impacts of the original materials and processes, choosing alternatives that best match the required data is not always straightforward and any inaccuracies can significantly affect the reliability of LCA results.

If no significant variation in environmental impact is found, the choice may have minimal influence on the final results. However, if large differences are identified, decisions should be guided by industry standards or expert insights. Alternatively, selecting the process with the highest environmental impact can help ensure results are not underestimated.

8.7 Phase 3: Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) phase of an LCA evaluates the magnitude and significance of potential environmental impacts associated with the product system by converting the documented elementary flows into environmental impact indicators related to human health, natural resources and the environment. This phase uses the LCIA method, the corresponding category indicators, whether midpoint or endpoint, and any applicable LCA software outlined in the scope phase. The outcomes of this phase provide the basis for the subsequent interpretation phase.

However, due to challenges related to data availability, with information frequently being outdated, of uncertain quality or not comparable, especially when considering specific regions or impact categories, LCIA methodologies tend to calculate environmental impacts as ‘potential impacts’, without accounting for local variations, time-specific factors or rare events. This generalization, coupled with assumptions about linear relationships between pollutants and impacts and the frequent use of worst-case scenarios, reduces their ability to accurately capture real-world environmental interactions. This inherent limitation can affect the reliability of LCA findings, so practitioners should be aware of it when interpreting results.

Life Cycle Impact Assessment method

To capture a wide range of potential environmental impacts aligned with the study's objectives, various life cycle impact assessment (LCIA) methodologies have been developed, including Revised Continuous Improvement and Progressive Embodiment (ReCiPe)[66] and the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). These methodologies focus on various midpoint impact categories (midpoints represent impacts at an intermediate stage in the cause-effect chain such as climate change, CO_2 emissions versus endpoints represent the damage to human health, ecosystems, and resource availability), such as global warming potential, ozone depletion and human toxicity.

Some also provide aggregated single-score endpoint indicators to evaluate broader impacts on human health, ecosystems and natural resources.

When using LCA software like SimaPro, inventory data is automatically classified into the impact categories defined by the selected LCIA method. Each contribution is quantified through characterization; for instance, global warming potential is typically measured in kg CO_2-equivalents at the midpoint level. At the endpoint level, impacts reflect more specific damages, such as species loss or human health effects measured in disability-adjusted life years (DALYs). Finally, the quantified individual impacts in each category are ultimately aggregated to provide an overall assessment of the product's environmental footprint.

Since the impact categories serve as outcome measures, the choice of LCIA method is crucial in shaping results. Therefore, when selecting these methods, it is essential to ensure they align with the study's objectives and address all relevant environmental issues associated with the analyzed system. Any exclusions of impact categories must be justified based on their relevance, while additional identified impacts require appropriate LCIA methods to maintain necessary standards. LCAs that model unique conditions or limit impact coverage may restrict the usability and transferability of results, so such limitations should be clearly identified from the start.

66. Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. (2009). ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, 1, 1-126.

Normalization and weighting

Normalization and weighting are needed for the interpretation of LCA results. Normalization helps to understand the magnitude of the impacts of the product under study relative to a broader context by adjusting the impact assessment data to a common scale or reference, such as national averages or per capita impacts. Weighting enhances the decision-making process by assigning different levels of importance to various environmental impact categories based on normative values. To ensure consistency in the application of these measures, they should be planned during the goal and scope definition phase. However, in studies producing comparative assertions intended for public disclosure, weighting is generally avoided to maintain neutrality and transparency in the findings.

Scenario and uncertainty analyses

Scenario analyses play a key role in verifying the robustness of comparative LCA results by evaluating the results under varying conditions, including best-case, most likely case and worst-case scenarios. This helps to determine whether the observed differences between systems are substantial enough to support claims of one system's superiority over another. These scenarios adjust for different data and methodological assumptions, such as variations in functional unit properties, inventory data values and allocation methods. Additionally, performing uncertainty calculations can enhance the robustness analysis by assessing the overall uncertainty of the conclusions due to natural variations in data values under specific conditions. However, these calculations are only useful when they have not already been used to develop the different scenarios in the scenario analysis.

Despite the importance of such analyses in enhancing the reliability of LCA findings, a systematic review on sustainability strategies for surgical instruments showed that only 19 out of 27 LCA studies included scenario analyses, particularly regarding reprocessing practices and end-of-life pathways, and only 8 out of 27 conducted uncertainty analyses. This underscores the need for greater emphasis on incorporating these analyses in LCAs of surgical instruments to ensure more reliable outcomes.

Reporting

The format and level of reporting should match the study's goals and the intended audience, ranging from simplified standalone data sets to detailed public comparative analyses. It's important to use standardized reporting formats wherever possible and to keep confidential information separate. The chosen level of reporting, whether for internal use, limited external distribution, or broad public access, should reflect the impact of the findings, ensuring that the presented information is clear and cannot be misinterpreted.

Critical review

Conducting a critical review by experts not involved in the LCA is crucial for validating the study's quality and credibility. Given that different data and methodological assumptions in LCA studies on surgical instruments may result from LCA practitioners' specific interests in the study outcomes, the need for external validation by independent experts is emphasized. This process encourages practitioners to clarify their views and assumptions. The type of review, whether being an internal independent review, an external review, or a panel review should be established from the start to ensure that the LCA meets review requirements, thereby optimizing the overall data collection, documentation, and reporting process.

8.8 Phase 4: Interpretation

In the interpretation phase the LCIA results are evaluated against the goal and scope, focusing on the quality of data and methodological choices and assumptions, including completeness, accuracy and precision, as well as their consistency. The interpretation guides iterative refinements of the LCI model until alignment with the study's goal and scope definition is achieved, ensuring methodological appropriateness and data quality. This thorough evaluation process of the results aims to derive robust conclusions and recommendations appropriate to the LCA's intended applications. Results should be presented clearly to allow the audience to assess the robustness of conclusions and understand any limitations.

Significant aspects identification

Effective interpretation of LCA results begins with identifying key aspects that significantly influence the outcomes. This includes major life cycle stages, processes and elementary flows, which are typically highlighted through contribution analyses. These analyses break down the contributions of each element, quantifying their impact and often representing the data visually in formats like pie charts or stacked columns. Additionally, methodological choices and assumptions that may substantially affect the results can be pinpointed through the evaluation of scenario analysis outcomes.

Results evaluation

The results are then assessed for completeness, sensitivity and consistency in relation to the data, methodological choices and assumptions, with particular attention given to the significant aspects identified earlier. Completeness checks determine whether all relevant processes and flows are included, while sensitivity checks make sure the accuracy and precision of the results meet the study's requirements, enhancing their robustness where possible. Consistency checks ensure that all methodological choices, impact assessment steps and data quality across processes align with the study's objectives.

Iterative approach

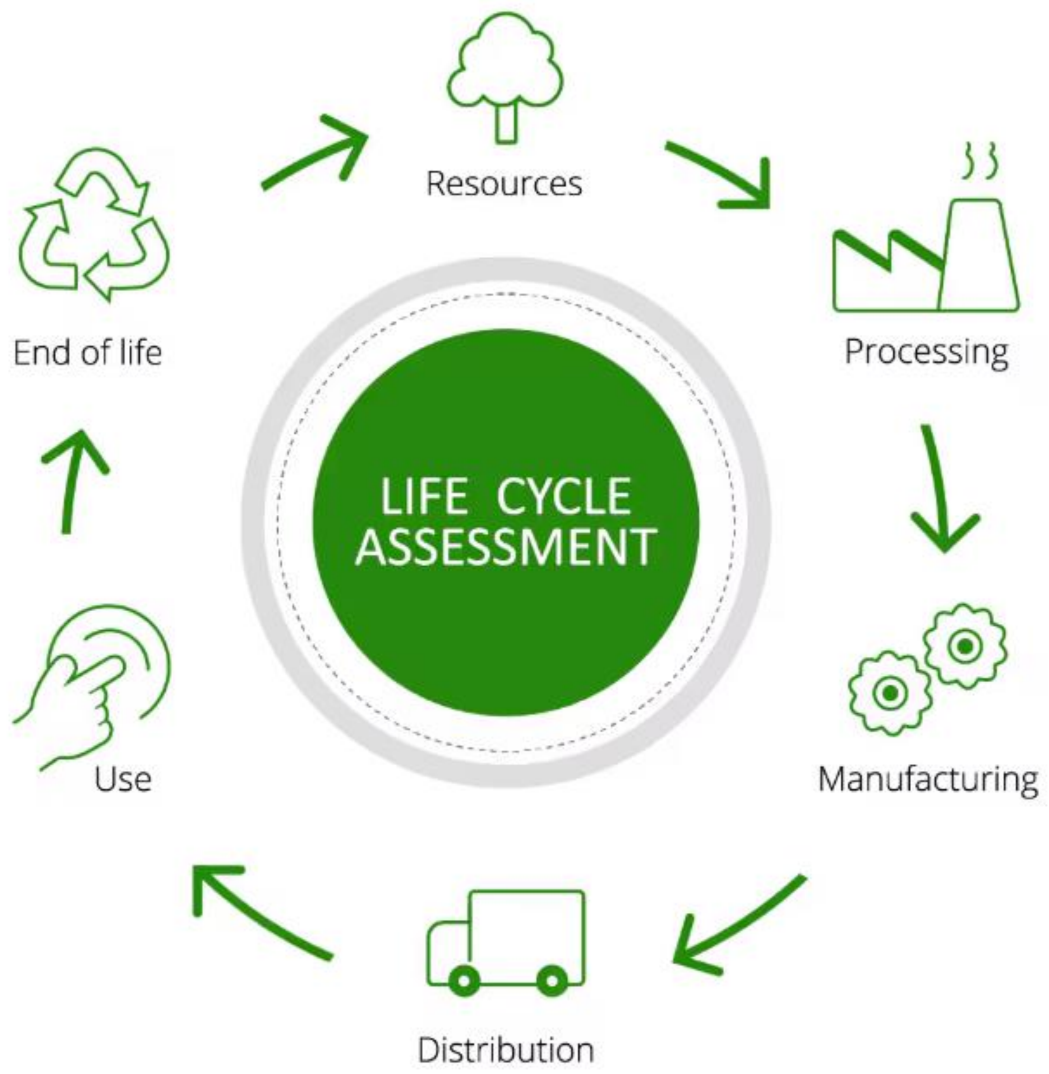
The iterative process is guided by the completeness, sensitivity and consistency evaluations, aimed at refining the life cycle model to meet the quality and consistency standards established during the goal and scope definition. Enhancements may include incorporating more specific primary data, improving the quality of data used in methodological decisions, and revising data for life cycle stages or flows that were initially underestimated. If enhancing data quality for certain contributors proves impractical, this should be documented, and those contributors may be excluded. After making these adjustments, the results are recalculated, and completeness, sensitivity and consistency evaluations are repeated to inform further iterations. It is important to note that insights gained from each iteration may require adjustments to the study's goal and scope definition, especially if data limitations cannot be resolved.

For LCA practitioners, it's crucial to find a balance between making early decisions, which tend to be more neutral but may suffer from data quality issues, and postponing decisions, which enhances data quality but introduces the risk of bias. Both practitioners and readers of the LCA report must be aware of potential biases arising from the iterative nature of LCA methodology, which allows for changes throughout the process, particularly if the findings do not meet initial expectations. Documenting all changes to methodological decisions and their impacts on results can be challenging, but the more clearly and transparently adjustments are recorded, the more robust and reliable the LCA methodology becomes.

Determining the optimal level of detailed data to accurately represent the product system's functional unit is complex, especially for new technologies and complex product systems like surgical instruments, which have not been as extensively studied through LCAs as instruments in other sectors.

Therefore, the reliability of LCA results heavily depends on practitioners' skills and experience in navigating this complexity and addressing data gaps while defining and modelling the product system. This highlights the importance of having a strong technical understanding of the surgical instrument in question, as well as expertise in LCA methodologies. Adequate training in these areas can significantly enhance the reliability of LCA's for surgical instruments.

Furthermore, this underscores the value of repeating LCA studies on surgical instruments to gather insights that could facilitate the collection of the detailed data necessary for accurate evaluations in this field. The initial LCA may utilize average data for processes related to the product system, combined with expert judgement, to identify key processes and elementary flows. Identifying major contributors early on enables a more targeted approach in subsequent LCA studies, which can result in obtaining more detailed data on the most relevant aspects of the system.



Conclusions and recommendations

Once the study's goals and application requirements are met, the results are analyzed across the entire system, integrating various scenarios and uncertainty assessments. Conclusions and recommendations are formulated while carefully considering any remaining data gaps, sensitivities and inconsistencies.

Table 1: Summary of identified risk factors and corresponding mitigation strategies of LCAs

Risk factor	Source of risk	Example	Mitigation strategy	Strategy implementation
Potential of biased decisions	The iterative nature of LCA methodology introduces the risk of bias, particularly if the findings do not meet initial expectations. LCA practitioners or the stakeholders funding the study may have specific interests in the outcomes, which could lead to biased decisions throughout the LCA process.	Although reusable surgical instruments generally offer environmental benefits over disposable alternatives, a study by Leiden et al. concluded that a reusable lumbar fusion instrument set was nearly seven times more harmful to the climate than its single-use counterpart. However, it was later revealed that the study had been funded by the manufacturer of the single-use set, raising doubts on the reliability of its finding.	Promote transparancy	Ensure full transparency regarding the motivations for conducting the LCA, the entities commissioning the study, the LCA practitioners involved, and any co-financing parties. Additionally, clearly document any changes made to methodological decisions during the process and their potential effects on the results. Engage a third-party auditor to periodically review the LCA methodology and key decisions to ensure alignment with industry standards and verify that changes are scientifically justified and unbiased.
Lack of standardization in functional units	Functional units are typically linked to the overall lifespan of a surgical instrument. However, since actual lifespans can vary significantly across countries, regions, or healthcare facilities, achieving standardization of functional units in LCAs involving reusable surgical instruments is challenging. Given that the functional unit serves as the reference for evaluating environmental impacts, such variability can lead to inconsistent or potentially misleading LCA results.	Rodriguez and Hicks found that a disposable speculum breaks even with a reusable speculum at around 40 uses in the ecotoxicity impact category. With a functional unit of 50 uses, based on an assumed lifespan of 50 uses for the reusable speculum, their results show the reusable option to be more environmentally favourable for this impact. However, if the speculum were only used 20 times, as assumed by Donahue et al., and the functional unit adjusted to 20 uses, the disposable speculum would be preferred based on ecotoxicity impact results.	Establish a well-supported functional unit and perform break-even analyses	Ensure that the functional unit is based on a typical or average usage scenario that reflects standard practices. This can be achieved by consulting healthcare databases or studies that monitor equipment usage and longevity, or by surveying practitioners and stakeholders with hands-on experience using the instrument. Perform break-even analyses to address uncertainties related to the instrument's lifespan, preventing incorrect conclusions from being drawn due to potentially inaccurate assumptions.
Incomplete inclusion of all relevant life cycle aspects and processes	The complexity of surgical instruments and their life cycles often leads to certain activities or components being overlooked or excluded without sufficient justification, despite their potential significant environmental impacts, especially in reprocessing practices. Additionally, the lack of specific and up-to-date data regarding their complex compositions and specialized life cycle processes further complicates the inclusion of all relevant life cycle processes and environmental interventions.	After adjusting for functional units, Donahue et al. reported a global warming potential for a stainless-steel reusable vaginal speculum that was more than double that reported by Rodriguez and Hicks. This variation was primarily attributed to Donahue et al.'s inclusion of sterilisation pouches, which were excluded in the analysis by Rodriguez and Hicks.	Carefully define and justify system boundaries	Carefully define and justify system boundaries, particularly in relation to reprocessing practices, based on the specific goals of the study and available data. Draw on insights from high-quality studies of similar products and consult subject matter experts familiar with the surgical instrument's life cycle to confirm the boundaries' thoroughness. Support any exclusions with quantitative reasoning, rather than relying solely on the type of activity or component. Provide a comprehensive overview of all life cycle processes and aspects excluded from the system boundaries, including their potential contributions to the instrument's environmental footprint, to enhance understanding, transparency, and completeness of the analysis.
Inaccurate management of multifunctionality in reprocessing practices	LCA results are significantly impacted by how multifunctionality in reprocessing practices is handled. While allocations based on the mass load of instruments in washing or sterilization machines are commonly used, these loads can vary widely between healthcare facilities and even across different reprocessing cycles, complicating the accurate attribution of environmental impacts to the specific instrument under study.	Friedericy et al. found that using aluminium rigid sterilisation containers (RSCs) was more environmentally beneficial than single-use blue wrap, but Rizan et al. reached the opposite conclusion. Rizan et al. assigned sterilisation impacts to instruments, only considering the washing of RSCs, which consumes significant energy and water, while blue wrap avoids these impacts. Moreover, Unger et al. showed that reusing a dental bur 30 times was more eco-friendly when machines were fully loaded, but with suboptimal loading, the benefits diminished, and in worst-case scenarios, reuse resulted in higher impacts than single-use.	Apply a well-supported multifunctionality approach specific to the instrument under study	Ensure that the approach for handling multifunctionality in reprocessing practices aligns with the chosen LCI modeling framework and the instrument's specific characteristics. Base data collection on a reference healthcare facility to obtain accurate information on reprocessing practices, and adopt allocations that reflect typical or average loading scenarios for the instrument, ideally customized to the reprocessing conditions of the reference facility. Engage reprocessing technicians and other stakeholders with practical knowledge of reprocessing practices to confirm that the selected allocations are realistic and representative.
Incomplete inclusion of all relevant environmental issues	If the selected LCIA methods not properly align with the study's objectives, important environmental issues related to the analyzed system may be overlooked, reducing the relevance and applicability of the findings.	-	Apply comprehensive and context-specific LCIA methods	Select LCIA methods that thoroughly address all major environmental aspects relevant to the analyzed system, ensuring alignment with the study's goals. Regularly review these methods against the study objectives to confirm that key impact areas are well represented. Exclude impact categories only when demonstrated to be insignificant for the system, supporting such exclusions with quantitative evidence and documenting them clearly. Incorporate additional LCIA methods if any unexpected or emerging environmental impacts arise during the study, allowing for a comprehensive and flexible approach.
Lack of data and inconsistent quality	The data collection process is hindered by a lack of primary data on the specialized life cycle processes specific to the surgical instrument under study, which is crucial for accurately assessing environmental impacts. This data gap is further widened by the varying priorities of stakeholders, who may possess relevant data but differ in their willingness to participate in the LCA process. Consequently, the available data may be limited and inconsistent in quality.	Suppliers of semi-finished products and raw materials, as well as instrument manufacturers, may hesitate to share data due to concerns about competitive disadvantage. Additionally, healthcare providers may adjust usage data to reflect personal preferences for certain instruments, resulting in either overly optimistic or pessimistic reports, or may choose to withhold data entirely.	Encourage stakeholder engagement and supplement with secondary data	Proactively encourage stakeholder participation by emphasizing the study's importance and urgency. Begin with outreach to build trust and foster collaboration, addressing any concerns about data sharing and clarifying the value of their data contributions. To encourage broader participation, consider offering incentives such as access to the LCA findings, co-authorship, or recognition in the final report. Where primary data is unavailable or inconsistent, use high-quality secondary data to fill gaps, ensuring more consistent and reliable data quality throughout the LCA process.
Reliance on average secondary data and assumptions	The data collection process is further constrained by a frequent lack of specific and up-to-date secondary data needed to address the gaps in primary data on an instrument's specialized life cycle processes. Secondary manufacturing and end-of-life data are often drawn from databases that rely on averages, which may not reflect the actual conditions, and using multiple databases can result in inconsistencies in data quality. Moreover, secondary data on reprocessing practices sourced from literature often varies widely, limiting its usability and transferability, especially due to differences in reprocessing techniques, reuse frequencies, and energy sources across countries, regions, and hospitals. Given the sensitivity of LCA results to assumptions about these variables, any inaccuracies can lead to coloured findings.	Databases provide insights into common materials for standard components, often using average market processes that may not accurately represent real-world conditions. Additionally, scenario analyses have demonstrated that extending the lifespan of reusable instruments, increasing reuse frequency, improving loading efficiencies, or switching to renewable energy can make reusable instruments seem more environmentally favourable than single-use alternatives, even if baseline results indicate otherwise. Therefore, inaccurate baseline assumptions can lead to biased or coloured findings.	Ensure accurate data representation, consistent data sourcing and perform scenario analyses	Ensure that secondary reprocessing data reflects typical or average scenarios based on standard practices and, where possible, aligns with the specific conditions of the reference healthcare facility. Validate these assumptions with input from experts experienced in instrument reprocessing. For the manufacturing and end-of-life phases, source secondary data from well-documented, externally verified databases that closely represent real conditions. To maintain consistency in data quality and methodology, rely on a single high-quality database whenever feasible. Additionally, conduct scenario analyses to address variations in secondary data assumptions, supporting the robustness of LCA findings and their applicability in real-world contexts. Apply a data quality assessment framework to evaluate and document the accuracy, completeness, and consistency of all collected data, enhancing transparency throughout the LCA process.
Inaccurate representation of inventoried data	Specialized LCA software tools are used to calculate a product's environmental footprint based on inventory data. However, these tools rely on databases that may not always include the specific materials or processes needed, particularly for complex instruments with specialized components and materials that are uncommon in other industries. Practitioners often face challenges in selecting the most suitable alternative from the available options, and in some cases, no appropriate alternative may exist. The need to use substitutes to approximate the original materials or processes can introduce data inaccuracies.	In a study by Samenjo et al., granulated polypropylene (PP) was substituted for homopolymer PP, wrought aluminium alloy for aluminium 6061, and extrusion techniques for injection moulding. These substitutes may not adequately approximate the original materials and processes, potentially compromising the accuracy of the results.	Select accurate alternatives for unavailable inventory data	When specific inventory data is unavailable, select alternative materials or processes that closely approximate the required specifications, using common practices from similar applications found in the literature. If multiple alternatives are available, compare their environmental impacts to assess potential differences. Where no significant variation in impact is observed, the choice of substitute is unlikely to influence the final results. If large differences in environmental impacts are noted, consult industry standards or seek input from subject matter experts to make an informed selection. If uncertainty persists and no definitive choice can be made, choose the alternative with the highest environmental impact to avoid underestimating results. Document each substitute choice, along with the rationale and supporting data, to ensure transparency throughout the LCA process.
Inaccurate representation of all relevant environmental issues	LCIA methods often calculate impacts as "potential impacts," relying on assumptions like linear relationships between pollutants and impacts or worst-case scenarios. These assumptions may overlook local variations, time-specific factors, and rare events, leading to results that may not accurately represent real-world conditions.	-	Acknowledge the inherent limitations of LCIA methods	When interpreting results, remain aware of the inherent limitations of LCIA methodologies, particularly their challenges in fully capturing the complexities of real-world scenarios.

Note: These risk factors include the inherent limitations of the LCA methodology that could compromise the reliability of findings in general, along with specific factors that may affect the reliability of conclusions drawn from LCAs of surgical instruments.

Life Cycle Assessment Design

The goal of Life Cycle Assessment Design (LCAD) is to accurately assess the environmental footprint of a new technology while identifying potential related design modifications to improve its environmental performance. This can be accomplished through a detailed and robust comparative LCA, incorporating insights from the initial research phase and following the adapted LCAD methodology for eco-design. Figure 11 shows the modified ‘circular’ LCAD approach for eco-design alongside the typical ‘linear’ LCA approach for eco-design.

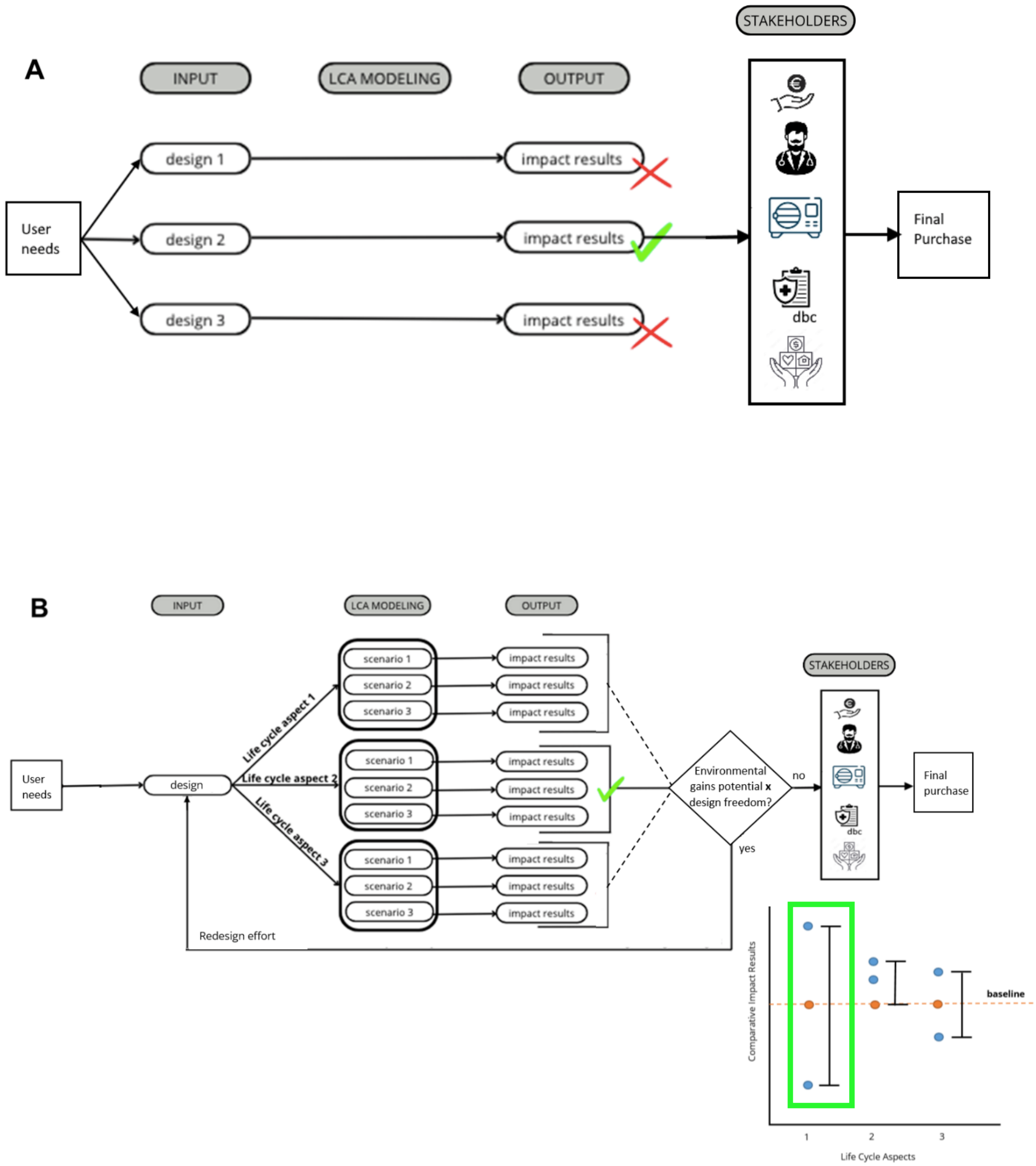


Figure 11: LCA design approaches for eco-design. Figure A shows the typical 'linear' approach, B the 'circular' approach. In the typical LCA approach for eco-design, the green checkmark indicates the design scenario with the lowest environmental impact, marking it as the most environmentally friendly option.

In the adapted approach, by analyzing comparative impact results for the product's current design relative to a functionally identical product across various modelled life cycle aspect scenarios (illustrated in the bottom-right section of subfigure B) and understanding how design decisions shape life cycle aspects, the life cycle aspect with the potential for the largest environmental gains through feasible modifications to the product's current design can be pinpointed.

This aspect, marked with a green check, will serve as the initial focus of redesign efforts. While other life cycle aspects may also show variations in comparative impact results across different scenarios, offering opportunities for environmental improvements, these gains are either smaller or lack feasible design modifications to realize them effectively, and therefore are not prioritized initially.

LCAD will support healthcare decision-makers in making environmentally conscious procurement choices and guide the developers of new technology in implementing environmentally responsible design improvements during its ongoing development. Although future design updates are expected to be informed by the insights from this LCA, post-implementation studies will be necessary to confirm that these updates indeed align with the environmental performance improvements indicated in the initial findings.

It is important to note that, before investing in an instrument with enhanced environmental performance, hospitals also consider factors such as costs, healthcare providers' preferences, the instrument's capacity for thorough cleaning and sterilization to ensure patient safety.

8.9 LCA-based design iterations

Typically, LCAs for eco-design involve modelling various hypothetical design scenarios, such as adjustments to materials or configurations, and comparing their environmental impacts to identify the most eco-friendly option. In these ‘linear’ eco-design approaches, each design scenario is treated as an input to the LCA, generating different impact results. The scenario with the lowest environmental impact is then identified as the most sustainable option, thereby guiding design choices. However, in some LCAs, where the environmental impacts of a product in its current design are compared to those of a functionally identical alternative, the focus could shift from creating hypothetical design scenarios to evaluating the product’s existing design for both comparative and eco-design purposes.

This can be achieved by using scenario analyses to not only strengthen the robustness of the comparative LCA results but also to identify opportunities for substantial environmental improvements within the product’s existing design. By modelling various scenarios for different life cycle aspects of the product’s current design, it becomes possible to identify the life cycle aspect that shows the greatest variation in comparative impact results relative to the functionally identical product across the modelled scenarios, theoretically indicating where the largest environmental gains could be achieved. Understanding how life cycle aspects are shaped by design decisions enables targeted design recommendations to realize these environmental enhancements.

However, recognizing that limited design flexibility may restrict the practical realization of these potential gains identified in the scenario analysis, redesign efforts will initially focus on the life cycle aspect with the potential to achieve the most significant environmental improvements through feasible modifications to the product’s current design. When it is not feasible to analyze different scenarios for every life cycle aspect, the scenario analyses can focus on aspects with known uncertain assumptions .

The functionality of the product
is essential


MANUAL OVERRIDE
ETHICON

9

Survey on stakeholder perspectives of LCA practices in the surgical field

9.1 The reliability of LCA findings

To enhance understanding of the issues affecting the reliability of LCA findings in the surgical field and to explore considerations for more reliable LCA practices, it is essential to engage key stakeholders in this domain to evaluate the perceptions of LCAs and their usage within this field. This was accomplished by developing and distributing a survey among the approximately 3,500 active members of the European Association for Endoscopic Surgery (EAES), an organization that plays a leading role in advancing innovation in endoscopic surgery to ensure safe and sustainable surgery for all. Membership in the EAES is open to professionals involved in any form of endoscopic surgery and minimally invasive techniques.

Methods

The survey was conducted from May 23rd to Aug 7th, 2024, using the online survey tool Qualtrics, with a reminder sent on July 1st to encourage participation. The survey consisted of 29 questions, divided into two sections. The first section examined participants' views on sustainability in the use of surgical instruments within their team and their familiarity with LCAs. The second section delved deeper into their experiences and opinions regarding LCA practices, particularly concerning their reliability in the surgical field.

Participants who identified as not familiar at all with LCA practices were automatically directed to the end of the survey after section one, thus skipping the second section. Others were free to skip the second section if they felt not very familiar with LCAs. Participants could choose to skip any questions they preferred not to answer and could withdraw from the survey at any time without providing a reason. All procedures adhered to EAES's ethical guidelines. The consent statement is available in Appendix B. The data was analyzed using frequency distribution.

Results

A total of 47 out of approximately 3,500 active EAES members responded to the survey, with 27 completing both sections 1 and 2. Since participants could skip any questions they preferred not to answer, there were variations in the number of responses per question. The results are summarized below and presented in Figures 2 and 3 for questions from sections 1 and 2, respectively, with data expressed as percentages of the total number of responses per question.

9.2 Survey section 1

Regarding the roles of the respondents, the largest group were surgeons (83%), followed by surgical residents/trainees (11%). The rest (6%) identified as an anesthesia assistant, OR nurse or technician (Figure 12A). About half of the respondents indicated that sustainability concerning the use of surgical instrumentation within their team is rarely or never discussed (combined 51%), while 19% suggested that it is discussed daily (Figure 12B). When asked if they felt there was sufficient awareness about the impact of using surgical instrumentation within their team, most respondents disagreed (44%), with more than half of them strongly disagreeing, while 25% agreed and the remaining respondents were neutral (Figure 12C).

Regarding sources consulted for information on the environmental impact of using surgical instrumentation, educational programs/workshops were the most frequently used, specifically by 48% of respondents. This was followed by academic or research articles/publications at 43%, and regulatory publications/guidelines at 39%. 15% of respondents admitted to not actively seeking information about the environmental impact of using surgical instrumentation (Figure 12D).

The influence respondents have on decision-making regarding the use of surgical instrumentation in their team varied. Most respondents (30%) contributed to discussions without having the final say, while 15% reported being uninvolved in decision-making. A minority (9%) indicated that they lead the decision-making process (Figure 12E). When asked if they would consider the environmental impact in their decision-making process if they had full decision freedom, the majority agreed or strongly agreed (combined 80%), while 4% disagreed (Figure 12F).

Most respondents considered themselves slightly familiar with LCA's (37%), followed by moderately familiar (24%) and not familiar at all (17%). The remaining 22% considered themselves highly or extremely familiar (Figure 12G). Moreover, 37% of respondents indicated that LCA's currently do not influence decision-making about the choice of surgical instrumentation within their teams, while another 37% stated that they do have an influence.

Meanwhile, 26% reported that they were uncertain (Figure 12H). One respondent (2%) indicated not to consider attending training sessions or workshops focused on conducting LCAs specific to surgical instrumentation or utilizing their findings if they were available.

The rest indicated they would attend these training sessions/workshops or might attend (50% and 48% respectively) (Fig. 8.2I). Most respondents would prefer online webinars for these training sessions (35%), but in-person workshops, interactive online courses, and hybrid training sessions were also favored (23%, 19%, and 16% respectively). 7% of respondents preferred recorded video tutorials (Figure 12J).

Preferences for the frequency of these training sessions varied, with once a month being favored by most respondents (29%). No one preferred weekly sessions (Figure 12K).

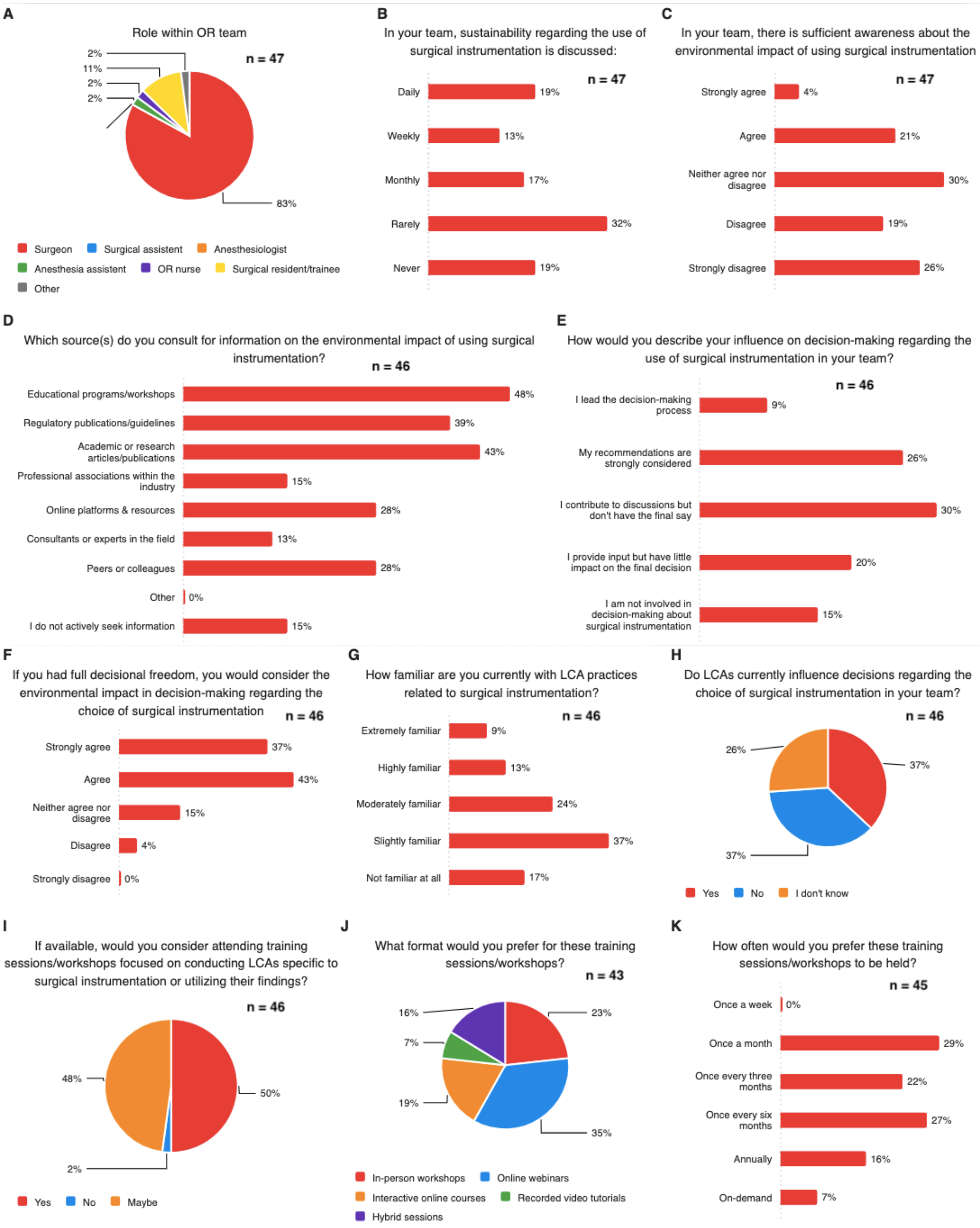


Figure 12: Survey data for questions from section 1. Note: The data is expressed as percentages of all responses, with each subfigure representing a different question. For the question represented in subfigure D, multiple answers could be selected, so the percentages of all answer choices do not add up to 100%.

9.3 Survey section 2

Among the respondents who completed both sections of the survey, a slight majority (52%) indicated they have never used LCA findings to understand the environmental impact of surgical instruments (Figure 13A). For those who sought information on using LCA findings, the most frequently used sources were academic or research articles/publications (48%), followed by regulatory publications/guidelines (41%) and educational programs/workshops (37%). 15% of respondents admitted to not consulting any sources for information on utilizing LCA findings (Figure 13B).

When asked about their trust in LCA findings related to surgical instrumentation, more than half of the respondents indicated moderate trust (52%). High trust and complete trust were each indicated by 19% of the respondents, while the remaining 11% expressed slight trust. No respondents reported having no trust at all in LCA findings (Figure 13C).

When respondents were asked about the degree to which certain aspects influence their trust in LCA findings, for each aspect most responses indicated a 'somewhat' influence, followed by 'highly' and 'extremely' (Figure 13D). Specifically, all aspects received an average influence rating between 3 and 4, reflecting a range of 'somewhat" to 'highly.' When asked for any additional aspects that influence their trust in LCA findings, one respondent mentioned the number of variables assessed in LCAs.

Additionally, one respondent (4%) indicated having personal experience questioning the findings of an LCA related to surgical instrumentation, as they were unsure of the methodology used in that specific LCA (Figure 13E). The vast majority (92%) reported not using any tools/methods for evaluating the accuracy and trustworthiness of LCA findings (Figure 13F). When asked if they considered the existing tools and methods sufficient for this purpose, the majority were neutral (52%), 32% agreed, and 16% disagreed (Figure 13G).

Among the respondents who completed both sections of the survey, the vast majority (96%) indicated they have never been involved in conducting an LCA related to surgical instrumentation, while one respondent reported involvement (Figure 13H). For those who sought information on conducting LCAs, the most frequently used sources were regulatory publications/guidelines (52%), followed by academic or research articles/publications (43%) and educational programs/workshops (39%). 26% of respondents admitted to not consulting any sources for information on conducting LCAs (Figure 13I).

When asked if they felt there is sufficient access to the necessary data/tools/methods/guidance to carefully conduct an LCA in the surgical instrumentation sector, the majority were neutral (58%), followed by 25% agreeing, while 17% disagreed (Figure 13J). Those who disagreed reported challenges such as the presence of too many variables, difficulty finding unbiased information, not knowing where to search for LCA information, and a general lack of awareness about LCAs.

Regarding the degree to which certain aspects contribute to doubts about the trustworthiness of LCA findings, for each aspect most responses indicated a 'somewhat' contribution, followed by 'highly'. Specifically, the average contribution rating for each aspect fell between 3 and 4, reflecting a range from 'somewhat' to 'highly' (Figure 13K). When asked for additional aspects that contribute to doubts about the trustworthiness of LCA findings, one respondent mentioned that LCAs often leave out important variables, making the results unreliable.

Similarly, when evaluating the degree to which certain aspects of surgical instrumentation are inadequately addressed in current LCAs, for each aspect most responses indicated 'somewhat', followed by 'highly', with all aspects receiving an average rating between 'somewhat' and 'highly' (Figure 13L). When asked for additional inadequately addressed aspects, one respondent mentioned spare parts and transport to and from cleaning and sterilization.

When asked whether they believed that introducing training sessions or workshops on conducting LCAs and utilizing their findings would enhance the quality of LCAs within the surgical instrumentation sector, a majority agreed (72%), with 16% strongly agreeing. 24% expressed neutrality, while one respondent (4%) disagreed (Figure 13M).

Regarding the aspects on which respondents would like these training sessions or workshops to provide guidance, more than half of the respondents selected defining the product or process, establishing system boundaries and functional units, and collecting data (56%, 60%, and 60% respectively). All other given aspects were also indicated by at least a quarter of the respondents as areas where they would like guidance (Figure 13N).

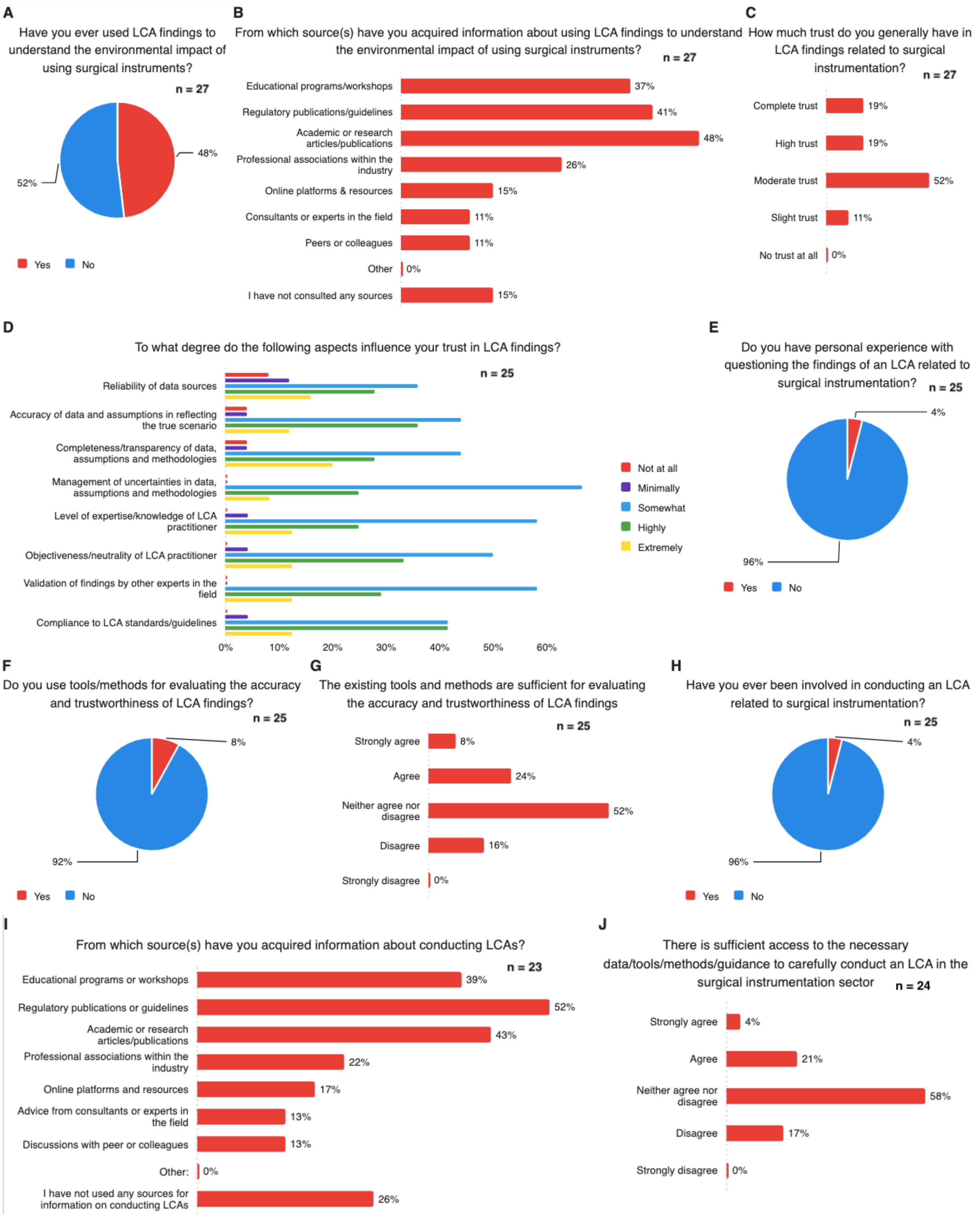
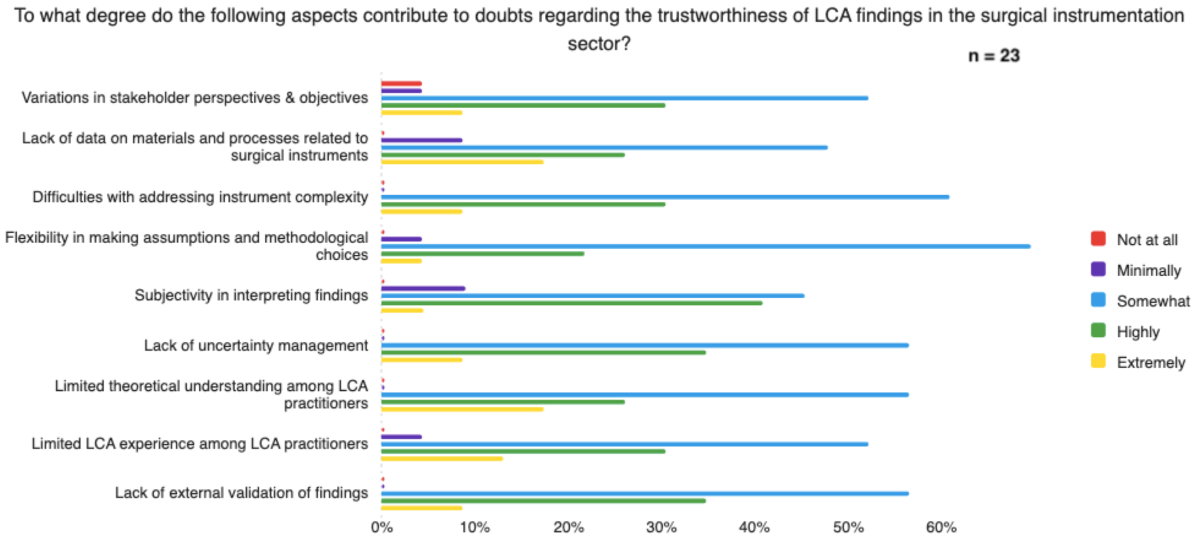


Figure 13 (part 1): Survey data for questions from section 2. Note: The data is expressed as percentages of all responses, with each subfigure representing a different question. For the questions represented in subfigure B and I, multiple answers could be selected, so for both questions the percentages of all answer choices do not add up to 100%.

K



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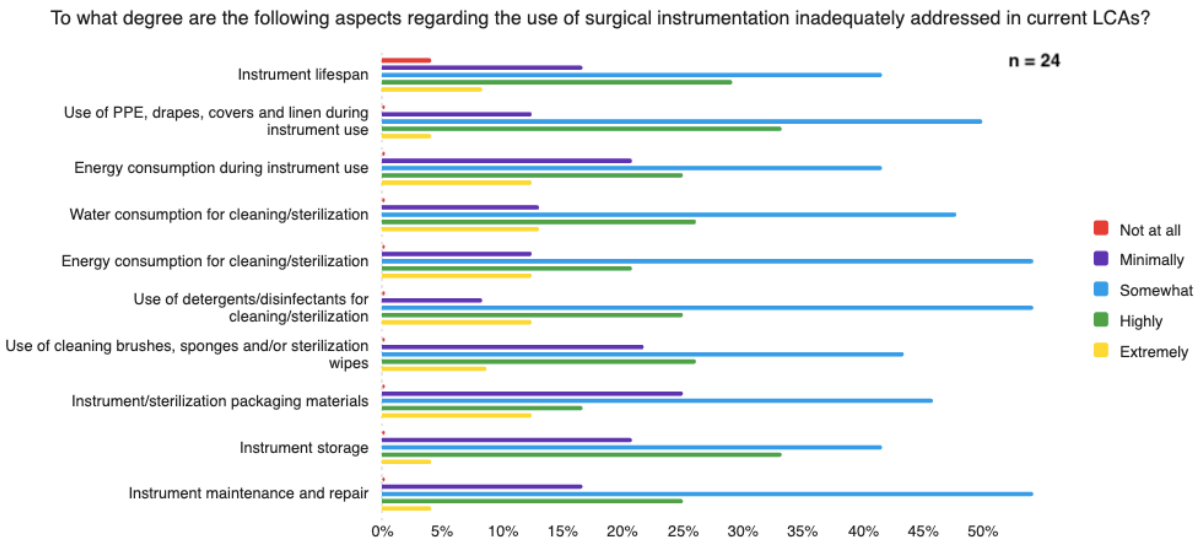

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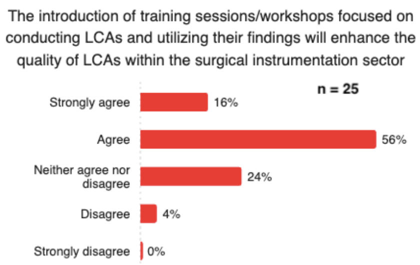

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Figure 13 (part 2): Survey data for questions section 2. Note: The data is expressed as percentages of all responses, with each subfigure representing a different question. For the question represented in subfigure N, multiple answers could be selected, so the percentages of all answer choices do not add up to 100%.

Discussion

The survey reveals several important insights into EAES members' perspectives on sustainability and LCA practices related to surgical instrumentation, as well as their application in this field.

Sustainability awareness

It's interesting to note that sustainability in the context of surgical instrumentation is rarely or never discussed within surgical teams, with only a small percentage reporting daily discussions on this topic within their teams. Despite the increasing presence of green teams focused on developing environmentally conscious practices within the OR, exploring strategies to minimize medical waste and resource consumption, there is still a considerable gap in attention and dialogue about the environmental impact of surgical instrumentation use in surgical teams.

This is supported by the finding that only a quarter of the respondents agreed there is sufficient awareness about the environmental impact of surgical instrumentation use, while nearly double that number disagreed, indicating that many surgical team members themselves feel that there is inadequate awareness and discussion on this issue.

9.4 Roles and influence of respondents

Most respondents indicated that they would consider the environmental impact when selecting surgical instrumentation if they had any influence in the decision-making process, highlighting a strong interest in sustainability among surgical teams. Surgeons are often expected to play a central role in discussions about surgical instrumentation within their teams. This positions them as key advocates for raising awareness and driving sustainability practices in the OR.

Indeed, approximately one-third of respondents contribute to discussions on instrumentation use but do not have the final say, while about a quarter reported that their recommendations are strongly considered. Although these findings suggest that not all surgeons lead the decision-making process, most are involved in some capacity and could therefore take on a greater role in advancing sustainability within their teams, especially since most of them feel there is currently inadequate awareness and discussion around this issue.

Familiarity with LCAs

Familiarity with LCAs is generally low, with only a small fraction of respondents considering themselves highly or extremely familiar. Within the teams of three-quarters of the respondents, LCAs do not influence decision-making, or it is unknown whether they do. This suggests a significant opportunity to enhance the impact of LCAs in the OR through education and integration of LCAs into decision-making processes regarding surgical instrumentation. Almost all respondents expressed openness to attending training sessions or workshops on LCAs.

Trust in LCA findings

Of the respondents who are familiar with LCAs, a slight majority has never used LCA findings to understand the environmental impact of surgical instruments. While LCAs are generally recognized as valuable tools for informed environmental decision-making, most respondents express only a moderate level of trust in LCA findings related to surgical instrumentation, which may further explain the limited use of LCAs in decision-making in this area. This suggests that there is room for improvement to enhance trust in LCA results for surgical instrumentation, potentially increasing their use in decision-making.

The majority of respondents do not use any tools or methods to evaluate the accuracy and trustworthiness of LCA findings, indicating a need for increased awareness of existing tools and methods, training on how to use them, or even the development of new tools and methods if the existing ones are of limited value. Very few respondents had any personal experience with conducting an LCA related to surgical instrumentation. This unfamiliarity explains why most respondents are not sure whether there is sufficient access to necessary data, tools, methods and guidance to carefully conduct LCAs in the surgical instrumentation sector.

9.5 LCA training and workshops

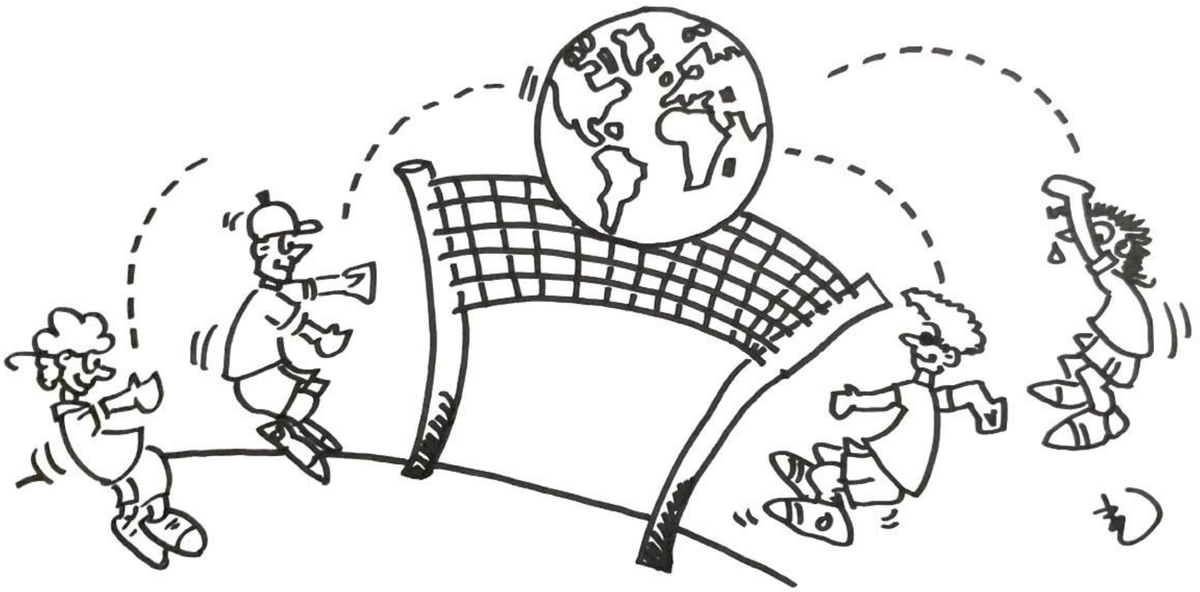
Most respondents who are familiar with LCAs believe that training sessions or workshops on conducting LCAs and utilizing their findings would enhance the quality of LCAs in the surgical instrumentation sector. Respondents expressed a particular desire for guidance on defining the product, establishing system boundaries and functional units, and collecting data.

Limitations

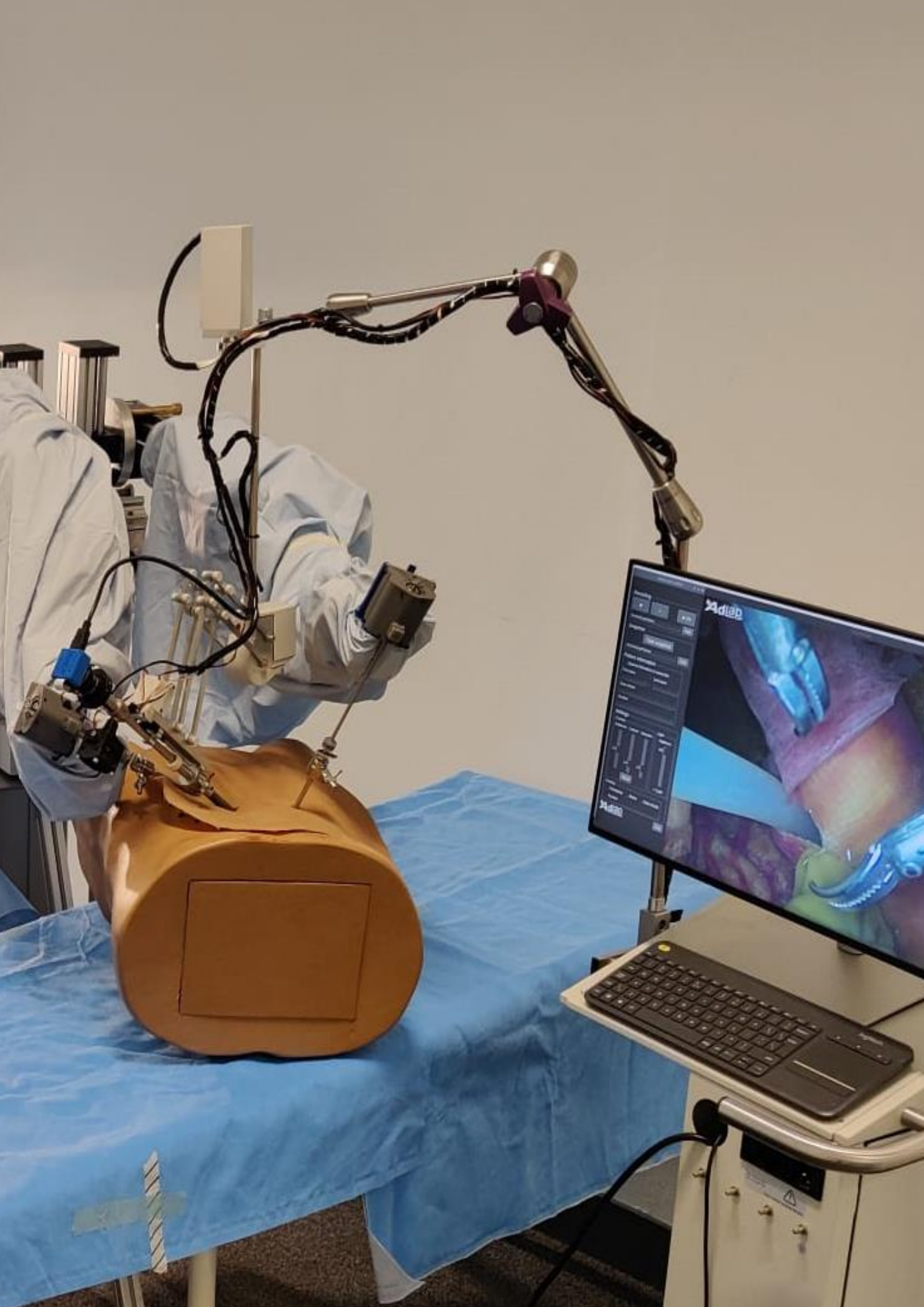
This survey has several limitations that may affect the reliability and generalizability of the results. Firstly, only members of the surgical association were invited to participate, which may not represent the broader population of medical professionals involved in surgical instrumentation. Additionally, the opening statement of the survey mentioned that it is a vital component of a research study in the field of sustainability within the surgical instrumentation sector, potentially attracting a group of active individuals who prioritize sustainability, leading to a biassed view of the results.

This might explain why the overwhelming majority agreed that they would consider the environmental impact in their decision-making process regarding the choice of surgical instrumentation if they had full decision freedom. Conversely, individuals who lack knowledge about LCAs might have been discouraged from participating due to the survey's title or introduction, believing they were not qualified, even though the first section was intended for all EAES members regardless of their familiarity with LCAs. Those who still chose to participate despite considering themselves slightly or moderately familiar with LCAs still had the option to answer all questions in the second section, potentially leading to less informed responses.

Furthermore, team dynamics could have influenced the results; if one person encouraged others within their team to complete the survey, it could result in more responses in the first section aligned with the views of this team. Therefore, if that team is particularly focused on sustainability, more answers will be aligned with this focus. Another limitation is that the survey design allowed participants to skip questions they preferred not to answer, which could result in missing data, particularly for questions requiring more time to complete. Lastly, the survey did not account for differences in respondents' countries of origin or work, which could have provided interesting correlations given that the focus on sustainability in healthcare can vary significantly by country.



The earth? We'll never drop it!



10

The role of technical universities in driving sustainability in hospitals

10.1 The role of technical universities, integrating academic research

Introduction

Hospitals, as resource-intensive institutions, consume significant amounts of energy, generate considerable waste, and rely on complex supply chains that can strain environmental resources. To address these challenges, technical universities play a pivotal role in fostering innovation, providing expertise and developing practical solutions that promote sustainability in healthcare settings. Through interdisciplinary research, partnerships with hospitals and training programs, technical universities bring cutting-edge knowledge and processing technologies to the forefront.

The case studies in this chapter, which are based on research and graduation papers, show how a collaboration between TU Delft and numerous hospitals and healthcare professionals resulted in the implementation of new waste recycle strategies for more challenging plastic waste categories, such as multi-materials, coated materials and mechanically advanced plastics. For this reason, this chapter is divided according to the content of scientific publications. That is, each section has a division into introduction, methods, results, discussion and conclusion.

By integrating academic research with real-world applications, technical universities not only empower hospitals to minimize their ecological footprint but also improve efficiency, cost-effectiveness and patient care. In these collaborations, technical universities and their field labs served as hubs of innovation and education, ensuring that the healthcare industry evolves to meet environmental standards while continuing to deliver high-quality care. This partnership exemplifies how academia, hospitals and industry can unite to create a healthier future for both people and the planet.

The interesting properties of ALP

Introduction

Autoclave laminated plastic (ALP) is an example of a material that is widely used and discarded as waste. ALP is used for medical sterilization pouches or laminate packaging and serves as a crucial barrier to maintain sterility and protect medical instruments during transport and storage.[67,68]

These pouches are widely used in healthcare facilities and medical practices where individual instruments are packaged, such as dental clinics, general practices and hospitals. However, their disposal after use results in a substantial accumulation of waste. A survey conducted at a medium-sized dental clinic with five rooms revealed that approximately 400 laminate pouches were used monthly. Extrapolating this to a working year of 10 months with two full-time dentists and five treatment rooms translates to approximately 48,000 laminate pouches per year. Considering there are 8,800 operational dentists in the Netherlands alone, this equates to around 4.4 million pouches annually, just for dental practices.

However, in fact there is potential for recycling this type of packaging used in medical settings, which could significantly reduce the plastic waste problem.[69] Various studies have already shown that it is possible to recycle medical plastic waste, such as blue polypropylene wrap[20] and plastic medical syringes.[70] The same potential exists for the recycling of laminate packaging containing carbon nanotubes. The exceptional properties of carbon nanotubes, such as high tensile strength, low weight, rapid electron transfer kinetics, high biocompatibility, chemical inertness, assistance in protein immobilization and numerous antibacterial and antifungal properties, make carbon nanotubes an ideal addition to polypropylene packaging material for instruments.

67. S. Ing, “It’s a Wrap! Everything You Need to Know About Sterilization Pouches - Medicom,” 7 2021.

68. T. P. Company, “All About Autoclave Bags - Types, Industries and Selection Criteria,” 2023.

69. E. F. De Ridder, H. J. Friedericy, A. C. Van Der Eijk, J. Dankelman, and F. W. Jansen, “A New Method to Improve the Environmental Sustainability of the Operating Room: Healthcare Sustainability Mode and Effect Analysis (HSMEA),” Sustainability, vol. 14, p. 13957, 10 2022.

70. R. Faesal and W. Bdaiwi, “Recycling of Waste Medical Plastic Syringesin Manufacturing Low-Cost Structural Sections,” Materials Science Forum, vol. 1050, pp. 115–123, 1 2022.

Understanding the feasibility and effectiveness of mechanical recycling of laminate materials could contribute to more sustainable waste management. Prior to this case study, a literature review[71] was conducted to explore potential methods for recycling laminated autoclave materials.

The review indicated that mechanical recycling of ALP is the most suitable recycling technique, since it offers advantages over chemical recycling, including better performance in terms of CO_2 emissions and cost-effectiveness. Additionally, mechanical recycling is favored for its lower energy consumption and ease of use. Ultimately, a mechanical recycling method involving melting, shredding and injection or compression molding was selected.

This case study aims to illustrate the proposed (thermo-)mechanical recycling method as illustrated in Figure 14. This approach combines thermal and mechanical treatment processes for recycling laminated sterilization pouches.

71. M. Hansen, “Recycling of Autoclave-Laminated Material: An Analysis Of Waste Management Techniques and Recycling Processes,” MSc Thesis Literature Study, pp. 1–29, 3 2023.

Methods

This case study comprises eight steps to analyze the feasibility of mechanically recycling ALP waste, with an investigation into its application in various products. The steps undertaken to address this research questions are outlined in Figure 14. These steps include collecting the ALP, performing X-ray diffraction analysis, developing a melting process, shredding the ALP, setting up an injection molding process, and analyzing the dogbones produced to determine the material properties.

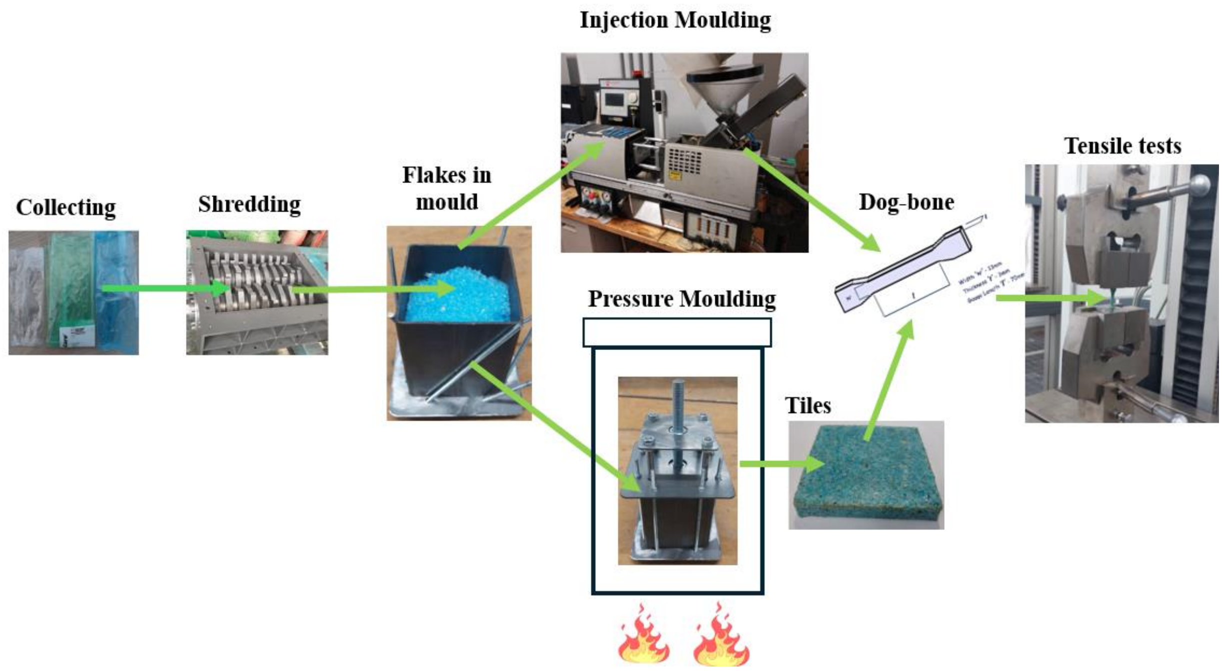


Figure 14: Overview of experimental steps, from ALP collection to end product, which was tested on the tensile bench.

ALP collecting

A logistical process was established to collect ALP waste (Figure 15) from two dental practices in the province of Zuid-Holland, The Netherlands, and the Department of Oral and Maxillofacial Surgery at Ikazia Hospital, Rotterdam, The Netherlands. Hospital staff were asked to collect used laminate packaging in separate plastic waste bags. After a collection period of two weeks, the bags from the hospital and clinics were transported to GreenCycl for inspection, and subsequently sent to TU Delft for further research. This study used uncontaminated medical sterilization pouches that had not come into contact with patients. Consequently, this type of waste was classified as general waste.[72]

72. A. Dehal, A. N. Vaidya, and A. R. Kumar, "Biomedical waste generation and management during COVID-19 pandemic in India: challenges and possible management strategies," Environmental Science and Pollution Research, vol. 29, pp. 14830–14845, 10 2021.

Figure 15: Overview of different versions of ALP pouches that were collected

X-ray diffraction analysis

The collected ALP underwent X-ray diffraction (XRD) analysis. A total of four XRD studies were conducted on different types of pouches: one with green laminated ALP, one with blue laminated ALP, and two with white laminated ALP. During the separation process of the different types of white ALP, it was observed that there were two distinct laminated sheets: one flexible and one rigid. Two separate XRD studies were therefore performed on the white ALP samples.

Shredding and injection molding

Plastic tiles were produced from the granulate of the laminated ALP using a process based on previously successful recycling methods applied in other studies within the Sustainable Surgery & Translational Technology research line at TU Delft.[20,73] For granulating the ALP, a Moditec Goliath Plus Granulator was used at the GreenCycl Field Lab.

73. Y. Q. Gill, M. Khurshid, U. Mehmood, M. Irfan, and F. Saeed, "Upscale recycling of nonwoven polypropylene waste using a novel blending method," Journal of Applied Polymer Science, vol. 139, 7 2022.

The granulate pellets made from the recycled laminate packaging were collected in a plastic bag and subsequently transported to Model Engineering (The Hague, The Netherlands) for injection molding into new products. The injection molding process was carried out using a BabyPlast Moditec injection molding machine to produce dogbones for material property testing. The injection molding process was performed at a temperature of 210 degrees Celsius.

Due to challenges encountered during the melting and injection molding process, an alternative recycling method was developed for melting plastic under high pressure. For this melting process, a custom-designed setup was used to test the potential of high-pressure melting. The goal was to create tiles from the used laminate packaging, measuring 94x94x10 mm. Approximately 90 grams of ALP waste was required for this process. The setup included a spring mechanism that applied continuous pressure to the ALP during the melting process. The compression in millimeters could be inferred from the height of the indicator connected to the top section of the setup. Figure 16 illustrates the injection and pressure molding setups.

Figure 16. Left: The Babyplast injection molding machine. Right: The mold with feather mechanism containing 90 grams of ALP pellets in the melting chamber. After assembly and filling with ALP waste, the setup was placed in the oven.

According to Patil et al. (2021),[74] the composition of the laminate, ALP has a glass transition temperature of approximately 162–165 degrees Celsius. Observed changes in the glass transition temperature were minimal, indicating that the presence of carbon nanotubes has negligible impact on the thermal behavior of polypropylene. Consequently, in this study, the influence of carbon nanotubes on the glass transition temperature of polypropylene is considered insignificant. Various melting processes were examined at temperatures ranging from 200 to 325 degrees Celsius, as these were also employed in the study by Van Straten et al. (2021) for recycling polypropylene.[20]

74. J. Patil, H. H. Patil, R. Sankpal, D. Rathod, K. Patil, P. R. Kubade, and H. B. Kulkarni, "Studies on mechanical and thermal performance of carbon nanotubes/polypropylene nanocomposites," Materials Today: Proceedings, vol. 46, pp. 7182–7186, 1 2021.

Strength testing

For the strength tests, three strips were extracted from the block to create dogbones conforming to the ASTM D638-V standard for tensile testing.[75] Initially, the block was divided into three equal parts. These parts were then processed using a milling machine to ensure precise dimensions and achieve a uniform height of 4 mm. After the milling process, the three pieces underwent further refinement using a laser cutter to accurately shape them into the characteristic dogbone configuration. This was accomplished with a laser cutting speed of 12 and a power setting of 95%.

Once the samples were shaped correctly, they were subjected to tensile testing using a Zwick Z010 tensile testing machine and analyzed with the testXpert software. The tests were conducted at a low tensile speed of 2 mm/min, and no preloading was applied.

Impact testing

Finally, the tiles underwent a ballistic test by firing 9.22-inch lead bullets at close range with an energy of 24 joules to examine their energy absorption potential (Figure 17).

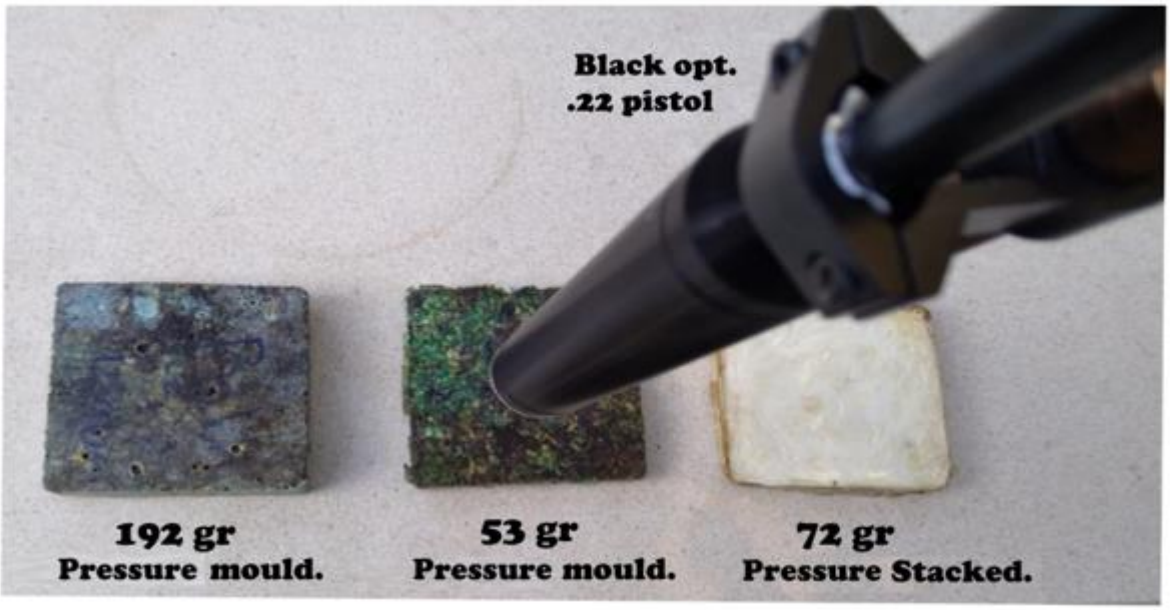


Figure 17. Impact testing for two different tiles made of ALP flakes with different consistencies, and one made of layered ALP.

75. ASTM. "Standard Test Method for Tensile Properties of Plastics" 7. 2022.

Results

The process of collecting ALP

The ALP from the dental centers was collected in three different colors: white, green and blue, as shown in Figure 18. The ALP collected from Ikazia Hospital, Rotterdam was exclusively blue. In total, approximately 1.8 kg of ALP was collected, with varying weights for each type.

X-ray diffraction testing

Figures 5 A-D show the results of the XRD analysis for the green ALP, blue ALP, white ALP with increased stiffness, and white flexible ALP. The peaks indicate the intensity of the crystalline phases, mapped using the ICDD PDF4 database (TU Delft, The Netherlands). The XRD graphs reveal that the green (Figure 18), blue (Figure 18B) and stiff white ALP (Figure 5C) consist of polypropylene (C3H6) and carbon nanotubes (C). The peaks in the XRD graphs closely match the peaks observed in the data for α-polypropylene (C3H6) and carbon nanotubes (C) from the ICDD database, indicating the presence of these materials in the ALP waste streams collected.

On the other hand, the XRD graph of the white flexible ALP (Figure 5D) showed alignment with the peaks of high-density polyethylene (C2H4), suggesting that the flexible white ALP consists of high-density polyethylene. The flexible white ALP was subsequently excluded from the case study.

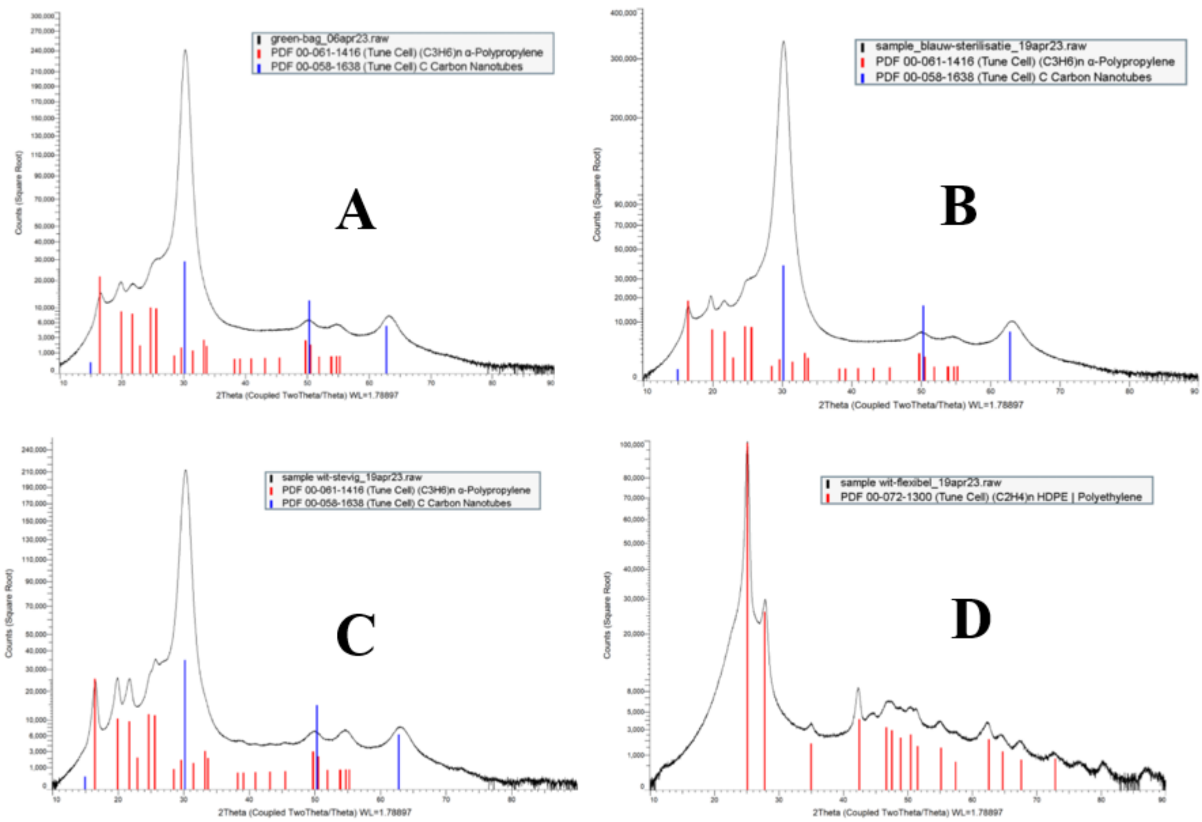


Figure 18: XRD tests of all identified ALP samples showing comparable characteristics despite the differences in color (A; green, B: blue, C: white). The last sample (D) appears not to be ALP and is excluded from the study.

Shredding and injection molding testing

During the melting process, it became clear that ALP posed greater challenges than materials such as blue instrument wrap.[20] An alternative approach was explored to bypass the melting process and convert the ALP directly into pellets.

Given the stiffness of ALP, it was hypothesized that shredding the material into flakes could be a feasible solution. These flakes could then be used in an injection molding machine, offering a potential method for further processing ALP waste. Due to the low mass of individual ALP sheets, however, the shredder blades struggled to effectively grip and shred them.

To address this issue, a solution was devised by compressing the ALP sheets into a metal bowl, increasing their total mass. This larger mass facilitated the shredding of the ALP sheets. The shredded material was then passed through the shredder three times. The shredded material was subsequently used as feedstock in the BabyPlast injection molding machine.

However, due to the small mass of the ALP flakes, the machine was unable to process the supplied flakes effectively. An alternative approach was attempted, where the flakes were manually placed into the plunger. The result of this manual process can be seen in Figure 19. However, this resulted in an insufficient amount of plastic to adequately fill the dogbone mold. This posed a significant challenge, as it prevented the fabrication of dogbone samples using the injection molding process. Consequently, this approach was not pursued further.

Pressure molding

During the melting process, the temperature and the compression of the spring were monitored. Figure 19 illustrates the progression of the spring pressure, melt oven temperature and time. After several experiments, it was found that the most effective method was maintaining a constant temperature of 230 degrees Celsius for 1 hour and 15 minutes.

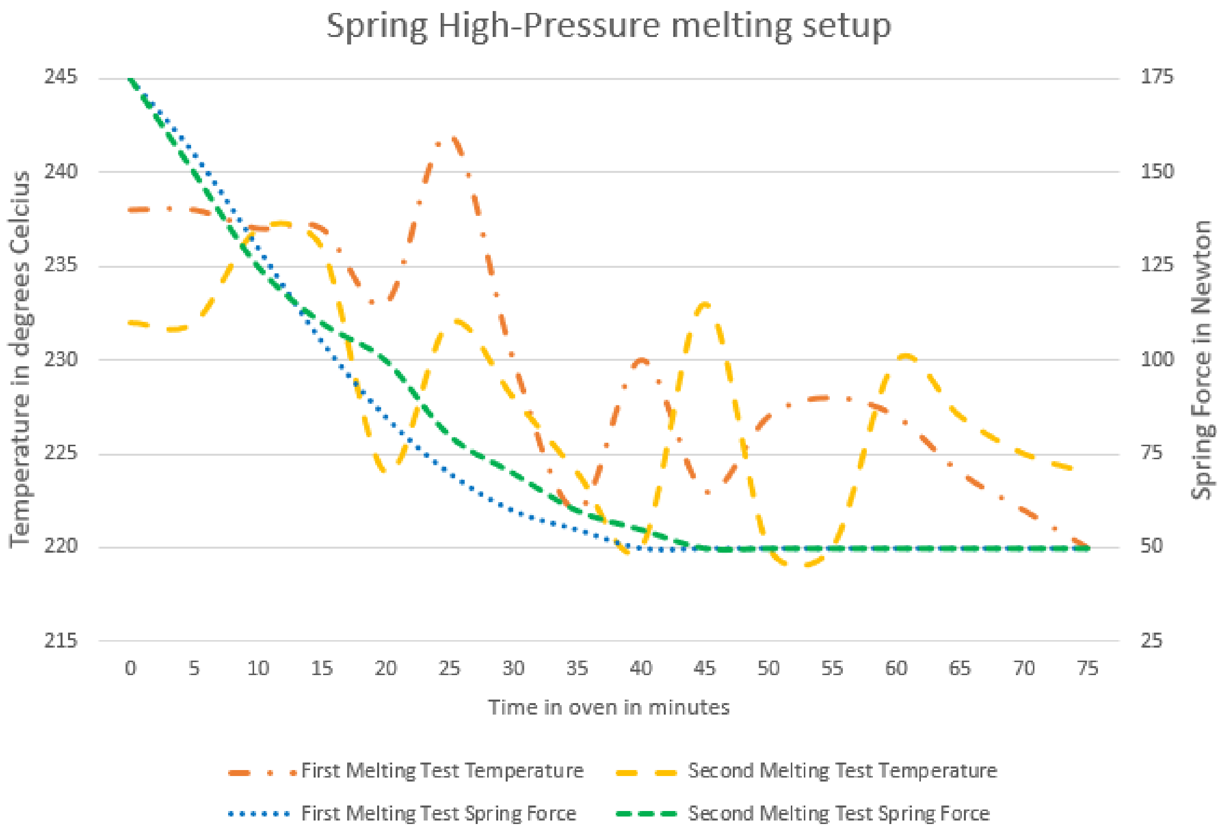


Figure 19: The melting flakes are pressed into a tile under pressure of a spring. The graph shows that the spring pressure decreases during the time that the setup is in the oven. The chosen time in the oven determines the density and material properties of the tile.

The ALP blocks that resulted from this process and showed the most potential were the blocks made from stacked layers of ALP sheets and the blocks made from flaked ALP sheets (Figure 20). Tiles made from 200 grams and 50 grams of flakes, as well as those made from stacked layers (75 grams), were further investigated.

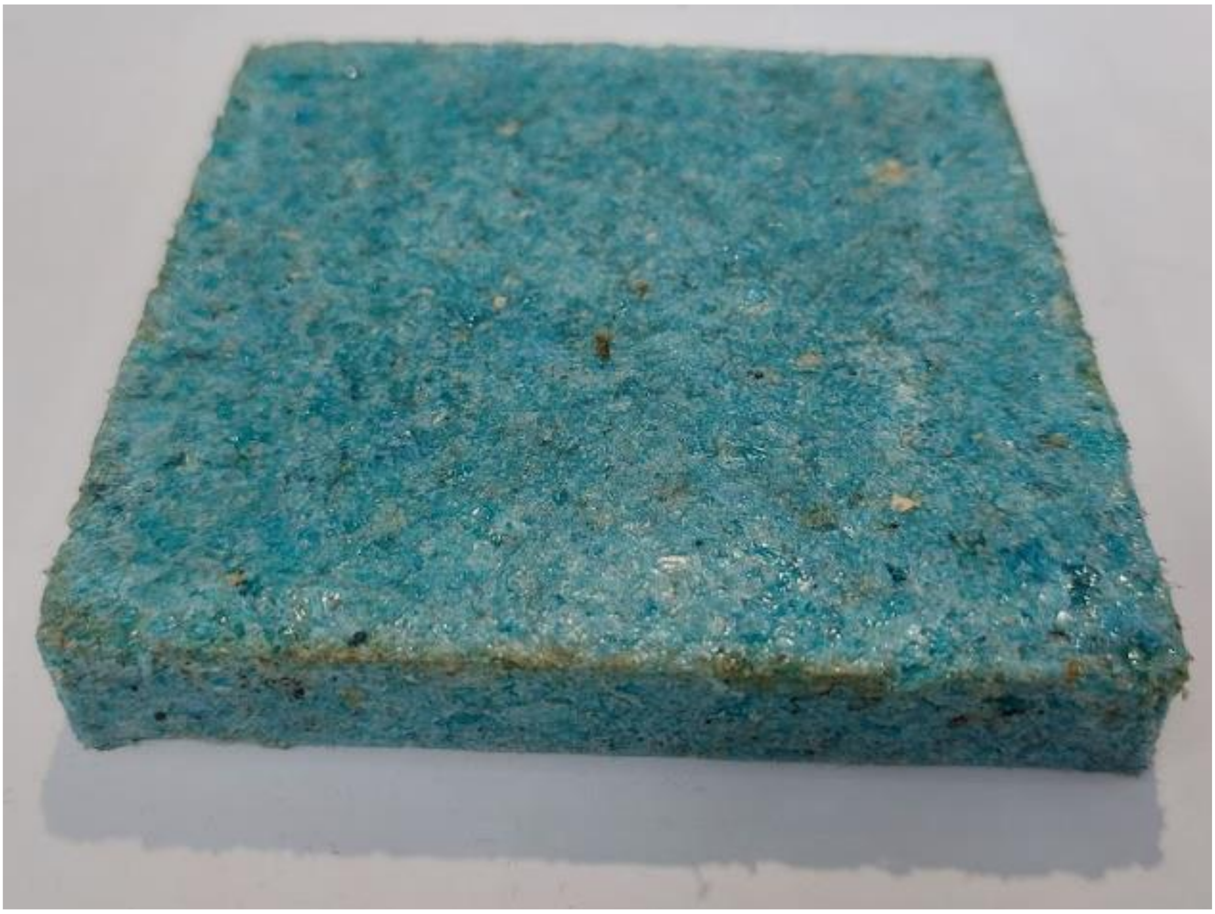


Figure 20: A standardized end product (tile) which can be used for further testing of material properties.

Strength testing

For the flakes, the average Young's modulus is 269 MPa, with a standard deviation of 85 MPa. The average tensile stress is 2.9 MPa, with a standard deviation of 0.5 MPa. The stacked laminate samples exhibited a much higher Young's modulus of 410 MPa with a standard deviation of 40 MPa and an ultimate tensile stress, with an average value of 3.6 MPa and a standard deviation of 0.3 MPa. Regarding elongation at break, the average value is 25%, with a standard deviation of 6%. These values provide valuable insights into the mechanical behavior of the material after processing into new feedstock.

Initial impact test

The ballistic short-range test with nine different .22-inch lead bullets fired at a velocity of 24 joules showed an indentation of 0.6 (SD 0.2) for the 50-gram stacked tile, 1 (SD 2.3) for the 50-gram granulated tile, and less than 0.05 mm for the 75-gram tile (Figure 21). No fractures or cracks were observed around the impact area. The 50g granulated sample revealed that one bullet was lodged in a cavity in the substrate.

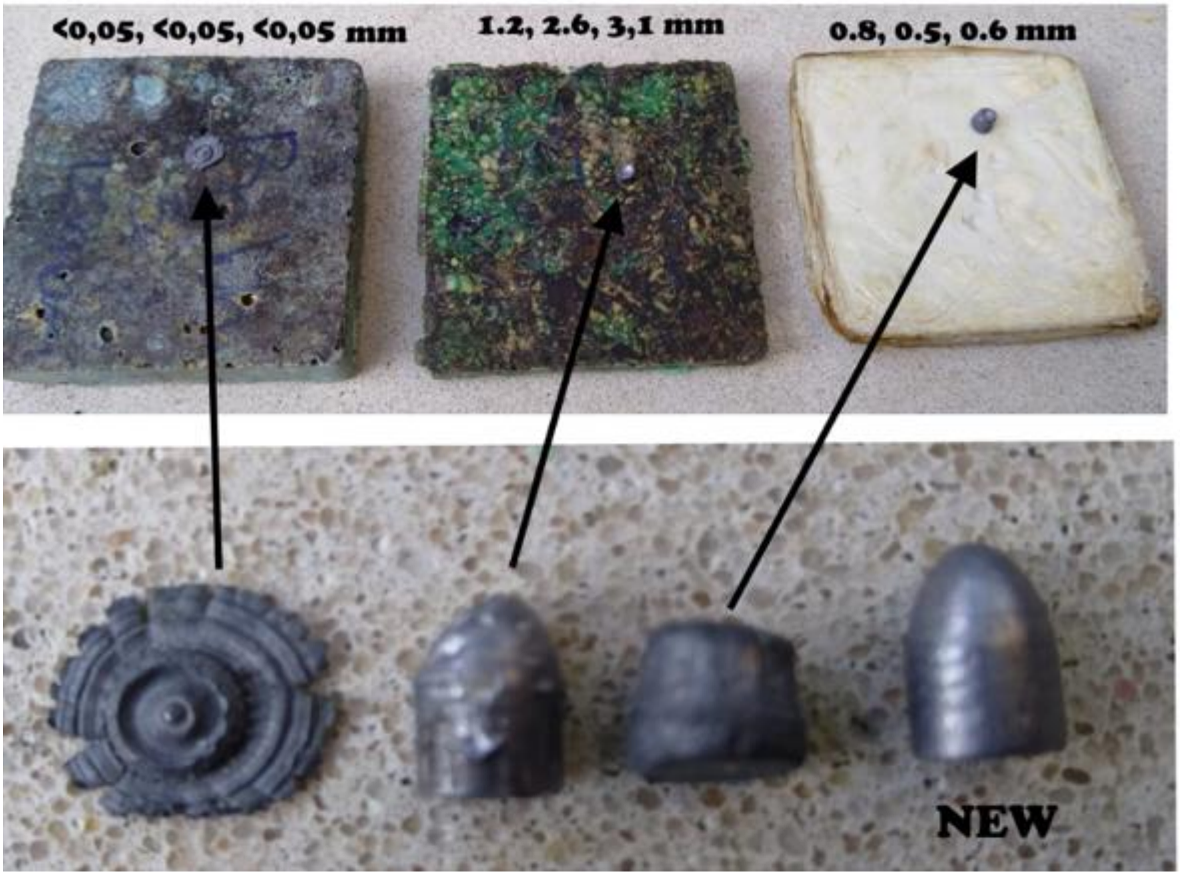


Figure 21. Top: Standardized end products (tiles) with different densities. The tiles were shot at with a .22 lead bullet in order to determine impact and depth. Bottom: The lead bullets after impact.

Discussion

The goal of this case study was to investigate the feasibility and effectiveness of mechanical recycling as a possible solution for ALP recycling. The findings of the high-pressure melt method with spring pressure demonstrated promising potential for the mechanical recycling of ALP.

However, removing stickers from the collected ALP proved to be very time-consuming. In future collections, it is crucial that no ink, stickers or paper residues remain on the ALP. Any remaining ink can affect its appearance, introduce defects and produce unwanted by-products.[76]

To avoid this, it is recommended not to write on ALP or to establish a process to remove the ink. Labels and stickers applied to medical sterilization bags change color after sterilization and are then affixed to the packaged instruments before sterilization. While the use of labels and stickers is necessary, it is crucial to explore whether they can be placed on the paper side of the bags or to establish effective methods for proper separation of ALP during the collection process.

The peak intensity in XRD graphs is influenced by various factors, including crystal structure, orientation, crystallite size and material amount. These variations can lead to differences in peak intensities, even for the same crystallographic planes.[77] The X-ray diffraction tests confirmed the presence of polypropylene and carbon nanotubes in the ALP and showed no significant differences between samples of different colors.

Therefore, all different laminate manufacturers use the same basic formula for their products, which have similar recycling potential. Although the funnel of the granulator, in which the ALP was converted to flakes, worked well, a small amount of plastic residue remained after each trial, contaminating the subsequent runs.

Producing the plastic tiles proved to be a greater challenge than initially expected, especially since the block kept sticking to the sealing box. The raised edges of the container made tile removal even more complicated. By using a different mold shape with angled side walls and a press that removes the product, this issue could be reduced.

76. Recycling Inside, “Ink removal in plastics recycling plants,” 11 2021.

77. N. C. f. C. D. P. Division of Oral Health and H. Promotion, “Sterilization: Packaging storage — FAQs — Infection control — Division of Oral Health — CDC,” 2 2016.

Multiple trials were conducted with the melting process to produce a solid block of recycled plastic. The behavior of the ALP, which consists of polypropylene and carbon nanotubes, differed from that of polypropylene wrapping paper, as described by Van Straten (2021).[20] In this study, it was observed that polypropylene from wrapping paper melted at temperatures ranging from 200 to 300 degrees Celsius.

However, when melting ALP, a temperature of 250°C was insufficient to achieve melting, preventing the material from passing through the filter, while using a temperature of 300°C resulted in the formation of charred plastic tiles, making them unsuitable for recycling with the melt hopper. The charring of the ALP can be attributed to thermal degradation processes in the polymer matrix. The presence of carbon nanotubes in the ALP, known for their high thermal conductivity,[70] appears to enhance the distribution that affects the thermal degradation process.

Unlike the experimental setup used by Van Straten (2021),[20] the melt hopper lacked a fully airtight seal, allowing air interaction with the ALP in the hopper, which may have also contributed to the charring. In addition to reducing the melting temperature and time, removing the filter as well as eliminating oxygen through the use of alternative support gases could further improve the process.

Improper handling of shredded plastic fragments can lead to negative environmental consequences, as shown by Suzuki et al. (2022),[78] where mechanical recycling without proper wastewater treatment resulted in the emission of microplastics into the environment. During the process, it is crucial to have sufficient material to ensure optimal flow and full mold cavity filling.

In this case, however, the bouncing motion in the funnel prevented the granulated ALP material from being effectively processed in the injection molding machine. This issue disrupted smooth material flow, hindering the injection molding process and requiring additional cleaning. Optimizing the process and hopper granulation components could minimize the risk of exposing the environment to residual particles from cleaning activities.

78. G. Suzuki, N. Uchida, L. H. Tuyn, K. Tanaka, H. Matsukami, T. Kunisue, S. Takahashi, H. V. Pham, H. Kuramochi, and M. Osako, "Mechanical recycling of plastic waste as a point source of microplastic pollution," Environmental Pollution, vol. 303, p. 119114, 6 2022.

High pressure injection molding

After several melting trials, it became clear that the spring-high-pressure melt setup met all the required specifications. When disassembling the setup, it was found that the ALP block could be easily inserted.

Moreover, the setup remained unchanged even after undergoing two melting trials, demonstrating its reusability and robustness. The insertion of the ALP block using spring pressure proved to be more effective than previous high-pressure melt configurations and seems to have potential for scaling up to sheet or tile production for construction, insulation or shock absorption. The impact of the nanotubes on insulation or conductivity properties and their potential still needs to be further studied.

The recycled ALP tiles exhibited a hard and non-porous outer surface. Interestingly, the tile showed a more robust internal structure, as evidenced by its resistance to manual breakage. This resistance was particularly remarkable because the 200g tile could not be broken with bare hands.

By cutting the ALP block into three parts, it was found that the individual ALP flakes remained distinguishable, and all flakes had completely melted. No flakes were formed, contributing to an mass-to-strength ratio with potential. The low weight of the material, smooth outer surface and light porosity where air is trapped may be valuable for many applications in the transport industry.

Bikiaris et al. (2010)[79] reported a Young's modulus of about 1250 MPa, an ultimate tensile strength of about 31 MPa, and a fracture strain of about 150% for polypropylene mixed with carbon nanotubes subjected to tensile tests after injection molding. It is clear that the mechanical properties of the recycled ALP in our study are significantly lower. For polypropylene with 0.5% carbon nanotubes, these variations in mechanical properties are likely attributed to the incomplete melting of ALP flakes during our specific recycling process. This is clearly visible in Figures 6 and 7, where distinguishable flakes can be seen in the material.

79. D. N. Bikiaris, "Microstructure and properties of Polypropylene/Carbon Nanotube Nanocomposites," Materials, vol. 3, pp. 2884–2946, 4 2010.

This inherent heterogeneity in the material's structure could lead to varying mechanical properties from one sample to another. Another possible explanation is that the dogbone broke due to a small air bubble in the fracture line. Another important aspect to highlight is that lasercutting the ALP resulted in the re-melting of the edges of the dogbones, affecting the materials. It is important to investigate whether testing larger samples and more precise curing techniques have an impact on the test results.

Future work

It is worthwhile to further investigate the optimization of the fundamental parameters for forming under high pressure with springs. The effects of various parameters such as pressure, temperature and melting time could be studied in terms of their impact on the mechanical properties and quality of the recycled ALP material. Further study should focus on determining the optimal process conditions for achieving the desired properties and product results. Further tests should include various physical, mechanical, chemical and thermal properties using appropriate testing methods. This will enable a comparison between the recycled ALP material, allowing for further exploration of its performance and potential applications.

The role of technical universities in driving sustainability in hospitals

Technical universities play a critical role in advancing sustainability in healthcare by bridging the gap between academic research and real-world application. Hospitals increasingly face the dual challenge of reducing environmental impact while maintaining high standards of care and safety. One powerful lever lies in rethinking how materials—particularly plastics and polymers—are used, processed, and reused within medical settings.

A compelling case in point is the investigation into recycled Autoclavable Lightweight Polymers (ALP), particularly their reformation under high pressure using spring-assisted processes. Technical universities can contribute by rigorously exploring fundamental process parameters such as pressure, temperature, and melting time, and their impact on mechanical properties and material integrity. This type of applied research is essential for validating whether recycled ALP can meet stringent clinical and regulatory requirements for medical device applications.

The study on more complex modified plastics demonstrates promising potential for the recycling of ALP with polypropylene and carbon nanotubes. The adaptive high-pressure melt setup with spring pressure showed potential for creating uniform, strong products with different properties depending on melting time, temperature, pressure and fiber orientation. By melting under higher pressure, the products become stronger and harder, making them suitable for construction purposes. When scaled up, recycled ALP can be applied in acoustic panels due to its low weight, smooth outer surface and light porosity.

These findings represent a meaningful step toward sustainability in the medical recycling industry and provide a solid foundation for further research and optimization of ALP recycling methods. Especially driven by current geopolitical situation, urban mining of rare earth elements out of complex multi-materials will be needed in the future to ensure that Europe becomes less dependent on other continents.


GC
GREENCYCL

10.2 Mechanical recycling of face masks

Introduction

GreenCycl, in collaboration with the research line Sustainable Surgery at TU Delft, developed a sustainable method for recycling medical polypropylene. The process involves melting plastic waste into blocks, which were then granulated into small pellets.

Figure 22 shows how an isolated waste stream from hospitals is used for the production of a new medical product. After determining the properties of the material recovered from the melting process, it can also be assessed whether (and how) different waste streams can be combined to achieve specific product specifications. For example, a container could be designed with a compliant hinge that needs to be very flexible, or a rigid coupling that requires a shape-retaining connection with high stiffness.

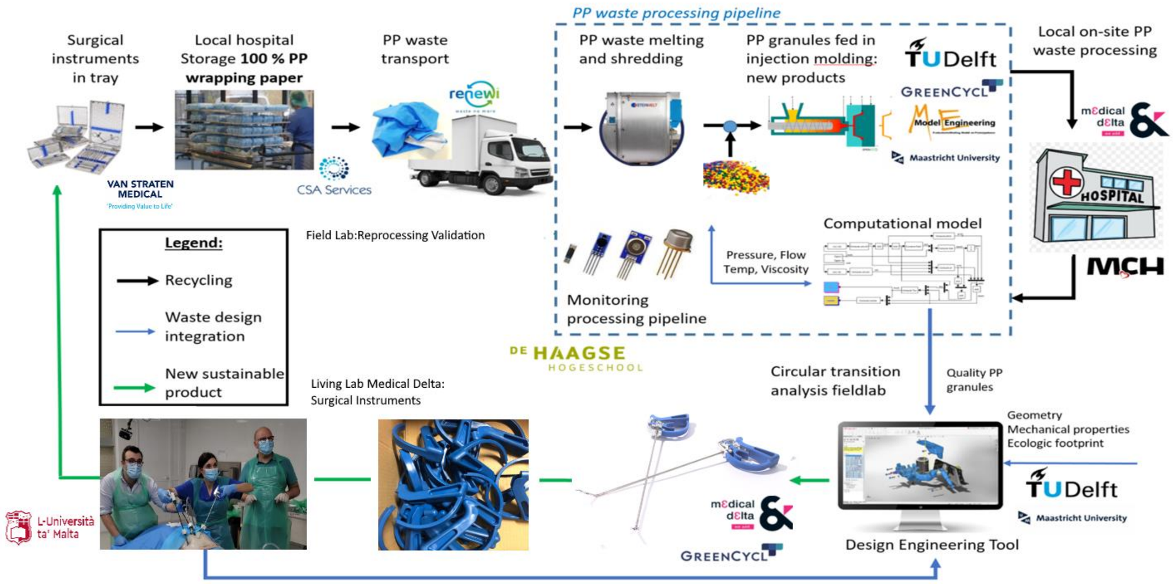


Figure 22: Example of how isolated waste streams from hospitals are used in the design of new instrument handles for surgical tools.

A ‘single-use’ product that is widely used in healthcare are surgical masks of type IIR and FFP2. These masks consist of, among other things, elastics, multiple layers of woven and fiber-bonded polypropylene, and a metal nose strip. FFP2 masks are often used in specific departments, including the ICU and nursing wards. During the COVID crisis, both types of masks - new and used - were collected from Dutch hospitals to investigate their reusability.[32]

This study shows that the masks can be sterilized by steam sterilization at 121°C, ensuring that the COVID virus is deactivated. Since FFP2 masks became sufficiently available again after the initial shortage during the pandemic, a wider application of this study is to determine how these masks can be recycled into raw materials for the production of new products. Both types of masks are primarily made from polypropylene (PP). This article examines whether it is technically feasible to recycle polypropylene surgical masks.

Methods

In the first phase of the research, a filtration system was developed to remove the metal strips from the face masks. After the remaining polypropylene was melted and granulated, the material properties were determined. Next, it was examined whether the recycled material can be used as raw material by producing various products via injection molding.

Functional requirements

To process the face masks on a large scale, a modular filtration system for the melting furnace was designed. It is essential that the filter separates 99% of the unwanted materials, such as nose bridge wires, in an efficient manner. The polypropylene from the face masks must melt and easily pass through the filter. Additionally, the filter must not clog and it must be reusable after cleaning. This filter should be replaceable within 5 minutes and ready for reuse within 30 minutes after cleaning. In total, 80% of the material must be recoverable. A test was conducted to determine whether the prototype met these functional requirements; during the test, 2000 face masks were melted at 270°C over 90 minutes.

Material properties

The material properties of the recycled material were tested with a tensile test. The recycled granulate (R-PP) was mixed with virgin material (V-PP) in different ratios, referred to as the R/V% PP ratio. The mixtures had the following proportions: 0R/100V% PP, 33R/67V% PP, 50R/50V% PP, and 67R/33V% PP. Six tensile bars of each mixture were injection molded by the Babyplast 6/10P at an injection temperature of 185°C. A tensile test was performed on the bars, in which the bars were subjected to a controlled tensile force until they break. The data from the tensile test were analyzed in Matlab R2020a. The material elongation [%], ultimate tensile strength [MPa] and material deformation [%] were determined. The properties of the mixtures were compared in a bar chart. Additionally, the hardness of the material was tested by the Shore Durometer Type D, Sauter HBD 100-0.

Producing components

Products were made to determine whether new products can be produced from the recycled material. Twenty labels are injection molded by the Babyplast 6/10P at 185°C with a 50R/50V% PP mix ratio.

As a test, six of the labels were mounted in a stainless steel instrument net and subjected to ten complete sterilization cycles within a week.

A standard disinfection and sterilization process was used for the tests. After one week, the labels were examined for thermal deformations and visual damage using a microscope at 100x magnification. Possible changes in chemical composition were analyzed using X-ray fluorescence by comparing three labels after the sterilization tests with three control labels.

Results

Filtration system

The filtration system is shown in Figure 23. The design consisted of two layers stacked on top of each other (Figure 23A). In the middle of the layers, a hole pattern was placed that allowed the polypropylene to flow through, while trapping the metal strips. The pattern of the layers was aligned in opposite directions, so that each opening of one layer was blocked by the other. The distance between the two layers was 5 mm, ensuring that the nose strips could not move sideways, bend or break through the filter. Additionally, both sides of the filter were bent at a 45°C angle to distribute the heat from the melting machine over the filter. The sides had no holes, ensuring more efficient heat conductivity (Figure 23B).

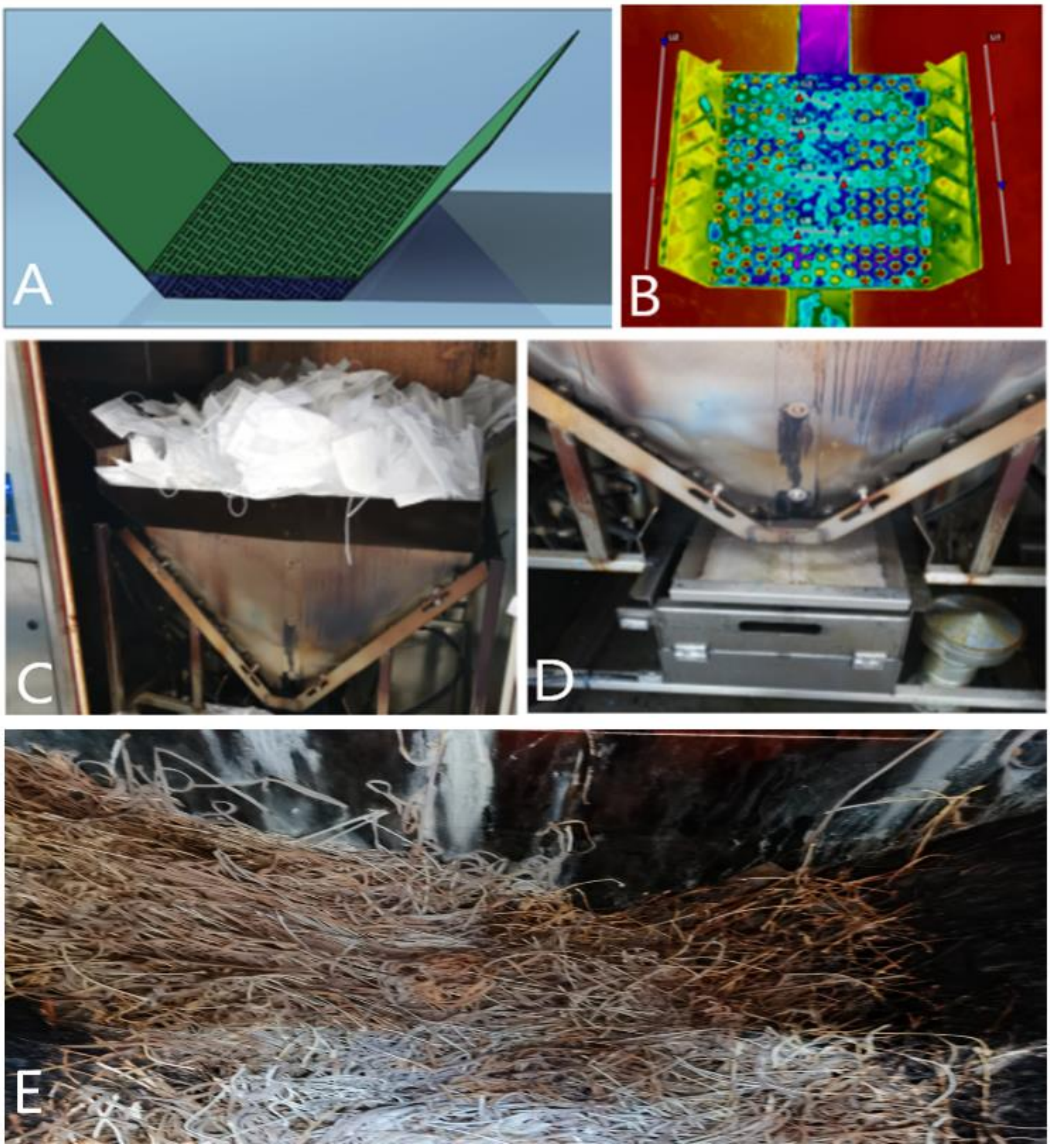


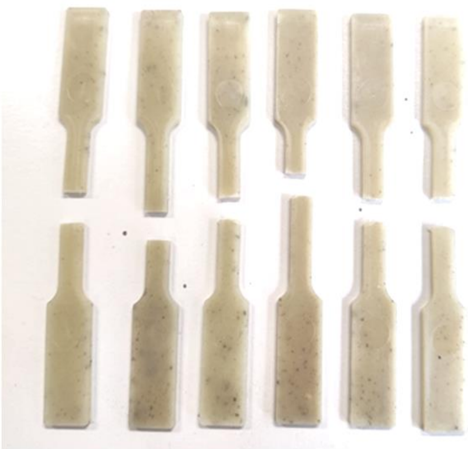
Figure 23: Filter for the Sterimelt, a melting oven for hospital waste used for face masks. A: 3D view of the system with two layers (green and blue). B: Thermal image of the heat distribution of the filtration system. C: Face masks in the Sterimelt for melting. D: Block of polypropylene from the face masks after melting. E: Captured metal strips from face masks.

The experiments showed that the filter could be cleaned within 20 minutes and installed within a minute, after which the face masks could be placed in the melting furnace without further adjustments (Figure 23C). During the melting process, the metal strips were captured in the filter, and the melted plastic was collected in a container (Figure 23D). The test determined that several dozen nose bridge strips passed through the filter; all collected strips formed a clump of wire (Figure 23E). After the melting process, the filter could be removed from the furnace and cleaned within one minute.

Material properties

To determine the material properties of the mix ratios, six tensile bars per mix were tested. Figure 24A shows the tensile bars with a material ratio of 67R/33V%. The results of the tensile test are shown in Figure 24B. The ultimate tensile strength and material deformation for each mix are depicted in a bar chart. Deformation decreases as the amount of recycled material in the mix increases, meaning the mixture becomes more brittle.

The bar chart also shows that the tensile strength decreases as more R-PP is added to the mixture. The values for the material properties of the mix ratios are shown in Table 1. The table shows that the elongation (ε) decreases as the ratio shifts towards R-PP, while the strength (E) increases. Additionally, the hardness of the material increases.



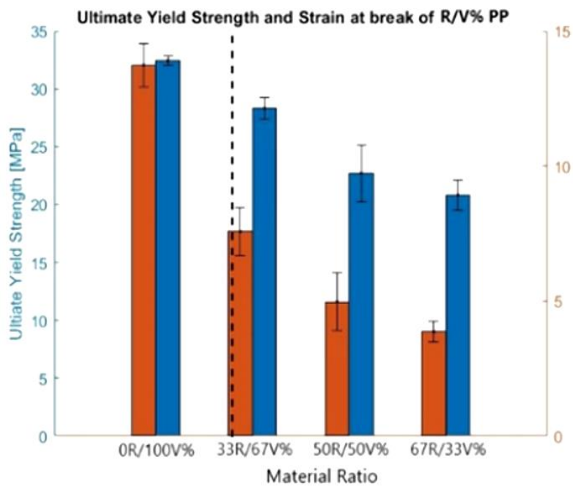


Figure 24: Tensile bar research for determining mechanical properties. A: Broken tensile bars (67R/33V%) after the tensile test. B: Bar charts of ultimate tensile strength and material deformation for different mix ratios.

The values for the material properties of the mix ratios are shown in Table 1. The table shows that the elongation (ε) decreases as the ratio shifts towards R-PP, while the strength (E) increases. Additionally, the hardness of the material increases.

Tabel 1: Material properties of recycled material

Ratio	ε [%]	σ [MPa]	E [MPa]	Hardness
0R/100V%	13.4 ± 0.8	32.4 ± 0.4	792 ± 13	67.0 ± 0.6
33R/67V%	7.6 ± 0.9	28.3 ± 0.9	791 ± 17	70.0 ± 0.9
50R/50V%	5.0 ± 1.0	22.7 ± 2.4	754 ± 16	69.7 ± 0.8
67R/33V%	3.9 ± 1.2	20.8 ± 1.3	781 ± 19	71.2 ± 0.8

Injection-molded products

In total, ten identification labels were produced with a 50R/50V% PP mix ratio and ten identification labels with a 75R/25V% mix ratio. These labels showed no visual defects, inconsistencies or deformations after production. Three labels of each type were mounted on a stainless steel instrument net (Figure 25) and subjected to the full sterilization process seven times within a seven-day period. After inspection, no damage, fractures or deformations were visible. After the decontamination and sterilization cycles, two of the three R50/V50% labels were torn, bent and/or broken. The R75/25V% labels showed no damage.

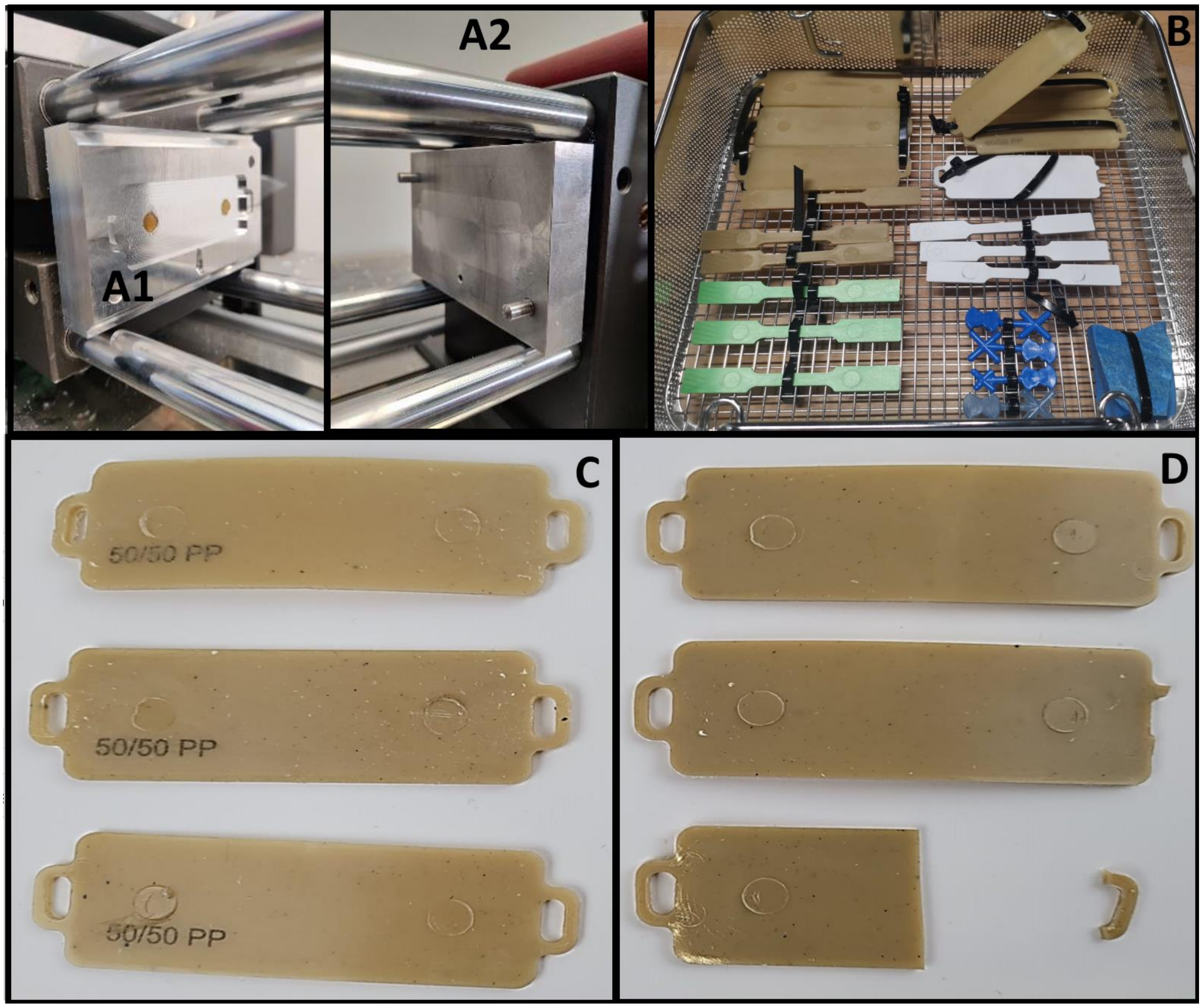


Figure 25: Testing with a label as a surrogate product. A1/A2: Two-part aluminum mold for labels. B: Sterilization container with labels and tensile bars as they undergo the cleaning and sterilization process. C: R50/V50% labels after seven decontamination and sterilization cycles. D: R75/25V% labels after seven decontamination and sterilization cycles.

Figure 26 shows a validation XRD (X-ray diffraction) diagram of virgin polypropylene mixed with face mask polypropylene at an R50/V50% ratio. The diagram shows a good fit with C3H6 polypropylene (red reference bars in the figure), with no other plastics identified. However, an unknown peak at 10 Theta is observed.

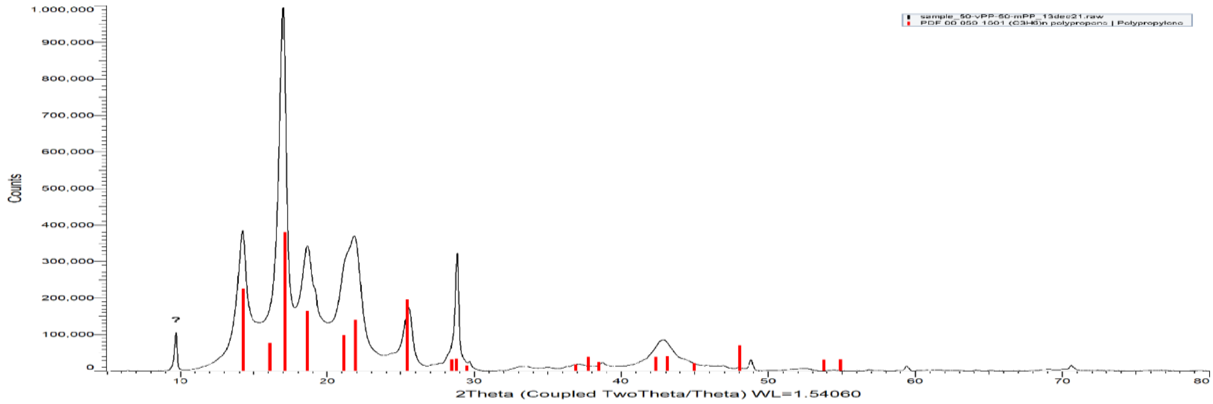


Figure 26: An XRD diagram of virgin polypropylene mixed with face mask polypropylene at an R50/V50% ratio. It shows a good fit with C3H6 polypropylene (red reference bars in the figure) and an unknown peak at 10 Theta.

Discussion

The filtration efficiency of the filtration system is 98%, but the remaining metal strips in the polypropylene mix can cause clogging in the granulator machine. These granulator machines have a roller geometry with milling blades, which can be damaged upon contact with solid metals. The granulator machine must be restarted each time due to the activation of the safety system.

Additionally, the captured wire pieces, combined with the remaining polypropylene, form a solid matrix. This requires significant effort to disassemble and clean the filter, which is undesirable. To improve the workflow, it is recommended to optimize the filter. The mechanical properties of the recycled material deteriorate compared to the original raw material of the face masks.

Downcycling (when the material has a lower than its original quality after recycling) is primarily caused by an increasing number of crosslinks between the long polypropylene monomers after a processing cycle which brings the material into a liquid state. The granulated material has a sand grain structure. After analysis, it was found that the material can be processed into higher quality granulate. Despite the reduced properties of the recycled material, it has been shown that products can be made. A mix of virgin polypropylene and recycled raw material provides sufficient strength. A ratio of up to 67% recycled material yielded satisfactory results, but the injection molding of 100% recycled material was found to be of insufficient quality.

The pellets stuck together, potentially clogging the injection molding machine inlet. The validation XRDs for the various mix ratios showed a good fit with standard polypropylene without identifying any other known materials. A comparison of the validation XRD with the XRD of pure virgin PP mixed with it shows that the peak at 10 Theta originates from additives (C_6H_{12}), which are non-toxic for use in the food industry.

The use tests with the labels on the stainless steel nets show that products up to a mix ratio of 50R/50V% are functionally usable and can be used in material-challenging environments, such as those found in a sterilization process. Further long-term research is needed to definitively determine the influence of chemicals and the continuous temperature changes on the aging process of the material.

While the results show that simple products can be produced from the recycled material, upgrading the material could improve both the mechanical properties and the mix ratio. After analysis at a granulate processing company, it was found that the material could be processed into better quality granulate. It is recommended to perform a toxicity test on the recycled material to determine whether the additives transform into harmful chemical compounds after heating.

Furthermore, it is likely that any bacteria and viruses are removed from the masks during the melting process, as the temperature in the melting furnace is around 270°C. The mechanical and thermal transformations the material undergoes during recycling are sufficient for the safe production of new parts. Compared to recycled material from blue wrap, it was found that polypropylene from face masks seems to flow more during injection molding due to the presence of additives. This may be caused by the water-repellent coating on the face masks. Some face masks are equipped with an ionizing coating, which attracts the smallest particles, under 0.1 microns. These additives may also contribute to the sandy structure of the plastic blocks and granulate. However, after injection molding, this structure becomes fully homogeneous again. The influence of this abnormal behavior will need to be further investigated.

The material properties of the surgical polypropylene face mask as compared to the recycling of blue wrap with similar mix ratios differ; the maximum tensile strength and deformation of the recycled face masks decrease by 32% and 45% across the board. The hardness is 3% lower than that of polypropylene from recycled blue wrap. These differences may also be caused by the additives.

Future work

The results of this research can be used to make medical products more sustainable. For example, components of wound drainage systems (such as from the brand Medinorm) can be made from recycled material. A Life Cycle Assessment from an internal study has shown that the ecological footprint of the materials in the wound drainage system will decrease as a result; energy consumption will be reduced by 21%, and the CO_2 footprint will decrease by 19%. In December 2021, a pilot project was started to test the recycling of surgical face masks on a larger scale, conducted by GreenCycl and TU Delft in collaboration with the dental and healthcare sectors.

The role of technical universities such as TU Delft

This example illustrates the pivotal role technical universities such as TU Delft and FieldLabs such as GreenCycl as they can play in developing scalable, evidence-based sustainability solutions for the medical field. By combining advanced engineering, materials science, and design thinking, technical universities provide the expertise and infrastructure needed to transform research findings into real-world applications.

In the case of wound drainage systems, the transition to recycled materials not only lowers environmental impact but also serves as a model for systemic change within medical device manufacturing. Through rigorous testing, validation, and life cycle analysis, the university helps ensure that performance, safety, and compliance standards are maintained while achieving significant ecological gains—such as the documented 21% reduction in energy use and 19% decrease in CO_2 emissions.

Moreover, the December 2021 pilot project involving the recycling of surgical face masks reflects how technical universities act as catalysts for cross-sector collaboration. In partnership with GreenCycl, healthcare providers, and the dental sector, TU Delft demonstrated how research can lead to closed-loop solutions for single-use medical products—one of the most challenging waste streams in healthcare.

The university's contribution extends beyond material research. It includes:

- Developing circular design principles that influence how future medical products are conceived.
- Prototyping and testing new production methods for recycled healthcare plastics.
- Training students and professionals in sustainable engineering and regulatory practices.
- Engaging with policymakers to create enabling frameworks for circular medical devices.

By embedding sustainability into every layer of innovation, technical universities ensure that ecological considerations become integral to healthcare design and operations. Their independent and interdisciplinary position enables them to lead the way in evidence-based transformation—from material science breakthroughs to market-ready, low-footprint medical products.

10.3 Rare and precious earth component recovery

10.4 The potential of critical and strategic material recovery from cardiac catheters

Modern medical devices, such as cardiac catheters, rely on rare, precious, and critical materials—including platinum, palladium and iridium. However, once used, these high-value components often end up as part of hospital surgical waste, destined for incineration. This practice not only contributes to environmental degradation but also represents a significant loss of finite and geopolitically sensitive resources.

Recovering valuable materials from used cardiac catheters presents a unique opportunity to align healthcare with the principles of the circular economy. By harvesting and recycling critical raw materials from medical waste streams, hospitals can reduce dependency on virgin extraction, cut down emissions associated with mining and manufacturing, and contribute to resource resilience in the healthcare sector.

Surgical waste streams are an overlooked but promising reservoir of critical and strategic materials. With the right infrastructure, disinfection processes, and recovery techniques, components from devices like catheters can be safely reprocessed or recycled. This approach supports global efforts to secure critical material supply chains, addresses rising concerns over trade restrictions and supply bottlenecks, and opens the door to new circular business models in healthcare.

Incorporating component recovery into hospital operations is not just an environmental imperative—it's a strategic one. It reflects a forward-thinking approach where sustainability, material efficiency, and innovation converge to create a more resilient and responsible healthcare system.

Introduction

Cardiac catheters are used to perform heart surgeries. In contrast to open heart surgery, where the heart is reached by making incisions in the sternum, a catheter is introduced through a vein, usually in the upper leg or arm. The heart ventricles or chambers are then reached by pushing the catheter through the vein. Figure 27 shows this path of a vein in the upper leg is used.

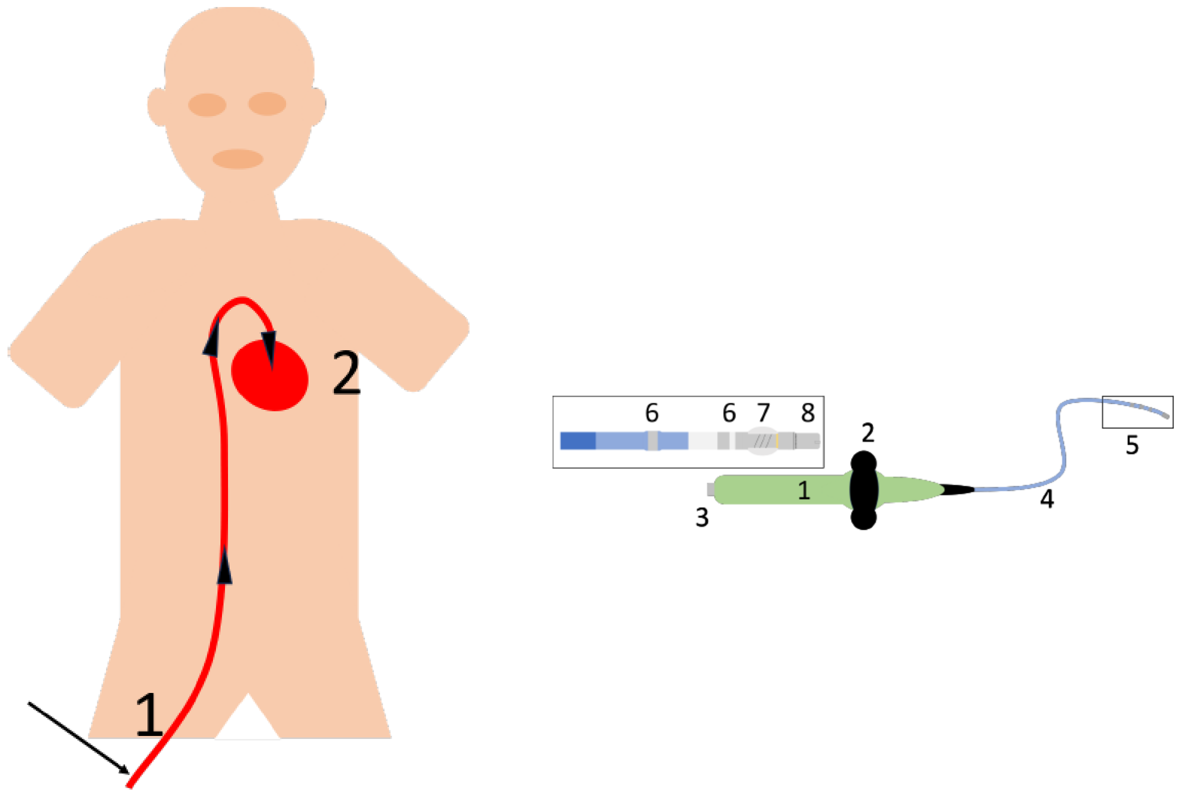


Figure 27: The basics of catheter intervention. Left: The schematic travel path of the catheter. Right: the complexity of a catheter tip is defined by the type of sensing and actuation present. Right, below: The general design of a cardiac catheter. The grip (1) has a steering handle (2) and the electronic input (3). The flexible and steerable sheath (4) has a tip (5) at the end, where the sensors are housed. For ablation catheters, these include ring electrodes (6), position and pressure sensors (7) and the tip electrode (8).

Since the surgical team cannot physically see what they are doing during a catheterization surgery, as the medical devices are inserted into the patient, sensors and monitoring devices are required to provide the medical team with such data. Cardiac catheters can house positioning sensors, force sensors, irrigation tubes, pulling wires and many other systems to perform the required surgery. This, in combination with multiple types of materials being used, makes these cardiac catheters very complex systems.

To make matters more complex, the catheters need to be inserted into a vein, limiting their size dramatically. Due to the size and complexity of the catheter, they come at a great financial cost. Especially the sensor components, made of rare earth elements such as palladium, iridium and platinum,[80] contribute to the high costs of these devices. Most of these cardiac catheters are single use devices (SUD), meaning that all catheters are seen as contagious waste after use and go to landfill or are incinerated.[81]

This means that even the precious metals present in the catheters are not reused. This shows the huge burden of cardiac catheters on both the environment and the national health budget. As it is unlikely that mechanical processing results in harvesting of the rare earth components in such a way that they can be reused, a new “mechanic-chemical” (MeChemical) process is being sought that combines mechanical and chemical reprocessing, such that metal components can be harvested with minimal damage while plastic parts are dissolved for later recycling.

80. L. Wigchert, T. Horeman, B. van Straten, “Reprocessing of uni-directional biosense webster ablation catheters: a novel disassembly method,” 2023.

81. G. Ditac, P. Cottinet, M. Le, D. Grinberg, J. Duchateau, K. Gardey, A. Dulac, A. Delinière, C. Haddad, J. Boussuge-Roze, F. Sacher, P. Jaïs, P. Chevalier, and F. Bessière, “Carbon footprint of atrial fibrillation catheter ablation,” EUROPACE, vol. 25, pp. 331–340, Feb. 2023.

Catheter types

Several catheter types are were investigated in this case study. The SMARTTOUCH and QDOT MICRO catheter resemble the general catheter design in shape and dimensions. As the SMARTTOUCH catheter is abundantly present in the catheters collected by GreenCycl, it was decided to include this catheter in this study as well. Three other catheter types that do not resemble the general design are the PENTARAY and OPTRELL, as their distal end splits into multiple smaller branches. Figure 13 shows how the catheters differ from each other.

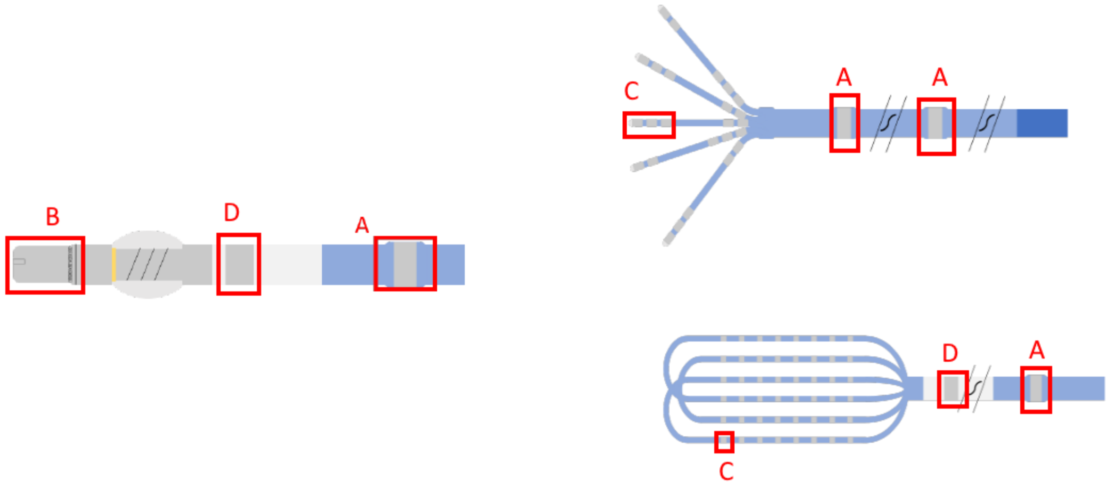


Figure 28: Three different kinds of catheters with relevant rare earth materials of different sizes (A-D) that can be found embedded in the plastics.

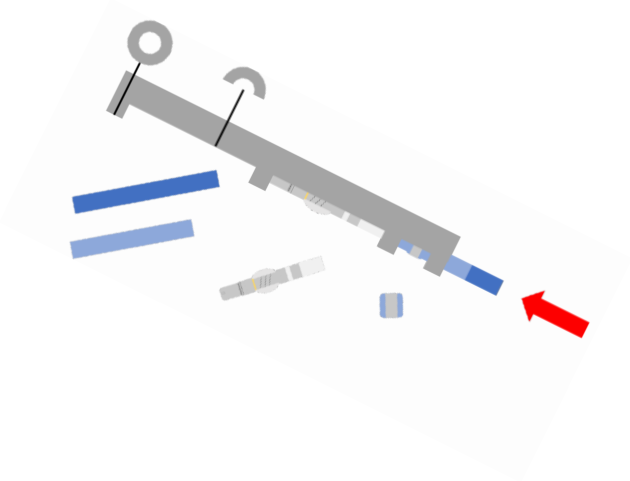
Methods

After looking at all possible material separation options, it was decided that the study would include three phases: a cutting phase, a chemical phase and a sieving phase. Since the main difference between the three phases lies in the chemical phase, the concepts are named after the chemical treatment: i.e., the concept with a cutting phase, an acid phase and sieving phase was named acid concept; the concept with a cutting phase, a melting phase and sieving phase was named pyrolysis concept; and the concept with a cutting phase, a warm benzene phase and sieving phase was named benzene concept.

Mechanical tip separation

To make a chemical treatment of the electrodes as efficient as possible, all pieces of catheter that do not contain electrodes were removed. This reduced the amount of chemicals needed and thus increased the yield of the procedure. A cutting device was designed. This device had to be compatible with all catheters from this research, so the QDOT MICRO, OPTRELL, PENTARAY and OCTARAY catheters, produced by Johnson & Johnson daughter company BioSense & Webster.

During the design of the cutting device, the following aspects were considered. Firstly, the system should be able to automatically detect the type of catheter. Furthermore, the device had to adjust the cutter spacing in order to cut only the relevant parts from the catheter. Finally, the system had to ensure that the relevant parts were separated from the remaining parts for more efficient harvesting and recycling. Thus, more rare earth materials can be recovered through the chemical treatment that follows. This optimalisation was needed because there is a limit to the amount of plastics that can be dissolved with a fixed volume of chemicals used.



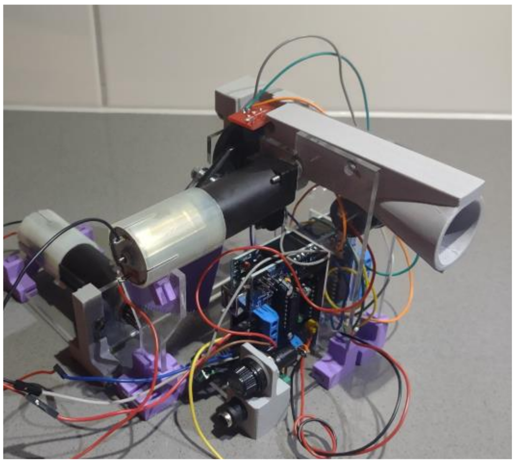


Figure 29. Left: The system should be able to separate the parts of interest from the remaining plastic waste before further processing is done with minimal impact on the chemicals. Right: A technical electrode separation system built and used in the study.

Chemical processing

In the second phase of the study, three fundamentally different methods were investigated to break down the integrity of the plastic catheter materials in order to free up the electrode rings made from rare earth materials. Acids, pyrolysis and warm benzene solvents were used in three different setups, each with their advantages and disadvantages.

Acids

Unlike non-polymeric materials, which dissolve instantaneously, polymer dissolution involves additional processes such as solvent diffusion and chain disentanglement. Non-polymeric materials typically dissolve through external mass transfer, with dissolution rates influenced by the material’s resistance to this transfer. In contrast, polymer dissolution can be more complex, involving multiple mechanisms. Internal material determination studies conducted at TU Delft identified the polymers present in the catheter. Following this identification, chemical data sheets for these polymers were analyzed.

While some of these data sheets were provided by the original equipment manufacturers (OEMs), more general polymer information - such as that for nylon 12 (PA12) - had to be further investigated due to the high versatility amongst the different nylons. Using these data sheets, various chemical agents capable of dissolving multiple types of polymers were identified. However, due to health hazards, certain agents are typically not available in most labs and deemed unsuitable for experimentation.

Chromic acid, for example, was excluded for this reason. Ultimately, two viable candidates were selected: 65% nitric acid and 96% sulfuric acid. These were chosen due to their effectiveness in reacting with PEEK, a polymer containing multiple benzene rings. PEEK can undergo aromatic substitutions such as sulfonation and nitration, making these acids particularly suitable for dissolution studies.

The final proposal setup (Figure 14, left) outlines the treatment process for the electrodes. The ring electrodes were subjected to nitric acid treatment, while sulfuric acid was used for the tip electrodes. The primary parameter evaluated in this study was the choice of chemical agents. To further optimize the procedure, additional factors such as temperature, pressure or the use of a catalyst could be considered. However, no elevated temperatures were required in this setup, minimizing energy consumption. The only equipment requiring power were the fume hood and the sonic bath, ensuring a relatively low energy demand for the process.

Pyrolysis

Pyrolysis is based on the principle that plastics decompose under high temperatures, whereas metals do not. Metals consist of metal atoms arranged in a matrix; when heated to their melting temperature, their intermolecular bonds break, causing the metal to liquefy. In contrast, the plastics present in the catheter are organic materials that undergo different thermal transformations. As temperature increases, plastics transition through several key phases.

First, they reach the glass transition temperature (Tg), where the polymer chains gain enough energy to move freely, making the material more flexible - often referred to as the “rubber phase”. As heating continues, the melting temperature (Tm) is reached, where the material becomes a liquid due to the breaking of intermolecular bonds.

Further heating leads to decomposition at the pyrolysis temperature (Tp), a process known as thermal cracking. At this stage, the polymer chains break down into smaller monomers. If the polymer structure is highly rigid, decomposition may occur before melting, as intramolecular bonds break first.

During pyrolysis treatment, an organic feedstock is heated in an oxygen-free container with the help of a propellant gas to expel any residual oxygen. The applied heat then triggers thermal cracking, breaking down the organic material into various monomer fragments. The resulting decomposition products can have high caloric value, making pyrolysis a valuable process for energy recovery.

This decomposition process is influenced by numerous factors, including operating temperature, duration, catalyst presence, feedstock composition and pressure. Due to the complexity and randomness of polymer chain cracking, by-products often form unpredictably. However, pyrolysis generally produces three main output fractions: a volatile gas fraction, an oil fraction and a solid char fraction.

The final proposal setup for the pyrolysis is shown in Figure 30, middle. Ionized argon was used as a propellant gas and the container was heated at a controlled rate of 8°C per minute until reaching 1000°C. Due to the container's size, only the catheter tip could be evaluated. During the process, no direct capture of polymers was possible, as the ionized propellant gas carrying the monomers was used to obtain quadrupole mass spectroscopy (QMS – to measure the gaseous decomposition products released during pyrolysis) and temperature, thermogravimetric (TG data – it indicates at what temperature the materials starts degrading). The detection of N^+ ions suggests the presence of nitrogen, which is logically linked to the Teflon present in the catheter.

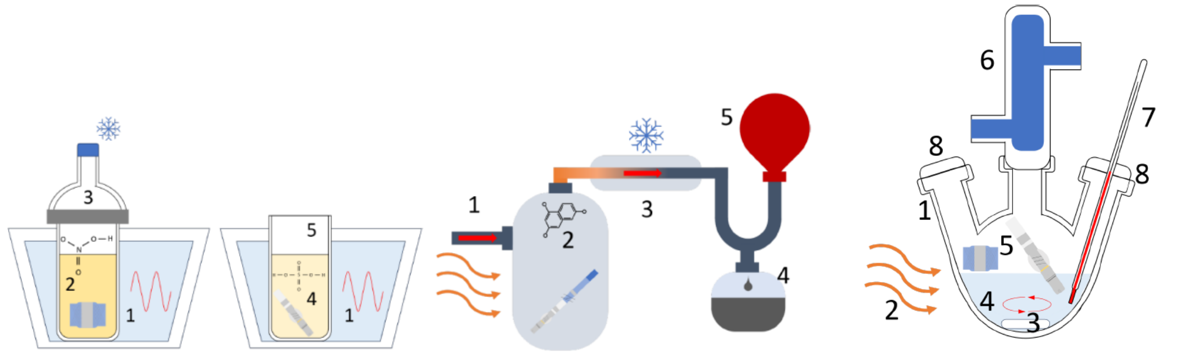


Figure 30: The three different setups that were used in the experiments. Left: The setup for nitric acid and sulfuric acid concepts, with a sonic bath in both cases (1) and a beaker with nitric acid and ring electrodes (2) with a condenser on the beaker (3) to close off the system. For the sulfuric acid, a beaker with sulfuric acid and tip electrodes (4) was used without a lid (5). Middle: The theoretical setup for the pyrolysis procedure, where the propellant gas (1) is pumped into an airtight container and heated. This causes the polymers of the catheter to evaporate and rise (2). These polymers and the propellant gas exit the container and are cooled (3). The polymers are captured (4) and the propellant gas and other gases are captured too (5). Right: The schematic setup for the warm benzene solvents, where a three-neck round bottom flask (1), is heated externally (2), e.g. with a heating mantle. The flask is stirred (3) with a stirring magnet and is filled with the agent (4); both the catheter tip and ring electrode (5) are present in the flask. The flask is sealed with a condenser that is constantly flushed with water (6), and a thermocouple (7) is present to manually read and adjust the temperature of the setup. The two open necks are sealed with lids (8).

Following pyrolysis, the electrodes were sonically rinsed for 30 minutes at 200 Hz to remove any remaining residue. The cleaned parts were then collected using a mechanical sieve. To further improve the process, an additional siphon system was implemented to ensure the efficient transportation of cracked polymers away from the electrodes.

Substitution reactions

Instead of using acids to dissolve the plastics in the catheter, alternative solvents can be used. To identify suitable options, chemical resistance charts for the relevant plastics were studied, with particular attention given to substitution reactions involving benzene rings. Based on this research, two candidates were selected: phenol and toluene. While chlorosulfonic acid was also considered due to its ability to perform aromatic electrophilic substitution, it was ultimately excluded due to the formation of hydrochloric acid by-products and other unpredictable reactions.

The chemical compatibility charts indicated that PEEK is resistant to toluene, whereas PA12 is vulnerable to it. PEEK (Polyetheretherketone) is a high-performance plastic known for its excellent chemical resistance, strength, and ability to withstand high temperatures—often used in medical implants and devices. PA12 (Polyamide 12) is a type of nylon that is flexible, durable, and resistant to moisture and chemicals—commonly used in tubing, catheters, and 3D-printed medical parts.

However, no documented reaction mechanism between PA12 and toluene could be found in the literature. In contrast, more research is available on the use of phenol as a solvent. Studies suggest that "exceptionally strong hydrogen bonding occurs between phenolic hydroxyl groups and amide bonds", which, on a macroscopic scale, leads to the structural decomposition of PA12.

Although no literature was found on the reaction between phenol and PEEK, chemical compatibility charts strongly advise against their combination, even at room temperature. Since the underlying mechanism for this recommendation remains unclear, further investigation is needed. It is suspected that phenol's ability to form hydrogen bonds may play a role in breaking the intermolecular bonds of polymers, leading to material degradation.

The experimental setup used for this study is shown in Figure 30, right. The experiments were conducted at ambient pressure; the selected temperatures were kept below the boiling points of the solvents to prevent excessive evaporation. For toluene, which has a boiling point of 111°C, a temperature of 90°C was used in all trials. For phenol, which has a boiling point of 182°C, an experimental temperature of 160°C was chosen. The temperature was manually monitored using a thermocouple placed in the flask.

The experiment examined four different exposure durations: 30 minutes, 1 hour, 2 hours and 5 hours. Mass change was measured to evaluate the effect of the procedure on the samples, with mass differences expressed as a percentage of the sample's initial mass to account for variations in sample sizes. If the sheath covering the electrode completely dissolved, the remaining catheter components were carefully removed from the flask using pincers.

Results

Acids

Among the tested acids, sulfuric acid was the more effective in dissolving catheter polymers. Figure 31, left, presents the mass fractions determined after treatment, providing quantitative insight into the dissolution process. To evaluate whether the acids affected the integrity of the electrodes, scanning electron microscopy (SEM) analysis was conducted. The surface areas of treated samples were compared to those of untreated samples, with the assumption that the inert nature of the electrode metals would result in minimal surface damage.

The SEM images of the ring electrode and catheter tip, in Figure 31, right, support this assumption, revealing only minor alterations to the surface. Additionally, since nitric acid failed to remove PEEK, it was concluded that sulfuric acid proved to be the more effective choice for polymer dissolution.

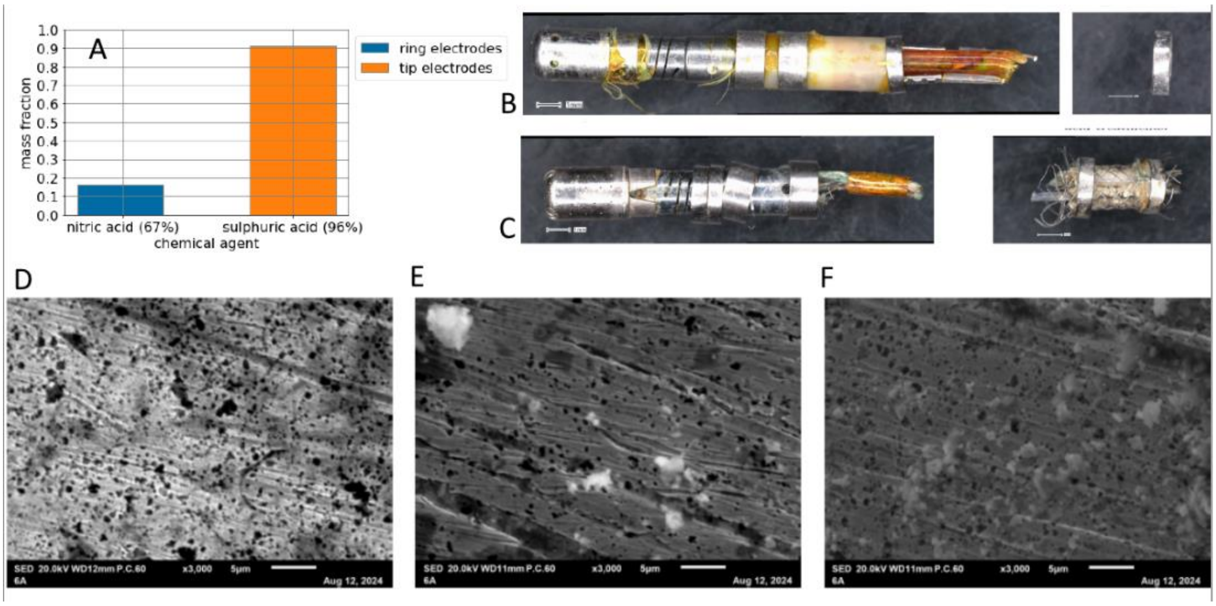


Figure 31: The results from the acid treatment experiments. A: The mass fraction of cold acids. The fraction is defined as the mass of the sample after the experiment divided by the sample's mass before the experiment. A clear decrease in mass can be observed, which is in line with the visual observations. B: A catheter tip and single ring electrode after nitric acid treatments. C: A catheter tip and single ring electrode after sulfuric acid treatments. D: An untreated catheter ring electrode as benchmark. E: A catheter ring electrode after sulfuric acid treatment. The white nuggets are sulfuric acid/polymer pieces. No significant decay was visible. F: A catheter ring electrode after nitric acid treatment. The grey nuggets are nitric acid/polymer pieces. No significant decay was visible.

Pyrolysis

A single test of this concept was conducted, after which the catheter tip was sonically rinsed and subjected to SEM analysis to assess potential damage to the electrode. Charring of the electrode was evident, even to the naked eye, and was further confirmed through both SEM and light microscopy. Since char is a known by-product of pyrolysis when decomposing organic material, its formation during this process is inevitable, even if minimized.

Therefore, charring of the electrodes is expected during pyrolysis treatment. However, there is no indication that the char cannot be removed, though an additional cleaning step would be necessary to achieve this.

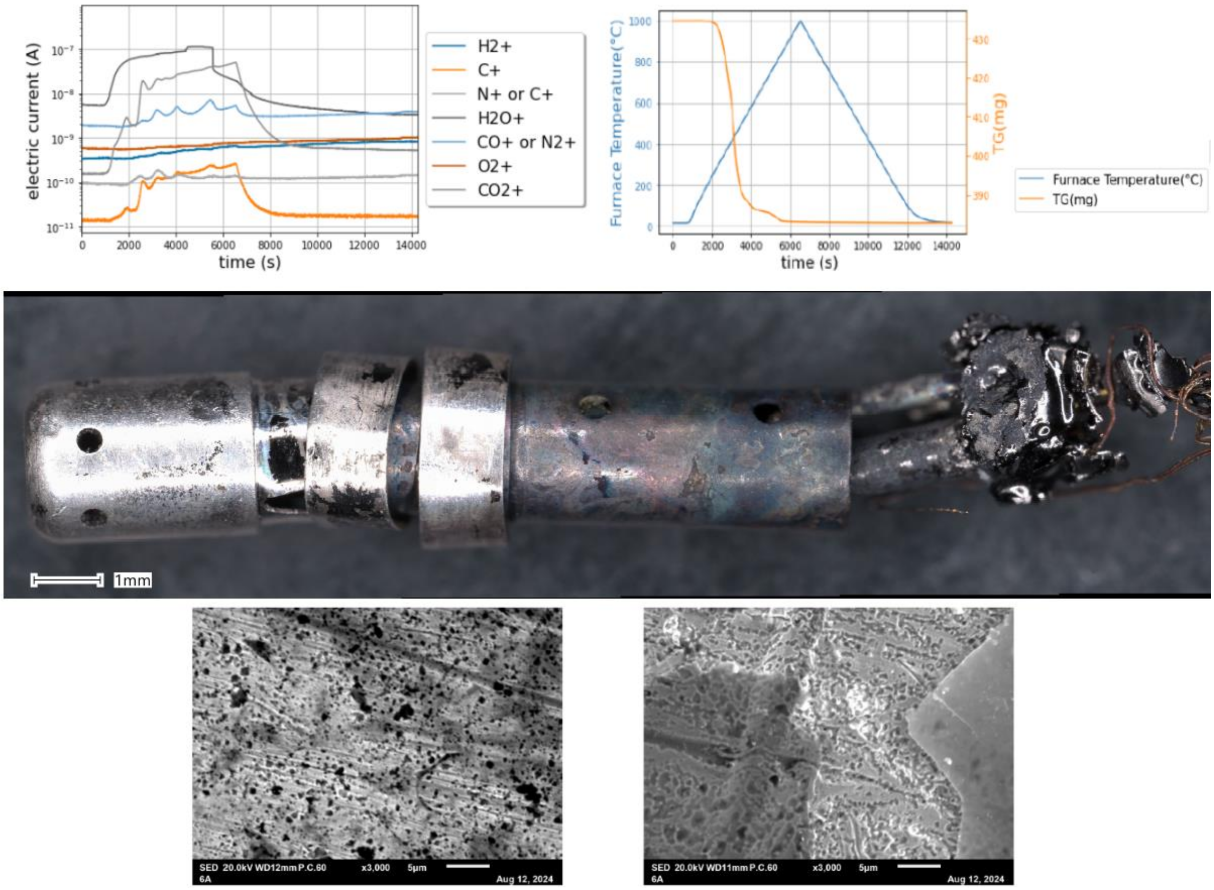


Figure 32: The results from the pyrolysis experiments. A: The QMS data from the pyrolysis experiment. The data show a large amount of carbohydrates, as is expected for plastics. Note the green line, which indicates the presence of nitrogen. It is believed that this is a result of the Teflon and PA12 present in the catheter. B: The temperature gravimetric (TG) data of the experiment. The decrease in the mass of the sample is compared to the container's temperature. C: A catheter tip electrode after the pyrolysis experiment and a sonic bath of 30 minutes at 200Hz. D: An untreated catheter ring electrode under magnification as a benchmark. E: A catheter ring electrode after pyrolysis and sonic bath. The smooth areas are clearly visible and are charred.

Substitution reactions

The mass fractions of the samples, Figure 33A, indicate that PA12 dissolved in phenol but not in toluene. However, PA12 did exhibit swelling in toluene, as illustrated in Figures 33C and D. While neither phenol (F) nor toluene (G) dissolved PEEK, phenol did cause visible damage to its structure, as seen in Figure 33C.

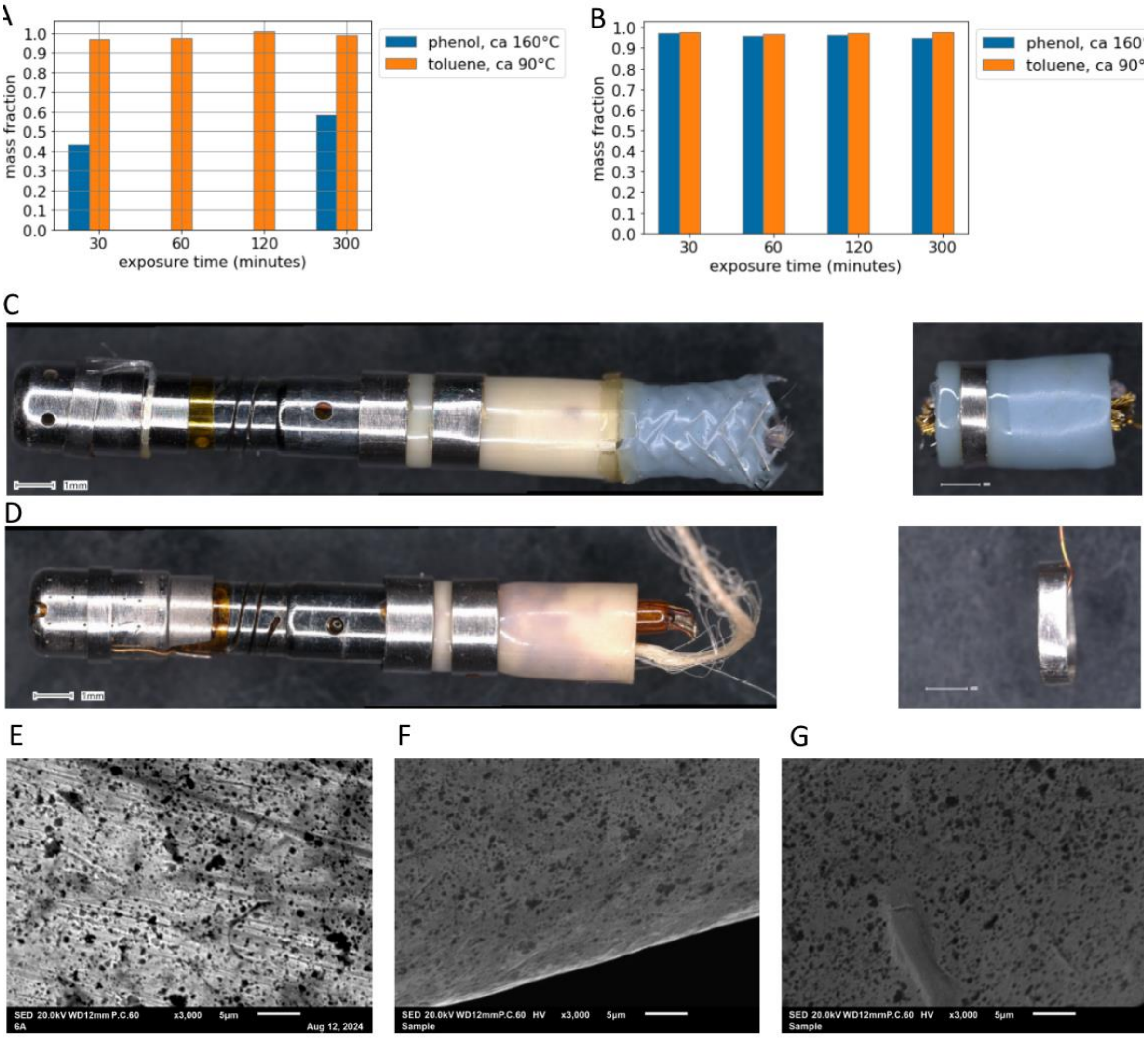


Figure 33: Results of the phenol and toluene substitution experiments. A: Mass reduction of the ring electrodes. Showing that the use of toluene is not effective in dissolving any of the polymers present, whereas phenol is. Since the PA12 in the ring electrode had dissolved after 30 minutes of exposure, no ring electrode was used in the 60 mins and 120 mins experiment. To assess if the electrode would be dissolved, the ring electrode was present at the 300 mins experiment. B) The mass reduction of the tip electrodes with PEEK. Minor loss can be seen in the phenol plots, but no significant loss in PEEK. C: A tip and single catheter ring electrode after toluene treatment. D: A tip and single catheter ring electrode after phenol treatment. E: Untreated ring electrode. F: A catheter ring electrode after phenol treatment. G: Ring electrode after toluene treatment.

Discussion

Regarding the mechanical separation of the tip and ring electrodes, it is believed that securing the catheter and utilizing (multiple) movable cutting blades will be advantageous, as this setup will prevent the catheter from jamming in the machine, thus addressing the current design flaw. This shift would allow the cutting device to operate more independently, reducing the need for constant human supervision and intervention. Furthermore, if the process is scaled up at a central location, exploring alternative methods to cut and recycle multiple catheters simultaneously will be essential for improving efficiency and productivity.

Chemical treatment of choice

The use of sulfuric acid to remove polymers from the catheters is the best method of the ones assessed in this study, but the difference between the concepts in terms of applicability is not very large. Therefore, the emphasis of the research team on specific criteria can be decisive. If removal of the rare earth materials from the PEEK by mechanical action would be possible instead of using sulfuric acid, it could mean that the pyrolysis concept would be the preferred concept. This requires a new combined “MeChemical” process that applies sheer force and pressure on rare earth materials during the chemical treatment to split them from the degrading tip plastics.

PEEK, a very resistant plastic, is designed to resist chemicals and was not much affected by the used removal attempts. Therefore, an easy method that does not involve dangerous chemicals or procedures was simply not possible. If less intensive procedures for regaining the electrodes are desired, the design of the catheter should be taken into account as well. It should be investigated if the PEEK components can be replaced or integrated in a different way.

A new processing line

The chemical separation concepts based on the use of nitric acid and phenol were able to remove only PA12, leaving PEEK structurally present. For catheters that do not contain PEEK, these concepts could be scaled towards a larger processing line. Therefore, distinguishing between catheters that do contain PEEK and those that do not is worth investigating; in this case, a processing facility like GreenCycl can develop two different processing lines for different catheter types. The illustration in Figure 34, left, shows the steps that are needed to scale up, before the valuable parts can be retrieved with minimal damage (Figure 34, right).

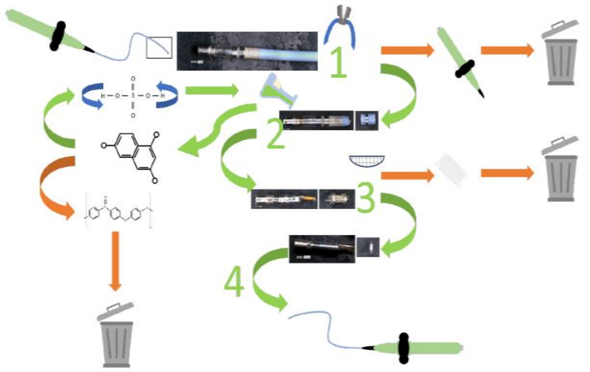


Figure 34. Left: Overview of the entire process in which catheter electrodes are separated from the rest of the catheter (phase 1). The catheter handle materials can definitely be repurposed, so no landfill is depicted. In phase 2, the PA12 and PEEK in the catheter are chemically removed. The spent agents are then regenerated, preventing the build-up of toxic waste. SPEEK can also be repurposed; PEEK can be regenerated from SPEEK as well. However, this PEEK does not contain mechanical characteristics comparable to virgin PEEK though. Lastly, the metal parts of the catheter are separated through a sieving process. The other metal parts can be repurposed, and the electrodes can be reprocessed and used in new cardiac catheters. Right: The parts that can be easily removed from the residue in step 3 and reused to build new catheters.

Process improvement

Charring during the process has a negative effect on the purity and quality of the end products and chemicals. Unfortunately, charring always occurred during pyrolysis in the experiments. There was no automated feedback loop from the thermocouple that measured the agent’s temperature and the heating element, other than the researcher.

This meant that there were overshoots in the heating steps of the warm solvent experiments. Through the use of controlled heating devices, these overshoots could have been avoided, preventing the contamination of the experiments and the forming of charr. Apart from tuning and control of the standard process parameters, the addition of other methods should be investigated.

Conclusion

The projects discussed here, executed by the Sustainable Surgery & Translational technology research line at TU Delft, demonstrated how the healthcare sector can work together with academic researchers to foster the transition towards a more sustainable and circular landscape. The presence of a LivingLab or FieldLab such as the GreenCycl FieldLab facilitates his kind of collaboration, as it translates knowledge to practice. In the FieldLab in this collaboration, it was demonstrated that it is technically feasible to recycle surgical face masks and use them as raw material for new plastic products.

It is essential to fully understand the material properties of the items to be recycled and how these are influenced by the use of additives and coatings. These insights can be used to optimize the processes to make granulate. In this way, both the speed of the process and the properties of the material can be improved.

The study that aimed to win rare earth materials from very complex metamaterial assemblies showed that the new MeChemical approach has the potential to win back high-quality ring electrodes with minimum damage. This means that for every ring that is reused, no ring needs to be manufactured, saving much more material than that present in the ring alone. Further research is needed to show how all these processes can be further scaled up towards national processing levels that include all hospitals.

It became clear in these case studies that a technical university is a strong partner in supporting developments at a very low Technology Readiness Level - a scale from 1 to 9 that indicates how mature a technology is (TRL level). Other types of funding are often out of reach in the idea phase, while a significant amount of manpower, effort and funding is needed to translate clinical ideas into physical processes and products, even if the economic and environmental potential is clear. In all three projects, the step from rough idea to a definite result was taken, allowing production and LCA specialists to start working on the business side of these projects. In this way, new products can be developed, when the recycling processes are implemented into a more comprehensive chain of manufacturing and marketing.

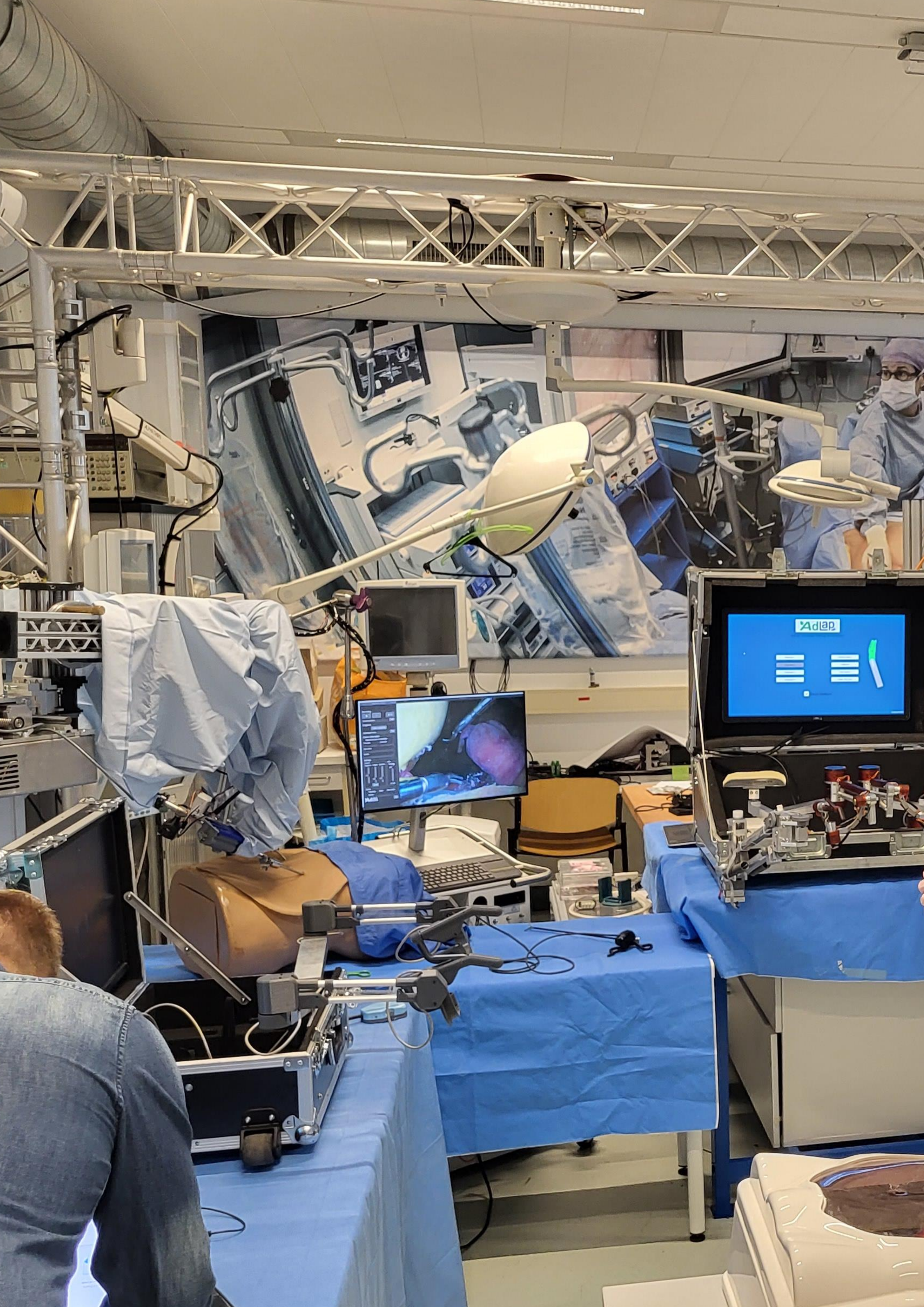
Through interdisciplinary research combining materials science, mechanical engineering, and biomedical design, universities like TU Delft can:

- Develop and optimize sustainable material processing techniques.
- Quantify environmental and mechanical performance using tools like Life Cycle Assessment (LCA) and finite element analysis.
- Collaborate with hospitals and industry to implement prototypes in clinical environments.
- Educate students and clinicians on sustainable innovation.

Moreover, research institutes within technical universities provide a neutral, trusted environment for testing, validating, and scaling solutions - especially crucial in healthcare, where risk mitigation and regulatory compliance are paramount.

By focusing on material innovations, reuse, refurbishment, recycling, technical universities help hospitals move from linear to circular models, reducing waste, decreasing reliance on virgin materials, and lowering carbon footprints - without compromising on safety or performance.


Driving sustainability


Adlap

In this video Bart van Straten and Bas de Blocq show how rare earth metals can be harvested. Scan the QR code to delve deeper into the topic.

https://www.youtube.com/shorts/o9cRTnlgZS4

11

Reflection

The population of Earth has grown from one billion humans in 1800 to over 8 billion in 2025. This is one of the major causes for the increase in greenhouse gases emissions, many negative ecological impacts and the increase in waste streams as a result of human activities.

This highlights the necessity to speed up the pace in introducing circular economy principles to create a more sustainable world. This means we have to change our behavior: we have to make choices that make the world more sustainable and circular, and create a vision on which policies and decision-making are based.

Making decisions and policies that are based on facts is of utmost importance, as is separating facts from emotions. We all have to find a balance within themselves between being a dreamer and a practical decision-maker. And we have to keep our back straight by not letting others tempt us to deviate from our path. Our actions can convince others and so we can play a pioneering role. Try to become a source of inspiration!

Policy makers can play an important role in increasing the speed of sustainability changes, for example by creating exemptions, through accelerated procedures for permits, by introducing emission taxes and stricter regulations. This will go faster if there is working in a circular way becomes mandatory.

In this book, we described the fundamental principles of the circular economy and how leadership, policies and decision-making can effectively stimulate those principles, specifically in the healthcare sector.

The circular economy is built on three principles which are fundamental for a more sustainable world:[82]

- Eliminating waste and pollution.
- Circulating products and materials as long as possible.
- Regenerating nature.

New circular economy policies based on the above principles will create new sustainable solutions, create new jobs, new technology and ecological stability.

The leaders of tomorrow, whether they are dreamers or practical decision-makers, can drive innovation and change with circular economy principles, inspiring people to take action.

Figure by B. van Straten (2025), based on the circular economy as defined by the Ellen McArthur Foundation.

82. Ellen McArthur Foundation. 2023. What is a circular economy? Retrieved from: https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

The realization that small decisions can have a big impact and therefore lead to collective consciousness is an important starting point. A circular vision, good leadership - in other words, the ability to guide, inspire and influence others towards achieving the common goal of realizing a circular economy - here you can make a difference.

Educating the world

Educating the world requires global collaboration, investing in teachers, and an educational infrastructure. By adopting a holistic approach, we can create a more educated global population in order to reach sustainable development and create a circular economy future.

Our aim is to speed up the process of creating a circular economy. The circular principles and circular design, including aspects of decision-making, are part of our elective Master course 'Medical Device Prototyping' at TU Delft. However, to spread knowledge of the circular economy and make a greater impact, our research findings and the technologies we developed are available to the world. This book is available as paper back and freely available to download via the TU Delft Repository:

https://textbooks.open.tudelft.nl/textbooks/catalog/category/def-textbooks

We furthermore created a Learning Community 'Sustainable Healthcare' in which we bring together stakeholders from across the working field including the medical industry hospitals, schools and universities:

https://www.evengroenevrienden.nl/en/learning-communities/duurzame-zorg

We also developed an online learning platforms on edX, which offers free courses on circular strategies to learners worldwide: https://online-learning.tudelft.nl/programs/circular-strategies-for-sustainable-healthcare/

GreenCycl FieldLab

Our GreenCycl FieldLab, Rijnzathe 2 De Meern – Utrecht (www.greencycl.org), is open to visitors who want to learn more about experimental setups of waste-to-product reprocessing lines. Furthermore, we encourage students, educators and researchers to join our FieldLab for internships, projects, graduation, research and experiments. We strongly believe in the universal principle of co-creation and partnerships with the right stakeholders at the right TRL levels.

The next page shows a photo of a lecture at TU Delft where the characteristics and possibilities of sustainable medical devices were discussed (photo by B. van Straten).

12

Epilogue

By Bart van Straten

I wrote this book from a personal vision. It is the follow-up to our previous book, *Creating a Circular Economy*. The need for a circular economy became abundantly clear while writing this book in 2024-25. Geopolitically, there is a shift taking place in the world order. A race has emerged between countries for increasingly scarce raw materials: the Middle East, rich in oil and gas; African countries with resource-rich mines; the Ukraine, Canada minerals and oil; Greenland, rich in raw materials. All these regions find themselves influenced or even controlled by other countries. This is the basis for trade barriers and political tension. Therefore, more than ever, we must ensure that we no longer regard waste as waste but as raw material. This not only makes us independent of other countries, but we also reduce waste streams and therefore greenhouse gas emissions. Burning medical waste leads to unnecessary pollution and perpetuates the struggle for ever-scarcer resources. We need a mind shift: new policies, people with courage and a fresh perspective who will change the future of the next generations. We want to contribute to that with this book.

By Bruno Bruins

If you, like me, grew up in Drenthe, the concept of *noaberschap* ('helping you neighbors') is never far away: looking after others, paying attention to each other. After my internship at the Ministry of the Environment, I realized that looking after others does not only involves people, but also the physical environment: the air, sea, forest, mountains, nature. Paying attention to each other and to nature – it seems obvious. Or not? In 2024, Earth Overshoot Day fell on 1 August. That means that in 7 months we had used everything that can be regenerated by Earth in one year. Yet this was not big news in the media on 2 August. Have we become too accustomed to gloomy messages about the environment and sustainability? Do we lack a perspective for action? That is to say: do we place responsibility for the respectful and sustainable handling of natural resources on others? On other countries, on science, multinationals or the government? I say: let's all do our bit to make the world more sustainable. That's why I enjoyed writing this book with Bart and Tim. It makes you think, and - I hope - act.

By Tim Horeman

Although I have been working on the prevention of surgical disposables by using sustainable design principles since 2015, the real intrinsic motivation to end the linear healthcare economy came during the COVID pandemic. After developing a reprocessing and testing method for FFP2 face masks when the market was collapsed and surgical procedures were postponed due to safety risks, our team received thousands of masks per day for reprocessing. When boxes and bags stuffed with used Personal Protection Materials (PPM's) were sent to us from all corners of the Netherlands, we realized that all this material that was filling our reprocessing facilities was normally incinerated.

This opened my eyes to the urgent need to investigate responsible options to deal with this waste stream in a sustainable way. This led to the new reprocessing and testing methods and facilities for surgical blue wrap and other materials. As it is incredibly important that the healthcare industry is well connected to scientific activities that have the potential to change the way we think and work, I dedicate a large part of my time to showing our lessons learned to the surgical community, in order to support the creation of new hubs and initiatives all over the world.

Feedback

Ee do realize that the reader might experience some errors, inaccuracies or construction issues that may have slipped through the editing process of this book. Please communicate this to us so we can update the work accordingly for the next release. We look forward to your feedback and we are happy to use it to update this book in order to provide an improved reading experience. We thank you for your support.

Final notes

Our adventure started in 2018, when Bart van Straten handed the first instrument made from recycled steel to Bruno Bruins, then minister for Healthcare, Welfare and Sport. None of us expected what this would bring about. Due to the lack of fundamental research, Bart started his PhD research at TU Delft the following year, with Tim Horeman as supervisor. This not only resulted in new scientific insights, but also to the foundation of the GreenCycl FieldLab, in which we carried out many experiments and developed new technology to make new products from waste.

Our work should not stand alone; we call upon everyone to get involved, do research, publish books, and come up with new technology that will allow us to use our beautiful, unique Earth in a more sustainable way.

Bart van Straten

Bruno Bruins

Tim Horeman

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Learning Community Sustainable Healthcare

The Learning Community Sustainable Healthcare was co-founded by Linette Bossen and Bart van Straten at TU Delft. Its mission: to find practical and innovative solutions to urgent societal challenges in the healthcare sector — particularly those related to sustainability and critical raw materials.

In this community, students from diverse disciplines and educational backgrounds collaborate with hospitals and companies. Together, they work on: Sustainable product development, Redesigning processes in healthcare systems, Behavioral research related to health and sustainability, Harvesting valuable materials from medical waste streams.

Through this interdisciplinary and hands-on approach, students not only expand their technical and research skills with shared and connected learning as core goals, but also contribute directly to a more sustainable, circular healthcare system.

The Learning Community Sustainable Healthcare aims to make real-world impact, together.

Photo on the next page: Learning Community ‘Sustainable Healthcare’ & ‘Critical Raw Materials’, founded by drs. Linette Bossen & dr. Bart van Straten, Delft, the Netherlands: www.evengroenevrienden.nl.


ROLES IN LEARNING COMMUNITY
Community Manager
Oversees the ecosystem and ensures that information is shared between (micro) learning communities. Interacts with directors (at institution level). Identifies needs among stakeholders.
Facilitator
Guides learning on process and co-creation and sprints/agile/stand-ups. Connection Identifies needs among stakeholders, and guides transformation process.
Works closely together with lecturers (content)
Coach/Lecturer/regisseur
Guides learning process on content. Built bridges between curricula. Preparation assignments, continuing assignments and identifies (new) lecturers, parties to join LCs.
MAATSCHAPPIJ
Facilitator
Facilitator
Interdisciplinair team
Mentoren Studenten
Mentoren Studenten
Mentoren Studenten
HBO
regisseur
Kennisplatform
12:46
donderdag 23 januari

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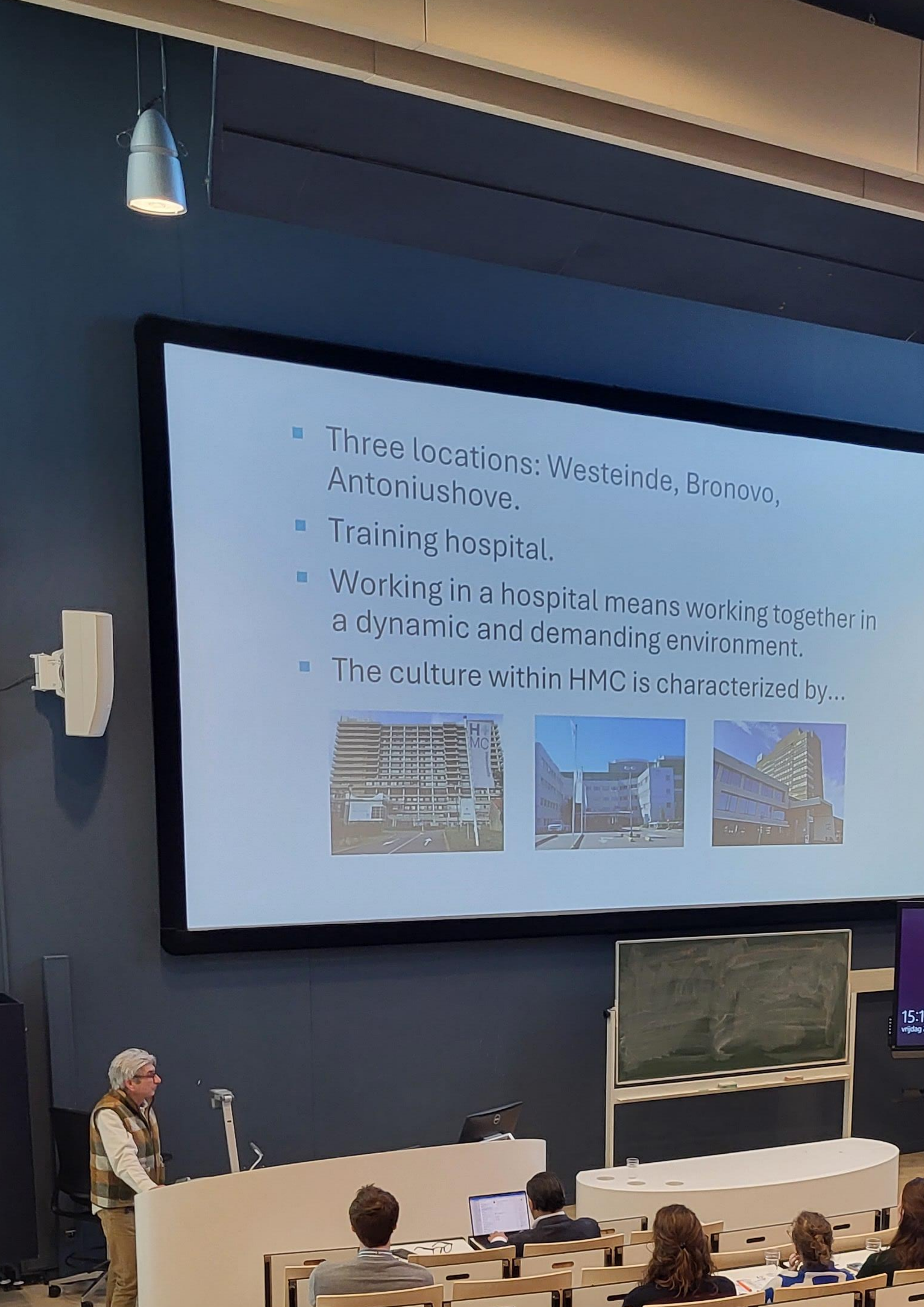
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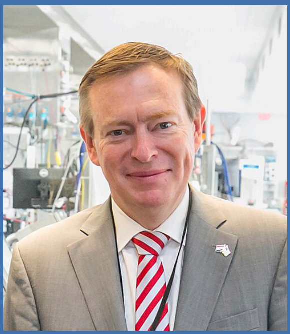
Transitioning towards a circular (healthcare) economy

Circular economy principles, leadership, policy and decision-making

Bart van Straten, Bruno Bruins, Tim Horeman

This book offers a comprehensive roadmap toward a circular and sustainable healthcare system, structured into three distinct parts. Part I describes circular principles and policy tactics. Part II serves as a practical guide to implementing circular strategies. Part III explores circular economy design principles on basis of successful examples. This part dives into real-world applications and measurable outcomes. It showcases successful circular design concepts and business models that have reshaped the market.



Bart van Straten is an expert in the field of sustainability and the circular healthcare economy and is affiliated with Delft University of Technology and several institutions and organizations including GreenCycl.

Bruno Bruins is Chief Strategy Officer of recycling company Renewi. He was coteacher in the online MOOC courses from TU Extension School which were developed by Bart van Straten and Tim Horeman and instructs in this course aspects such as the climate law, the Green Deal and other circular economy strategies leading to sustainable healthcare.

Tim Horeman created the research line Sustainable Surgery and Translational Technology and is (co)founder of several health startups and sustainability initiatives. Tim is affiliated with Delft University of Technology and coordinator at GreenCycl Living Labs.

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