Creating a circular healthcare economy

Circular strategies for a sustainable healthcare

Bart van Straten, *Letizia Alvino*, *Tim Horeman*

TU Delft OPEN

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Contents

We are borrowing this world from our children. Therefore, we need to create technological solutions that minimize waste, so that future generations can enjoy a more sustainable environment.

About the authors

Dr. Bart van Straten, **MBA**

Bart van Straten is an expert in the field of sustainability and the circular healthcare economy. He is affiliated with several institutions and companies including Van Straten Medical and GreenCycl as well as educational and government-related institutions. He co-founded GreenCycl, an organization with a mission to decrease the amount of medical waste. Bart holds a doctorate in BioMedical Engineering from Delft University of Technology/TU Delft with a specialization in the circular reuse of surgical devices and surgical waste materials. During his PhD research, 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 won several awards, for example in the Utrecht Circular Innovation Top 20, as builder of the world's first recycling process for hospital waste.

Bart joined the research group Sustainable Surgery & Translational Technology led by Tim Horeman at TU Delft, where he is a lecturer on medical device prototyping and teaches several related courses. Bart focuses on integrating sustainable engineering and circular design in education as a researcher and lecturer. He has published widely on using the operating room as gold mine for new raw materials. As chairman of the Royal Dutch Normalization Institute, NEN Platform Sustainability & Medical Devices, he was involved in writing the Dutch national NEN-3 guideline for reusing single-use medical devices which was published by NEN on 1 June 2020.

Dr. Letizia Alvino

Letizia is Assistant Professor of Marketing at the Faculty of Behavioural Management and Social Sciences (BMS) at the University of Twente. Her expertise is in neuromarketing. Letizia investigates the neuronal and cognitive mechanisms that identify and define decision-making processes and buying behavior in marketing, both B2B and B2C. In particular, she analyses and studies the biological basis underlying the buying decision process in relation to different marketing operations (e.g., branding, pricing) and product characteristics (e.g., label).

Letizia has been a visiting scholar at various universities, research institutes and business associations including TU Delft, Private Label Manufacturers Association (The Netherlands), IULM University (Italy), SRK University Bhopal (India) and Global Alliance of Marketing & Management Association (Japan).

Dr. Ir. Tim Horeman

Tim Horeman is Associate Professor in Sustainable Surgery & Translational Technology and Academic Portfolio Director (APD)-Medical technology of 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, that 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, Surge-on 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 within his newly created definition of “Hospital mining”.

Preface

On 18 June 2018, during a healthcare symposium, Bart van Straten presented Bruno Bruins, Minister for Health, Welfare and Sports of the Netherlands, with a surgical instrument mesh basket. This instrument basket was made partly from reprocessed and melted stainless steel.

What could not be predicted at that time was the impact this gift would bring to the world. In fact, this moment can be seen as the start of a time period in which the current linear economy standards for hospitals started to lose their strength For us, this special day in June to be the kick-start of what became our journey towards a circular healthcare system. Bart joined the research group Sustainable Surgery and Translational Technology led by Tim Horeman, which resulted in a wonderful co-operation between academic and general hospitals, scientific institutes, governments and the medical industry. This particular day was meant as a message on how to create awareness. Awareness to protect our beautiful but vulnerable planet and awareness regarding the limited resources available from our earth.

Together with some leading researchers in the field, the authors examined the world of circular healthcare and sustainability from different perspectives. In this book, we present our findings on how to create sustainable healthcare by introducing circular strategies. By using our experiences as practical case studies, we will demonstrate what strategies and actions can be taken in order to implement sustainable strategies for a circular healthcare.

This book discusses how hospital waste streams can be used as sources for raw material, through the lens of science as well as based on our practical experience. It also shows how to accomplish circular results in team efforts, by motivating others to create a green team. Within the more holistic perspective of product development and usage, we also deepen circularity from the viewpoint of neuromarketing. Neuromarketing can be a powerful tool to study consumer behavior and investigate neuronal processes involved in the memorization of brand names and logos, but also reward mechanisms linked to brand loyalty, sustainability and circular products. Finally we look at a Bare Minimum design philosophy for medical devices. This method is currently in development and aims to reduce parts in instrument designs without compromising functionality in order to become more sustainable.

This book follows the course of the EdX TU Delft MOOC courses which we developed. This MOOC, or Massive Open Online Courses, are freely available for participants from all over the world with a laptop and internet connection who want to extend their knowledge on a specific subject. Our online program “Circular strategies for a sustainable healthcare” consists of two courses:

- Circular strategies for hospitals
- Circular suppliers for MedTech suppliers

More information is available at: www.edx.org/professional-certificate/delftx-circular-strategies-for-sustainable-healthcare

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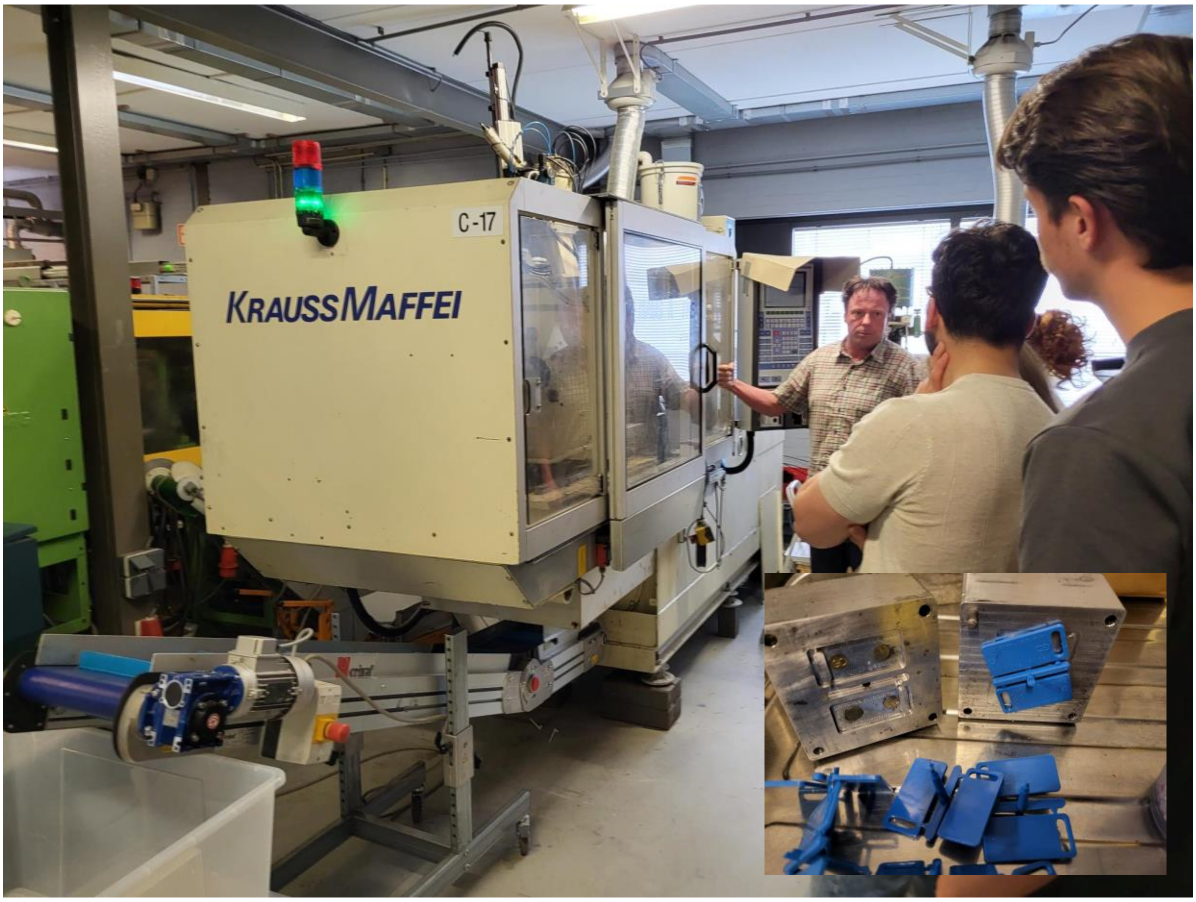
We are also grateful to TU Delft staff and students who assisted us during the lab experiments, in particular Daniel Lijtsman who helped us modifying the melting oven at TU Delft. Special thanks go out Jeronimus van Pelt, visual artist and imaging connoisseur, for his contribution and professional visualization of our research. Furthermore, we would like to thank the team at the TU Delft departments of BioMechanical Engineering and Materials Science, and in particular Ruud Hendrikx for the X-ray analyses and material spectroscopies. We would like to acknowledge our partners at the hospitals, especially Corinne Riekwel at Maasstad Hospital and her team, and the team members of GreenCycl and Van Straten Medical. We are grateful to Edgar Willemse and Rene Hiemstra for their time to review this book, their suggestions and expertise. We also extend thanks to Saskia Roselaar, the editor of this book, and Jacqueline van de Riet and the team at TU Delft Repository. We would like to thank Pieter van Nimwegen from Model Engineering for his expertise in injection molding and his willingness to injection mold dog bones and products with our granulate, made out of melted hospital waste. In particular we would also like to thank him for his for his openness in providing our students the opportunity to learn how molds are designed and made and the process of injection molding with recycled granulate.



Excursion to a research injection molder affiliated to the GreenCycl initiative. Pieter van Nimwegen, the Netherlands, instructs TU Delft students about injection molding with recycled plastic from the operation room. Photo by Bart van Straten.

Finally, we would like to thank all those who contributed to our online edX MOOC course program ‘Circular Strategies for Sustainable Healthcare’, which is inextricably linked to this book, in particular the team of TU Extension School, Jeronimus van Pelt, Prof. Dr. Jenny Dankelman, Ir. Arnoud van den Berge, Dr. Joost van der Sijp, MD, Majid El Mortadi and Mr. Drs. Bruno Bruins.


SCIENCE IN WASTE

Part I

Circular Engineering Principles

1

Engineering a circular healthcare: The curse of global growth

Our world is the only planet, as far as we know, which hosts life. The number of humans on our planet, however, has grown tremendously in the last two centuries. It took 200.000 years for earth's population to reach one billion, in 1800. This number has grown to over 8 billion in 2022. In 2057 an estimated 10 billion humans will inhabit the earth.[1]

A result of this growth, the amount of primary greenhouse gas emitted by human activities, carbon dioxide (CO_2), has grown as well. These emissions, and those of other greenhouse gases, constitute a growing environmental threat for the next generations. The increased concentrations of greenhouse gases in our atmosphere cause the long-term increase of earth's temperatures, also referred to a global warming.

On 12 December 2015, an international treaty was signed by 196 parties in Paris to limit global warming to less than 2^0C, preferably less than 1.5^0 C.[2] European climate law demands that the European Union should become climate neutral by 2050. The aim is to decrease CO_2 emissions by 49% (later increased to 55%) in 2030, compared to 1990.

A large part of these emissions is caused by burning fossil fuels and farming. The generation of electricity is a large source of pollution, since in many countries electricity is made by burning coal and gas. The transformation to renewable energy, including solar, wind and hydrogen energy, is therefore essential.

While the earth's population grew, so did our mass consumption society. During the globalization, humans have become focused on consumerism and individual growth. This development has changed our socioeconomic system and consequently, our personal norms and values. Human priority continues to be aimed at economic growth and personal wealth, even when it became evident that the hole in the Ozon layer above the South Pole was caused by humans, and that temperatures continue to rise in the lower atmosphere.

After the Second World War, humanity experienced gigantic global economic development, including great technological improvements. Computers, laptops, airplanes, tablets and the internet connected humans and equipment with each other, all over the world. The hunger for plastics and steel grew as all products had to be manufactured in ever-increasing volumes. As economies developed, so did our needs for the growth of wealth. Products became more complex and more different materials were combined.

With the rise of products such as computers, tablets and smartphones, more and more materials were included in devices. This was further supported by the introduction of single-use products, so-called disposables that can be seen as a product of absolute wealth. Where people bought a television in the last century, it was expected to last for many years. Now, people purchase a new smartphone or tablet every year. And as an absolute disastrous black page in sustainable health evolution, new disposables like E-cigarettes were allowed to enter the market and consists of an atomizer, a poisonous power source such as a battery, and a container which often end up on the street after being used.

Thus, a growing population with a growing need for disposable wealth needs more and more resources. Humanity is caught in a spiral in which the use of materials increases like a curse, from which we have as yet not managed to free ourselves. In fact, we no longer realize how much disposable material we consume in both the consumer markets as well as in the business industry (Figure 1).

Figure 1. Growing need for single-use products. Disposables in the medical field are designed for single-time use after which it is disposed. Photo by Jeronimus van Pelt

1. Worldometer. (2021, September 26). World Population. Retrieved from: https://www.worldometers.info/world-population.

2. United Nations Climate Change. (2021). The Paris Agreement. Retrieved on 15 August 2021 from: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

Evolving healthcare

The same applies to the healthcare sector, and specifically to hospitals. The number and different types of medical devices and disposables has grown considerably. With the growing population, the number of patients grew as well. Medical instruments, which were mostly reusable in the previous century, were converted from reusable to disposable. New technology and disposable devices, developed for single use, meant higher sales volumes for the medical industry and more products consumed by hospitals. From an engineering perspective, these products were designed with requirements that fit mass production and mass consumption. With the introduction of robotic surgery, even more disposables were needed, including disposable endoscopes, disposable energy devices, disposable robotic instruments and many more. While new technology was introduced in the operating room, there seemed to be no awareness of the growing volumes of waste this generated. The growing amount of hospital waste and its impact on the environment appeared to be a direct consequence from the growth of the human population, the introduction of new technology and the increased use of disposables.[3]

Only recently the challenges posed by this development became more evident, as awareness has risen of the shortage of raw materials, the waste generated by hospitals and the environmental impact that result from both the production of medical devices as well as from the consumption of these devices. The consequences of availability of (raw) materials became clear during the Covid-19 pandemic. Shortages suddenly emerged all over the world; for example, the unanticipated scarcity of face masks lead to circumstances in which doctors and nurses were not protected when treating Covid patients.[4] Another consequence was that the waste generated by hospitals as a result of the Covid pandemic grew with thirty percent. Although (plastic) medical waste is incinerated in many countries, we also find this type of waste on landfills or even in the local environment. In the first year of the Covid pandemic, 52 billion face masks were manufactured, with an estimated number of over 1.56 billion entering our oceans.[5]

Medical plastics

Finally, the environmental impact of specifically medical grade plastic waste streams appeared extremely high, considering that many medical plastics like drapes, gowns and face masks are made out of polypropylene, a thermoplastic polymer. Polypropylene (PP) belongs to the group of polyolefins and has comparable characteristics as polyethylene. Compared to polyethylene, the material is affordable, it is relative strong and has a good chemical resistance. Hence the reason why companies such as Tupperware prefer to use this material for storage of food and drinks. For these reasons also many medical devices are made from this type of plastic.

3. Mohee R., 2005. Medical wastes characterization in healthcare institutions in Mauritius. Waste Management 25: 575–581.

4. Van Straten B, Ligtelijn S, Droog L, Putman E, Dankelman J, Weiland NHS, Horeman T. A life cycle assessment of reprocessing face masks during the Covid-19 pandemic. Sci Rep. 2021 Sep 3;11(1):17680. doi: 10.1038/s41598-021-97188-5. PMID: 34480045; PMCID: PMC8417283.

5. OceansAsia, 2020. COVID-19 Facemasks & Marine Plastic Pollution [WWW Document]. OceansAsia. URL https://oceansasia.org/covid-19-facemasks/.

Polypropylene (PP) is a highly easy-to-mold material and therefore used all over the world for injection molding. Despite its semi-crystalline nature, its low viscosity means it flows very well during injection molding. The melting point and strength mean an endless range of products can be made out of polypropylene. Disposing of polypropylene products raises some concerns, however. Greenhouse gases are emitted when it is incinerated, as well as dioxins and vinyl chloride. If it decomposes in landfill, it has harmful effects on ecological systems. These are especially caused by the additives used in PP to enhance its mechanical properties, to stabilize the polymer and to make it easier to process.

Many medical products are currently designed for single-use application, not only made of PP but also other types of plastics and metals. The types of plastic products found within the plastic waste streams may differ per hospital, however. In the OLVG hospital, in Amsterdam, the Netherlands, an overview showed that 50% of the total plastic waste consisted of disposables packaging. Based on their weights, these materials were made up mainly of polypropylene (PP), followed by polyethylene terephthalate (PET), mixed high-density polyethylene (HDPE) with coated medical-grade paper, and polyvinyl chloride (PVC). Bubble wrap, composed of low-density polyethylene (LDPE), used for deliveries, made up 25% of total plastic waste.[6]

Medical metals

Stainless steel types 304 and 316 are mostly used for medical instruments. Type 316 is more corrosion resistant, since it has a higher chromium and nickel content. Medical instruments need to be disinfected, washed and sterilized after every procedure. This is done in a Central Sterilization and Services Department (CSSD) as shown in Figure 2. Corrosion resistance for instruments is very important, as the washing and sterilization procedure are chloride-exposing. Type 316 is also more expensive than 304. This is why single-use instruments are typically made out of type 304 and reusable instruments of 316.[7]

6. Herman J Friedericy, Cas W van Egmond, Joost G Vogtländer, Anne C van der Eijk, Frank Willem Jansen. 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, 2021.

7. B. van Straten, J. Dankelman, A. van der Eijk, T. Horeman, A Circular Healthcare Economy; a feasibility study to reduce surgical stainless steel waste, Sustainable Production and Consumption, ISSN 2352-5509. https://doi.org/10.1016/j.spc.2020.10.030.

Figure 2. Central Sterilisation Department, CSSD Services/CSA Services in Utrecht - De Meern, the Netherlands. An external disinfection and sterilisation service provider, processing instrument sets for external hospitals. Photo by Jeronimus van Pelt.

Single-use metal instruments are used in growing volumes in hospitals around the world. The trend in the wealthier parts of the world has been to switch to single-use steel instruments. They are cheaper, always sterile and need less stock management. A stainless steel disposable instrument set consisting of a needle holder, tweezers and scissors usually costs less than 3 Euros. The medical industry has set up a lucrative line to sell these single-use products in large volumes to hospitals. After one use, these instruments are collected by waste processors in order to be incinerated.

Market dependency

Reusable instruments are up to 50 times more expensive than their disposable alternatives they need to be (re)sterilized. Since long-term use is not taken into account in budget calculations for most hospitals, it may look cheaper to use single-use products, regardless of their impact on the environment or on patient safety. In some cases, devices are only offered to hospitals as single-use variants, since reusable versions have been phased out by manufacturers of the production programs due to cleaning and sterilization issues or the reusable versions were considered not to be profitable enough. Thus, the hospitals depend on the options available in the market and cannot easily decide on their own initiative to change to reusable products.

Undoubtedly, economic growth and globalization have brought wealth to the western world, but they have also led to a tsunami of mass production. Products that were once reusable can now be used only once. Higher sales volumes mean the economy is growing and so is the income of shareholders, investors and local economies – but also the impact on the environment.

How can we turn the tide? Is waste reprocessing best option to reduce these negative impacts on the environment and where should we start? These are the questions that will be elaborated on in this book.

Global awareness

In this book we will explore possible solutions which will have a positive impact on the environment. Or rather, measures we can take to reduce the negative impact on the environment. Some of these measures are easy to take and others require more effort. The most important is to change awareness of the general public. Individuals can have a great influence on this. In this book we provide a number of tools to help to create a society producing less waste. Readers with both technical and non-technical backgrounds can have a major impact on reducing waste.

While the world is struggling with scarcity of raw materials and the finite capacity of natural ecosystems, we will discuss in this book some strategies through which the (healthcare) economy can continue to grow and still become sustainable. As a counterpoint to the geological raw materials extraction from conventional mines, urban mining extracts raw materials from waste: the operating room is a goldmine for raw materials hence the creation of the new term "Hospital Mining". We will see how this promising concept could solve our major sustainability and raw material scarcity problems.

By turning surgical waste into new products, we will experience a new era of possibilities in the circular economy. We will learn how to reduce and reuse waste but also how to reprocess plastic and metal waste contaminated and non-contaminated from hospitals, thus reducing scarcity, reducing costs, and reducing climate change impact.

It will become clear that the reprocessing of metals is not only environmentally-friendly but also has a direct financial benefit, as some materials are valuable and can generate a revenue. Therefore, we will investigate how we can eliminate waste by following new (re)-design methodologies.

We will also discuss how we can change from mass-consumption driven product design to sustainable design, using the Butterfly Diagram as an engineering model and fundamental principle to create a circular economy. Moreover, various aspects and possibilities will be analyzed in this book for how to design a green (dream) team.

We will take you through the steps you need to take to get from a good idea to shared agreements with all stakeholders involved. Finally, we will discuss how we can create more public awareness and influence the buying behavior of consumers. It seems that everyone is talking about the circular economy but very few concrete actions are being taken after problems are identified. If we want to achieve the climate goals, we will have to make an impact with an ever-growing group. This book was created to provide some guidance by using evidence-based examples that were published in scientific journals, in order to allow new circular initiatives to emerge. With willpower, technology, evidence-based solutions and common sense, we will achieve this.

Disposable medical instruments made from stainless steel, aimed to be used only once, after which they are disposed of. Image: Bart van Straten/Jeronimus van Pelt.

Main takeaways of this chapter

- It took 200.000 years for mankind to grow to one billion humans in 1800. Only 222 year later this number has grown to over 8 billion in 2022; it is expected to pass 10 billion in 2057.

- While the earth's population grew, so did our mass consumption society. After the Second World War, the world experienced a gigantic global economic development with great technological improvements and more complex products, resulting in the use of more materials.

- As a result of this growth, the emission of carbon dioxide (CO_2), the primary greenhouse gas emitted by human activities, has increased significantly.

- The impact on the environment of hospital waste grew apace, as a direct consequence of the growth of the human population and the increased use of disposables in hospital care.

- Challenges which became more evident during the past decades are the shortage of raw materials, the waste generated by hospitals and the environmental impact that results from both the production of medical devices and the consumption of these devices.

2

Circular engineering and the Butterfly Diagram

The post-war global economic development, also referred to as the golden age of capitalism,[8] meant global expansion of economic growth. The term globalization began to be used in the 1980s, although many historians claim that the globalization of international trade had already started with Columbus's arrival in America in 1492. The exploration of new continents led to worldwide trade and eventually to globalization of individuals through their connectivity in global networks. This connectivity reflected the technological developments that enabled international trade and cross-boundary transactions. In essence, this could be considered a positive development, bringing the world closer together. The technological developments in aviation, logistics and the internet in the 1990s changed the world further and new markets and producers emerged. The generation born in the 1940s saw revolutionary technological developments such as the introduction of the television, jet planes, personal computers, space exploration, the fax and the digital camera. All these developments led to more complicated products, which consisted of more different materials. These days, products such as laptops and complex surgical instruments consist of almost all elements of the periodic table.

This growing wealth and global prosperity, in combination with a rapid growth of the population gave birth to the mass consumption society, as described in chapter 1. This society was based on the principle 'make – use – dispose', also called the linear economy. This economy uses raw materials and transforms them into products that are consumed and then discarded as waste. The economic value model is based on manufacturing and selling as many products as possible.

After decades of severe natural resource depletion, it is now clear that a move is needed towards a circular economy. This is based on the principle 'make – use – reuse'. In this system, the product lifecycle is extended and waste is minimized or even completely absent, as all elements are reused.[9] Stahel[10] mentions that the circular economy consists of "closed loop systems", distinguishing two different types of loops: (1) reuse of goods, and (2) recycling of materials.

8. "Post-war reconstruction and development in the Golden Age of Capitalism", Ch. 2 in World Economic and Social Survey 2017. United Nations (2017)

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

10. Stahel, W. R., "The utilization focused service economy: Resource efficiency," in B. R. Allenby and D. J. Richards (eds), The Greening of Industrial Ecosystems, National Academy Press, Washington, DC, 178–190 (1994).

The circular economy as a term appeared for the first time in 1988 in "The Economics of Natural Resources".[11] It was used by China in 2002 - by that time the world leader in the manufacturing of products - as a political measure with regard to combating environmental damage and resource depletion. The Ellen McArthur Foundation, a non-profit organization creating evidence-based research on the circular economy, promoted the concept of the circular economy and published a guideline called "Towards the Circular Economy"[12] in 2013 to find solutions for growing problems like climate change, waste and pollution. The European Union uses the circular economy as a recovery strategy to stimulate a more EU.[13] Clearly, the importance of creating a circular economy is now widely recognized, but it has not yet become reality.

A circular economy typically follows the approaches of reduce, reuse and recycle.

- Minimizing the use of resources (R of reduce).
- Maximizing the reuse of packaging, products, components, water, energy (R of reuse).
- Recycle products and packaging when reuse is not feasible anymore (R of Recycle).

Indonesia receives significant amounts of plastic waste, which is exported to the country by high-income countries such as the Netherlands. This photo from Bali visualizes the importance of the three Rs and the impact the western world has on these countries. Photo by Bart van Straten.

11. Kneese, Allen V. (1988). "The Economics of Natural Resources". Population and Development Review. 14: 281–309. doi:10.2307/2808100. JSTOR 2808100.

12. 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

13. European Commission. (27 May 2020). Europe's moment: Repair and prepare for the next generation. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_940 (accessed on 27 November 2020).

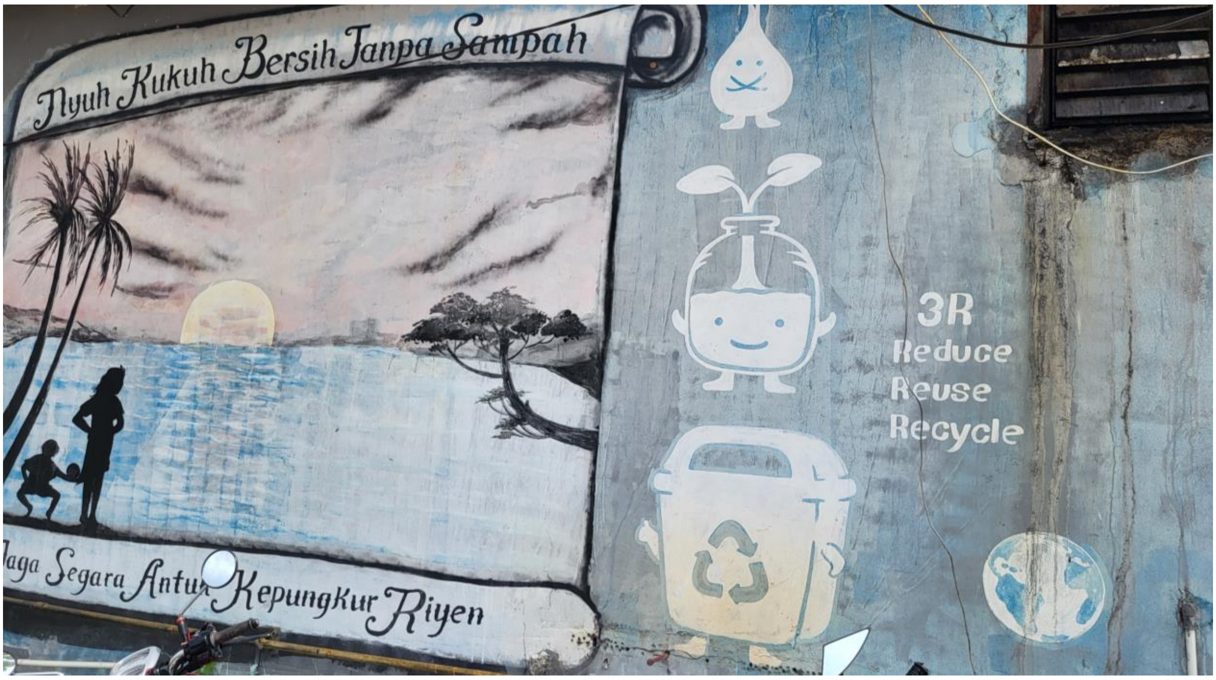
Taking the three Rs into consideration during the design of new products and processes is essential. Used products should be the resources for new raw materials and new products. Reuse, repair, maintenance, remanufacturing, recycling keep products and materials in circulation which will result in reduction of waste streams.

A circular healthcare economy

A circular healthcare economy can be achieved by designing products and processes which lead to reuse of products and components, again and again. In other words, value is recreated every time a product or component is reused. It is clear that from an engineering perspective, circular economy principles require another mindset, a different design approach. Therefore, it's time to rethink how we design, make and use the things we need.

Introducing a circular economy approach to hospital waste streams is not easy. Hospitals are frequently standardized on single-use products. Even worse, concepts such as pay-per-use, the sharing of capital goods between hospitals, and reuse, repair, maintenance and refurbishment, i.e. extending product life cycles, are unknown and often not considered or desired for various reasons. It will therefore take time to reinvent the healthcare sector and the products it makes and uses.

The next generation of designers and visionaries can help the world to reinvent product design and the processes around new products, based on the idea of designing out waste: designing in such a way that products can be reused entirely without generating waste. The Butterfly Diagram,[12] published by the Ellen McArthur Foundation, is a model which can help us to explore strategies to eliminate waste.



Highlighting the necessity of the three Rs, painted on a wall in Bali, Indonesia. Photo by Bart van Straten.

The original Butterfly Diagram

The Butterfly Diagram, as shown in Figure 1, visualizes the circular economy. The cycles on the left- and the right-hand side illustrate the circular strategies. The circles on the left-hand side show the biological loops creating renewable flows. The nutritional values of biodegradable materials are returned to the earth to regenerate nature.

The right-hand side shows the technical loops by which materials are kept in circulation through cycles such as reuse, maintenance, refurbishment, remanufacturing and recycling. These circular strategies minimize the generation of waste. They extend the product lifecycle and aim to reuse waste as raw material if other strategies are not possible.

Circular strategies help to protect our natural resources by reducing the use of primary raw materials. Waste is prevented by keeping products in use for longer. Circular strategies contribute to preventing shortages in the supply chain. Furthermore, they limit the environmental impact resulting from the production and consumption of products and the generation of waste.

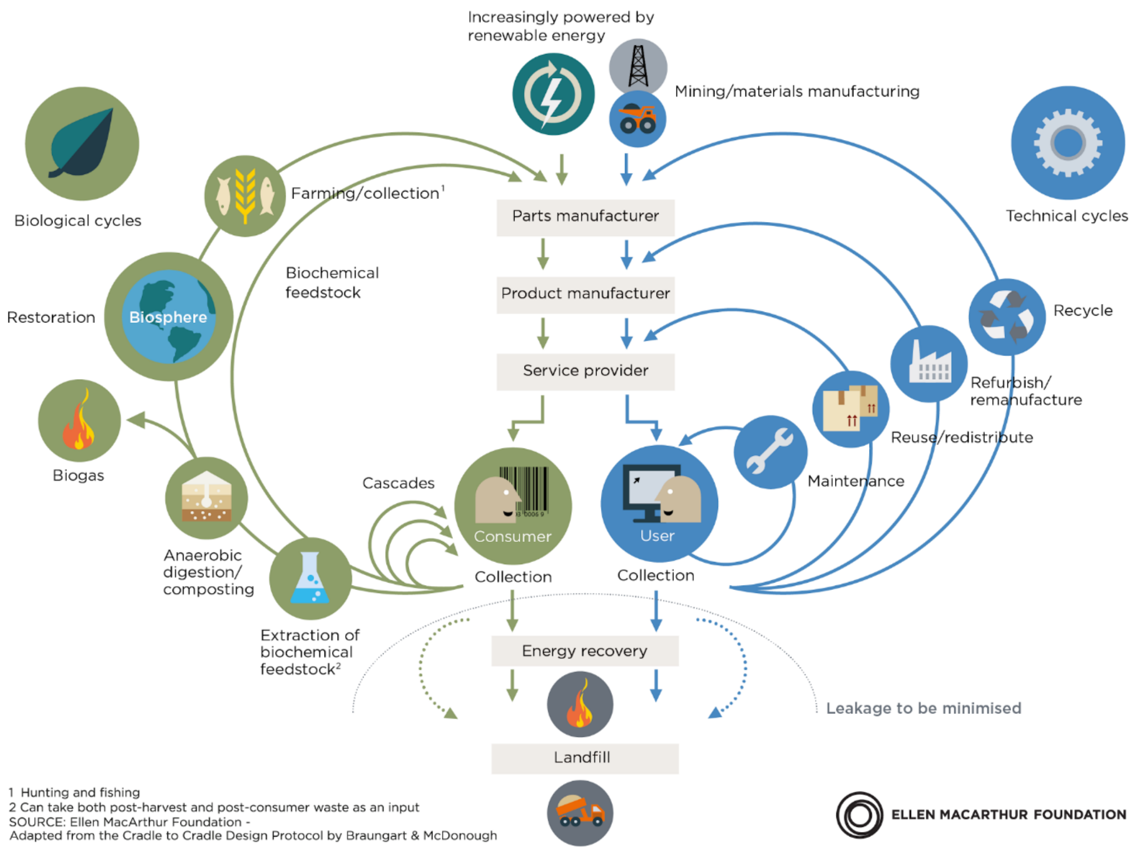


Fig. 1. Butterfly Diagram showing the circular strategies, by the Ellen MacArthur Foundation.[12]
No further use is allowed without prior permission of the Ellen MacArthur Foundation: https://ellenmacarthurfoundation.org/circular-economy-diagram

Designing out waste: how to design for future generations

A large part of the materials we use for medical devices is made from fossil fuels and iron ore. Eurostat, the official statistics website of the European Union, describes fossil fuels as non-renewable energy, including coal, coal products, natural gas, derived gas, crude oil, petroleum products and non-renewable waste.[14] The extraction of these natural resources, their manufacture into products, the transport and use of these products, and their disposal after use have a variety of environmental impacts. Climate change, measured in carbon dioxide (CO_2) emissions, is one of the most important ones.

Designing products which require less materials and less energy will result in the reduction of CO_2 emissions. A design transformation from single-use to reusable products will therefore help to reduce the amount of waste and its environmental impact.

Currently, humanity is producing over 380 million tons of plastic each year. According to Earthday.org,[15] the amount of plastic produced every year is more or less equivalent to the entire weight of all humans on earth. The organization also reports that humans use 1.2 million plastic bottles per minute, approximately 91% of which are not recycled. About half of the worldwide annual plastic production is destined for single-use products. For example, 500 billion plastic cups are used around the world every year. When disposed, these plastics break down into tiny toxic particles called microplastics that contaminate the soil and waterways and enter food chains.

Sustainable design

Sustainable design starts at the beginning, by selecting materials that increase the lifetime of the product and have a low(er) impact on the environment. This has a significant impact on the reduction of waste streams. It’s preferable if products can be repaired easily and are made of materials that can be recycled. Using special design techniques may further help to design out waste and pollution. An example is honeycombing, which increases the strength and reduces the amount of material used. The reduction in weight not only means less raw material is necessary, but also fewer parts. Furthermore, the weight to be transported is lower and, in the end, less energy is needed for recycling. Good design choices have a lasting impact on CO_2 emissions, creating a positive impact for years to come.

14. Eurostat. European Union. Glossary: Fossil fuel. September 2019. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Fossil_fuel

15. Green Cities. Fact Sheet: Single use plastics. March 29, 2022. https://www.earthday.org/fact-sheet-single-use plastics/#:~:text=Around%20380%20million%20metric%20tons,was%20introduced%20in%20the%201950s.

Circular design

The terms sustainability, circular economy and circularity are often used interchangeably. Sustainability is more broadly defined and refers to people, the planet and the economy. Obviously, from the environmental context we mean ecological sustainability. But if you would ask an economist, you will hear a definition of sustainability from a business context, economic sustainability. Let’s use a broad definition, depending on what perspective you have. Most importantly, it’s all about not being harmful to the environment or depleting natural resources.

When it comes to the circular economy, we see a more focused definition. The circular economy aims to minimize through smarter product design, longer use, remanufacturing, recycling and to regenerate nature. When we speak about circular design, we mean the design of products and processes which keep raw materials longer in production cycles and which can be used repeatedly with the aim of reducing or even preventing waste. Where we could consider sustainable design to be defined as reducing negative impacts on the environment in general, circular design is aimed at developing durable, reusable, repairable, re-manufacturable and recyclable products that generate no waste, and using products, components and materials over and over again. The principle of circular design of any product or process is that waste must be minimized or prevented. This type of design aims to keep the product in use as long as possible. It applies circular strategies in the design, such as possibilities for reuse, repair, refurbishment, remanufacturing or recycling of the product, as described in the Butterfly Diagram. Basically, circular design can be seen as a movement, a philosophy, a different way of thinking that develops products, processes and business models based on preventing waste and preserving the earth’s natural resources. Three design strategies can be used to avoid disposal at the end of the life of the product: [16,17]

16. V. P. Gkeleri and V. D. Tourassis, “A concise framework for disassemblability metrics,” in 2008 IEEE International Conference on Systems, Man and Cybernetics. IEEE, Oct. 2008. [Online]. Available: https://doi.org/10.1109/icsmc.2008.4811521

17. F. Afrinaldi, M. Z. M. Saman, and A. M. Shaharoun, “A new methodology for integration of end-of-life option determination and disassemblability analysis,” in Treatise on Sustainability Science and Engineering. Springer Netherlands, 2013, pp. 31–49. Available: https://doi.org/10.1007/978-94-007-6229-9 3

1. Extending product life by designing a durable product with a long lifetime. Use features that enable repair of the product by replacing broken components or allow maintenance. Design easy access to components and easy removal and replacement of components. Strategically replace components that limit the lifetime of the total system (often for commercial reasons) by new sustainable designs.

2. Reuse or remanufacture.
The best option is direct reuse without any changes. If the product cannot be reused 'as is', then next are products designed with components which can be harvested at the end-of-life of the product and reused for the (re)manufacturing of a new product.

3. Recycling and material recovery.
Design for recycling means selecting specific materials which can be reprocessed and re-used after the disassembly of a product. Recycling not only means that no new virgin or primary raw materials are needed, it also means that no CO_2 emissions are caused by the manufacturing of such virgin or primary raw material.

Following the Butterfly Diagram, the following circular design concepts can be applied to remove waste from the design:

- Design for reuse.
- Design for repair.
- Design for refurbishment.
- Design for disassembly.
- Design for remanufacturing.
- Design for recyclability.

The common factor of influence of all these strategies can be found in the effort it takes to disassemble a device. The easier it can be disassembled, the less energy is used and the "greener" the product becomes. Therefore, a more generic strategy, "design for disassembly" is often found in the literature.

Design for Reuse

Design for reuse keeps products in use with a longer product lifecycle. Every time the product is reused, it does not enter the waste stream and no energy is needed to manufacture new products. Furthermore, this method prevents raw materials being extracted for making new products. In this case, new sales models have to be created, since reuse leads to lower manufacturing and sales volumes.

Design for repair increases the product lifecycle. Due to growing complexity, in recent decades many products have become harder to repair, with growing waste streams as a consequence. Products based on the “design for repair” concept should facilitate repair whenever needed. This concept involves easy-to-repair principles imbedded in the design, including ease of disassembly and reassembly, and good accessibility of components and replacement parts. Furthermore, this design method should facilitate the use of standard tools.

Design for refurbishment is aimed at making products which can be serviced at any given time in order to increase their lifespan. This may include repairs, but also thorough cleaning, lubrication, replacement of components and surface treatment, such as glass pearl, aqua blasting or polishing. The repair of medical devices is often seen as a reactive response, i.e. products are repaired when they malfunction, while refurbishment can be considered a pro-active treatment in order to prevent breakage or damage of the device.

Design for remanufacturing means designing a product, of which the parts can be used in combination with new and/or other reused parts to (re)manufacture a new product. The new product, made out of the reused parts, functions according to the specifications of the original product. The parts can also be used in the manufacturing for various other kinds of products.

Design for recycling means designing products which include compatibility of the product components and packaging with known recycling streams. Recycling can be done with less energy than primary production, thus reducing CO_2 emissions. An important aspect is using more of the same types of materials when designing products and packaging. The fewer different materials, the easier it is to recycle the product at the end of its product life.

Design for disassembly is one of the fundamental principles to use across all of these design concepts. The effectiveness of design for disassembly determines the product lifecycle and the level of waste prevention. After all, the easier a product is disassembled, the easier it is to repair, refurbish, remanufacture or recycle. This means, first of all, minimizing the number of components and designing components made from high-quality materials. In all cases, destructive disassembly must be prevented. Therefore, special attention needs to be directed to the fasteners between components, which should prevent destroying components when disassembling. Preferably, connections should not be glued, but made with screws or snap-fit connections, leaving components intact for reuse. Furthermore, clear instructions for repair and soft disassembly of the product should be provided. Table 1 shows the various options for circular design principles.

Table 1. Examples of circular design approaches

Design examples	**Reuse**	**Repair**	**Refurbish**	**Remanufacturing**	**Recycling**
Use standardized (snap-fit) fasteners		√	√	√	√
Design easy access to connecting parts		√	√	√	√
Design to disassemble with standardized toolings		√	√	√	√
Use ferromagnetic metals to allow magnetic sortening				√	√
Avoid the use of glue					√
Reduce the number of parts		√	√		
Use high quality materials which last longer	√	√	√	√	
Use the same materials where possible					√
Use materials fully compatible for recycling					√
Use recycled materials	√	√	√	√	√
Use non-toxic materials and additives					√
Use the same material for labels, packaging					√
Consider printing on product instead of labels	√	√	√	√	√
Modular design for cleaning/exchange of parts		√	√	√	
Design parts into modules which are replacable		√	√	√	
Design a collection process after use of the product	√	√	√	√	√
Easy-of-disassembly without breaking parts		√	√	√	√
Avoid paints or coatings which reduce recyclability					√
Provide disassambly and repair instructions		√	√	√	

Applying circular design principles means products and components have longer lifecycles. Product designs which are compliant with the circular economy will last longer and generate less waste than linear products. They will be easier to reuse, repair, remanufacture and recycle. Thus, they contribute to the objectives of the circular economy:

1. Having enough resources.
2. Reducing waste streams associated with these resources (production and consumption).
3. Reducing environmental pressure.

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Designing circular processes

Reuse is a strong aspect of the circular economy. It is often said that refusing to use disposable products automatically results in reuse. However, it is not always possible to refuse using disposables. This is the case, for example, with the FFP2 face masks used to protect healthcare professionals during the Covid period. The first Covid wave in the spring of 2020 brought a lot of uncertainty: Covid vaccines still had to be developed and the consequences and severity of the disease were not yet foreseeable.

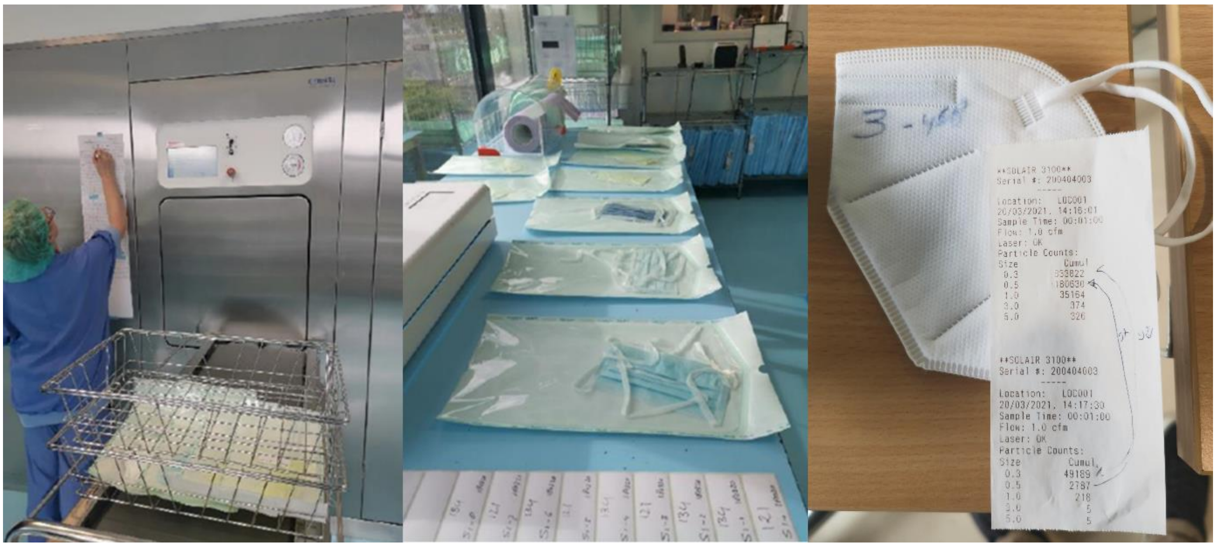
It was therefore deemed unsafe to use face masks more than once, leading to a massive surge in the use of disposable face masks. The pandemic resulted in global scarcity of various products and materials. This was also the case with FFP2 face masks; the scarcity of personal protection equipment led to life-threatening shortages for healthcare professionals.

Born out of necessity, the authors of this book, affiliated to TU Delft and GreenCycl, developed a fast reprocessing and testing method that showed how the reuse of single-use medical devices led to an impactful solution for the scarcity, as well as a reduction of cost and CO_2. The reprocessing method allowed the safe reuse of face masks for a maximum of five times.

From March 2020 to June 2020 our team reprocessed, as requested by several hospitals, more than 75,000 face masks, using steam sterilization at 121^0C. Our methods were published in academic journals, so that hospitals around the world could sterilize and reuse their face masks as well.

The benefits of the circular economy became evident in this case study. First of all, the scarcity of face masks was counteracted by reusing products. Secondly, we learned that through the use of circular strategies, waste was limited: face masks were not disposed of, but collected in order to be sterilized. Thirdly, the environmental impact of the waste was reduced.

We conducted a lifecycle assessment, a study that calculates the environmental impacts throughout the entire lifecycle of a product, from extraction of raw materials to production, transport, use and end-of-life. We calculated that CO_2 emissions were reduced by 58% when reusing face masks five times, instead of disposing of them after one use. The environmental impact when reusing face masks was calculated using 18 impact categories, showing a 70% reduction in land use and 57% reduction in water consumption, despite the fact that the face masks were reprocessed using steam sterilization.



Reprocessing disposable FFP2 face masks with the purpose of reuse. Photos by T. Horeman extracted from scientific work. [18-20]

18. B. van Straten, PD Robertson,… T. Horeman (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. https://doi.org/10.1371/journal.pone.0257468

19. De Man, P., van Straten, B…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.

20. van Straten, B., Ligtelijn, S…Horeman, T. (2021). A life cycle assessment of reprocessing face masks during the Covid-19 pandemic. Scientific Reports, 11(1), 17680.

Main takeaways of this chapter

- The linear economy is based on a “make – use – dispose” premise, whereas the circular economy is based on a “make – use – reuse” principle. A circular healthcare economy is aimed at reducing hospital waste volumes and is a derivative of the circular economy.

- The right-hand side of the Butterfly Diagram shows the technical loops where materials are kept in circulation through cycles such as reuse, maintenance, refurbishment, remanufacturing and recycling. The loops are circular strategies helping to minimize the generation of waste.

- Circular strategies protect natural resources by reducing the use of raw materials. Waste is prevented and keeping products in use for longer contributes to preventing shortages of resources in the supply chain, as well as limiting the environmental impact of waste.

- Following the Butterfly Diagram, the following circular design concepts can be applied to limit waste: Design for reuse, Design for repair, Design for refurbishment, Design for remanufacturing and Design for recyclability.


Adjustable pressure valve for wound drainage
AN INTRODUCTION TO
WOUND DRAINAGE SYSTEMS
CONCEPTS

3

Designing a green (dream) team

Circular engineering goes further than just designing a sustainable product which can be used again and again. It involves the input of people, organizations and markets, since the product must be acceptable for all involved parties. Taking back used products or packaging in order to reuse or recycle the materials could be part of the circular concept; the focus could also be on repair, maintenance and availability of spare parts and potential remanufacturing possibilities. All of these aspects determine whether a circular product or service will be successfully accepted by the market, but they require a different vision than most current business models. Therefore, developing a circular product which is embedded in a circular process requires vision, strategic thinking and communication skills.

The awareness that our economic system has directly damaged the environment has led to increased motivation for many to do something about it. More and more people have a personal desire to stop environmental damage. More people in the medical sector too are willing to work together in a team with highly intrinsically motivated colleagues and partners to come up with solutions to make a difference. Evidence based circular solutions, leading to green results, can be a motivator on a small or large scale. We exclude from this discussion “greenwashers” who use sustainability as a motivator to make money, but have no positive effects on the environment in the long term.

Integrating circular processes in an organization

Implementing processes which are dedicated to reducing CO_2 emissions may not be received enthusiastically by everyone. It requires managing people with different values; this is often considered as one the most challenging and most critical processes when implementing change.

A growing phenomenon in hospitals and medical companies is the formation of special circular task forces, so called green teams. These green teams aim to shape and roll out sustainability in their organization. In practice, however, it is common to see that not everyone is willing to step out of their comfort zone. Some are actively resistant, while a more passive lack of engagement among medical staff may also be a showstopper for introducing new (sustainable) processes and products.[21]

When establishing a green team, it is important to define critical success factors. Kotter defined eight steps which could be applied when designing new processes to be introduced in an organization.[22] These steps can be helpful in many situations, such as designing and creating a circular product line at a medical supplier or establishing a team at a hospital in order to increase the level of sustainability.

Managing people with group projects, students, experts and staff discussing technical principles of their circular designs. Photo by Bart van Straten.

21. Robin D.C. Kumar, Leadership in healthcare, Anaesthesia & Intensive Care Medicine, Volume 14, Issue 1, 2013, Pages 39-41, ISSN 1472-0299, https://doi.org/10.1016/j.mpaic.2012.11.006.

22. Laig, Roumel & Abocejo, Ferdinand. (2021). Change Management Process in a Mining Company: Kotter’s 8-Step Change Model. Journal of Management, Economics, and Industrial Organization. 31-50. 10.31039/jomeino.2021.5.3.3.

The following steps help to create a successful basis for team performance:

Step 1. Create urgency

Define the need for a circular process; establish what the advantages and opportunities are.

Step 2. Create a vision for change

Define a clear vision. Project five years ahead. Align you vision with business values and make it inspiring.

Step 3. Create Key Performance Indicators (KPIs)

Create Key performance indicators that allow you to define success based on real evidence. Use tools that are often seen in Heath Tech Assessment (HTA's) and Live Cycle Assessments (LCAs) to gather and process data in a responsible way and to extract the right knowledge.

Step 4. Form a powerful coalition

Ask ambassadors for your team who are able to convince others. Establish a diverse mix of people from different departments.

Step 5. Communicate your vision

Communicate the circular vision frequently, in newsletters, internal communications and digitally, to all levels and all departments.

Step 6. Remove obstacles

Identify people who are reluctant and talk to them. Stimulate those who defend your vision.

Step 7. Ensure short-term wins

Identify quick wins. Share and communicate successes. Reward the people who help you to reach your goals and successes.

Step 8. Build on change

Build on your successes. Use the key success factors and apply these.

Step 9. Anchor the changes in organizational culture

Share you vision with the entire organization and make it visible to outsiders. Define the organization's core values and share these with new staff. Create a long-term plan.

Example of a Dutch green team established for the reprocessing of blue wrap

In 2021 a team was set up to recover blue wrapping paper waste from the operating room (OR) of Maasstad Hospital, Rotterdam, the Netherlands. The mission was ambitious. As a TU Delft research team, the authors wanted to be the first in the world to create a reprocessing process for blue wrapping waste from the OR. Blue wrap is made from polypropylene, and prices and delivery times for polypropylene continue to increase; it therefore seemed a promising material for reuse. A field lab (GreenCycl Fieldlab) was created with a reprocessing line consisting of disinfection machines, a melting oven, a granulation machine and an injection molding machine.

The idea was to process, granulate and injection mold new products out of surgical waste at the field lab. The sense of urgency (step 1) was created by stating that we wanted to be the first to develop a validated process for surgical waste reprocessing.

The team consisted of influential people from different departments from Maasstad hospital, including the staff from the operating room and the central sterilization and services department (OR, CSSD), staff of waste reprocessing company Renewi, team members from GreenCycl and from TU Delft - a diverse mix of team members (step 2).

A concrete goal was set for the 'blue wrap reprocessing' green-team based on a clear vision (step 3). This vision included that the GreenCycl field lab, based in the center of the Netherlands, would become the central hub in the country. New processing technology was validated with regard to efficient workflows, based on Key Performance Indicators (KPIs). These aspects were tested with researchers from Delft University of Technology (step 4). In the long term a recycling facility would be set up for all other hospitals offering their waste for reuse; a facility where waste would be converted into raw materials and new medical products all based on throughout validation of the material flow after each transformation step. This vision was based on the growing scarcity of raw material. Furthermore, the vision was to create a healthcare environment with fewer CO_2 emissions for all participating hospitals.

This vision was repeatedly communicated (step 5). A video was made showing the entire process, and launched through social media, including YouTube. Maasstad Hospital communicated this vision on a frequent basis both internally and externally through multiple conferences. Furthermore, the media were contacted to share our vision, which led to extensive coverage in many magazines and trade journals. We also invited stakeholders such as representatives from hospitals, industry, government, NGO's, schools and universities to come and visit the field lab, so that our vision could be visualized.

As with many new developments, physical and mental obstacles were encountered during the process that hamper process which needed to be removed (Step 6). An important obstacle to overcome were legal limitations. By law, medical waste in the Netherlands must be incinerated. Permits or exemptions were therefore necessary to start a process which deviates from existing procedure. This obstacle was finally overcome by personal contact with the Ministry of Health, Welfare and Sports, as well as the local enforcement agency, responsible for enforcing the waste regulations. These parties were invited to discuss the collection of waste; they supported our initiative and were eager to create legal possibilities.

Rather than an obstacle, this became a great opportunity for co-operation with officials who were willing to look beyond the rules and were just as enthusiastic as we were. They even helped us to categorize waste as raw material, so that the standard rules no longer applied. After nine months, we were granted a license to reprocess potentially contaminated surgical waste into raw material. This was a giant step for the green team, but also for the whole country, since this was the first time in history that surgical waste could be transformed into raw material and new medical products. Mental obstacles were often found to be related to an increase of expected task time due to changes in the workflow. These obstacles can be taken away by explaining the urgency, showing the bigger picture and by ensuring that all employees become part of the sustainability experience.

Most of the resistance was encountered when we published our progress on social media, when people posted objections to our posts on LinkedIn and Facebook. Remarkably, most of the objections came from people who were active in the recycling industry or in start-ups working on similar activities. Even though it is possible that these objections were based on feelings of competition or envy, it is important to analyze criticism and enter into discussion with anyone who objects. Open and transparent communication can have many advantages.

Our team realized a quick win (step 7) when the first batch of blue wrap was collected and melted in our field lab. This was celebrated with the team members and communicated among all participating organizations. A video was produced and published. Dutch media covering the first results further contributed to sharing the first successes. Thus, we were able to demonstrate the value of circular processes, which in turn created feelings of trust, openness and commitment to promote circular processes in hospitals, and encouraged others to start similar projects.

Step 8 was to build on the successes we accomplished. When the process was validated and results were benchmarked, the process was scaled up in terms of volumes and anchored in more hospitals, extending from Maasstad Hospital to eleven other hospitals. We also started to make a larger variety of products out of the reprocessed waste. The first product, an instrument opener, received CE approval on 22 March 2022. After that date, more medical devices were designed and made out of the reprocessed waste. The results were published in the *Journal for Cleaner Production*.[23]

The 9th step was, and still is, to standardize the way of working in all participating hospitals regarding the process of collecting blue wrapping paper waste from the OR and transporting it to the field lab, where it is melted, granulated and used for injection molding of new medical products.

23. B. van Straten, D.R. van der Heiden,… T. Horeman, Surgical waste reprocessing: Injection molding using recycled blue wrapping paper from the operating room, Journal of Cleaner Production, Volume 322, 2021, https://doi.org/10.1016/j.jclepro.2021.129121.

Working with academia

Circular processes aim to reduce waste streams, but also to learn and create new insights that lead to new areas of expertise. Collaborating with universities and colleges is an excellent opportunity to bundle knowledge and record it in education. A good start is to follow a multi-disciplinary approach, as knowledge is of great importance within a well-functioning team. It goes without saying that a team within a single entity will have the knowledge required for the many processes, products and waste streams within a hospital. That is why it is important to actively collaborate with knowledge institutions such as universities, colleges and centers of expertise. Experts with a technical, social and psychological background are highly valuable as team members or external consultants.

From this context, collaborative skills are essential for the success of a green team and therefore every team member should have these skills. To facilitate new multidisciplinary green team projects in an initial phase, an existing course at TU Delft was modified in 2021. The following two examples illustrate the value of collaboration and sharing expertise with different experts.

Every year ten projects are formulated during the TU Delft course 'Medical Device Prototyping'. These projects are suggested by manufacturers, developers, surgeons or other healthcare professionals. The students need to find a technical solution for a problem statement for which they have to deliver and present a validated prototype at the end of the course.

One of those projects was to come up with a protective solution for sharp instruments. This protective solution, as a product, had to be made from hospital waste. The tips of sharp instruments are vulnerable and must be protected during transport, handling, cleaning and sterilization.

A reusable tip protector was to be designed, using recycled polypropylene waste from the hospital. An additional factor in the design was the recovery of the instrument openers at their end-of-life, for instance if they wear out or break. A special collection box would enable to recover the instrument openers in order to reprocess them into granulate in order for the material to be reused as (new) raw material.

A collaboration was set up between the students, Leiden University Medical Center, the companies Van Straten Medical and Model Engineering (injection molding) and, an independent expert in sterile medical devices. A true multi-disciplinary team with experts from different fields. Blue wrapping paper waste was harvested, melted and recycled into granulate. 3D prints were made of the tip protector and tested on the CSSDs of Leiden University Medical Center and CSSD Services. Within 3 months, several workable and validated models were presented (Figure 1).

The second example concerns a project to recover energy from washing machines at the CSSD. A series of washing machines (medical thermal disinfectors) at GreenCycl were modified and used to disinfect medical devices so that they could be reprocessed safely (Figure 2).

A typical CSSD washing machine washes and disinfects instruments around 90 ^{0}C. The water is discharged into the sewer system after a washing cycle. This is not only a waste of water but also a waste of energy. The goal of this project was to design and develop a circular process for the heat recovery. In other words, preventing the heat to be disposed by reusing it for the next disinfection cycle.

Figure 1. Collaboration and sharing expertise resulted in a prototype series of different instrument tip protectors designed out of hospital waste. Photo by Bart van Straten.

A team collaboration was set up with students working together with the technicians of Van Straten Medical, GreenCycl and CSA services. The team was supervised from within the TU-Delft research line SS&TT, that also streamlined the communication with manufacturers of thermal washing machines and hospital staff experts.

Thus, there was a large diversity of team members, bringing different perspectives, skills and experiences. This project shows that initiating this kind of projects within a TU Delft course appears to foster structured problem identification and solving: every team member learns from existing evidence-based design structures, in a collaborative mindset that incudes important communicative aspects such as active listening and constructive feedback. As a result, a complete infrastructure (Figure 3) was built with smart heat exchanger systems that could be monitored and controlled from the cloud.

Within this system, the heated water was returned to the boiler where the energy was used to heat up the next disinfection cycle. Sensors were built in to monitor the process. Ultimately, this circular system saves 43% on heating per washing and disinfection cycle.

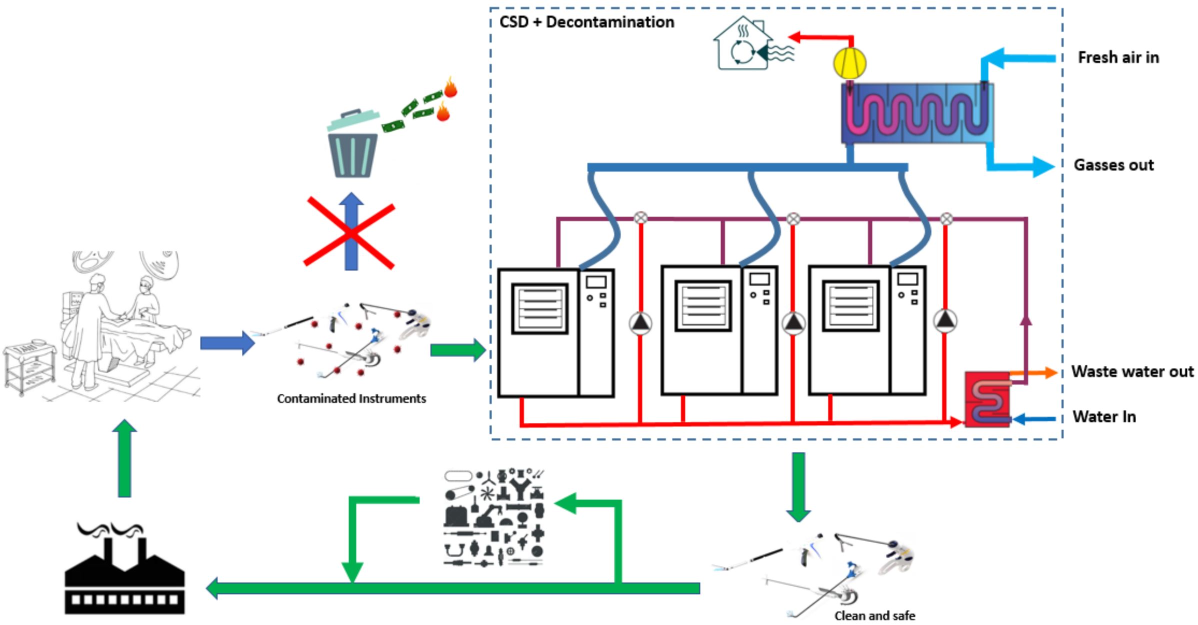


Figure 2. New sustainable processing street for safe decontamination of disposable instruments. Figure by Tim Horeman.

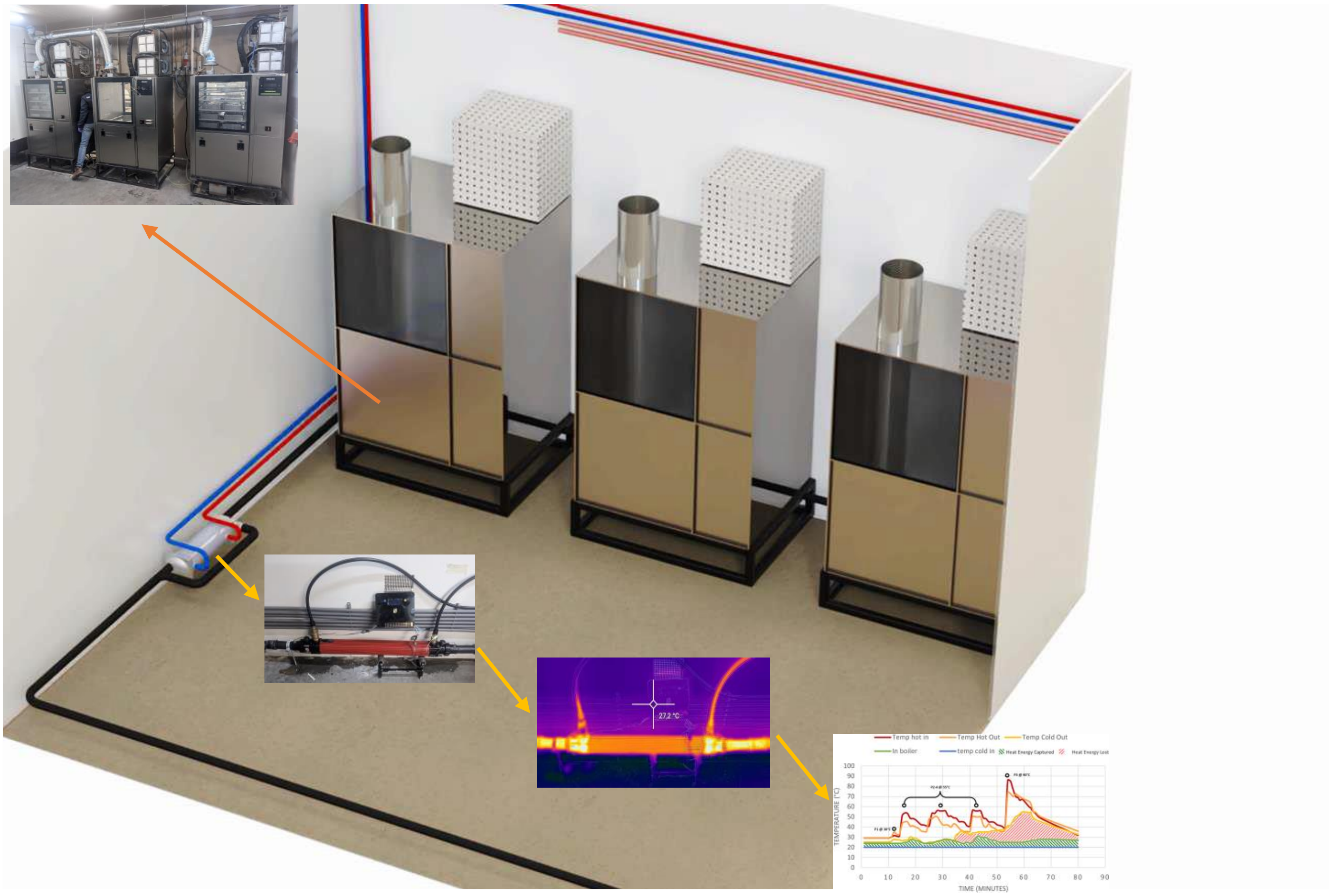


Figure 3. ReoThermia: Reusing heat in waste water after each washing cycle, A collaborative project between academia, hospitals and the industry. Figure by Tim Horeman.

Both cases reflect the benefits of collaboration between the university, hospitals, industry and independent experts. The collaborative skills contributed to the success of developing a circular product within 5 months, driving performance and innovation. In order to solve difficult waste problems in a complex environment, smart collaborations and sharing of the findings with others are needed. These insights and best practices can be used in education and are a potential accelerator for new green processes.

Lessons learned

Designing and setting up a green (dream) team requires group effort and team performance. During our time working together in this team, it became clear that it is of great importance to have regular meetings on set days and times. Even if not all team members were able to join, the meetings took place, because it gives structure to the progress of the project and highlights its importance among all team members. One of the key success factors was the drive of the team members, as well as their persuasiveness towards others. Setbacks were extremely well absorbed and the team just kept going. One person acted as project leader, to maintain structured team discipline, which turned out to be a critical success factor. The presence of such a person of strong character increases the chances of success. Furthermore, there was a continuous focus on achieving collective results. The vision of reducing medical waste and CO_2 emissions through our newly developed process felt as a collective responsibility. Finally, it is important to include a strong and an experienced visionary to the steering team (Figure 4) for students and employees to look up to and to follow.

Figure 4. Left: Drs. Rene Hiemstra lecturing on presenting a circular proposal and using rhetoric during the course ‘Medical Device Prototyping’, TU Delft. Right: Mr. Drs. Bruno Bruins lecturing on how to pitch a circular design proposal during the course ‘Medical Device Prototyping’, TU Delft. Photos by Bart van Straten.

In short, during our studies into circular reprocessing of surgical waste, we experienced an overwhelming flow of engagement, universal compassion and intrinsic motivation among all those involved.

Main takeaways of this chapter:

- Developing a circular product, which is embedded in a circular process, requires not only design skills but also vision, strategic thinking and communication skills.
- When establishing a green team, it is important to define critical success factors.
- Create a diverse team of specialists and include influential people in the team.
- Share successes with your team members and other stakeholders.

Part II

Using medical waste as source for raw material


ETHICON ENDO-SURGERY

4

Hospital mining: The operating room as goldmine for raw materials

We have entered an era where we need to reinvent ourselves and develop new technologies to use raw materials without depleting our natural resources. The reality is that we have been depleting the earth's natural resources on behalf of our economic wealth too long and too much. Our economic system is unsustainable in the long run if it keeps relying on the extraction of natural resources. Therefore, we need to change. In order to transform to a circular economy, it is necessary to promote awareness for a more sustainable society. We can achieve this by setting up projects with green teams that serve as an example for others as a source of inspiration. Urban mining is an important aspect of the circular economy and plays an essential role as a source of raw materials. In this chapter we investigate how valuable urban mining can be as a new phenomenon in hospitals.

Urban mining versus conventional mining

Mining of oil, gas, iron ore and other natural resources from underground geologic formations has taken place for millennia. The significant increase of the world population and global economic growth, which increased exponentially from the 1970s, resulted in an enormous increase in the extraction, production and consumption of oil, gas and iron ore. Oil is mainly found in the USA, Saudi Arabia and Russia; gas in Russia, Iran, Qatar, Turkmenistan, the USA, Saudi Arabia and Iraq. Iron ore – minerals from which metallic iron is extracted to make steel – is mined mostly in Australia, followed by Brazil, China, India, Russia, South Africa and Ukraine.

The supply of these raw materials thus relies on just a few countries in the world, with a few extraction locations in each. The supply is easily disrupted, with immediate effects for the rest of the world, if anything happens to the mines or to the country where the mines are. The price sensitivity of products made from these raw materials also strongly depends on the political and economic situation in those countries. In other words, the global economic system is balancing on a thin thread, being dependent on these few supplying countries. We saw this most recently with the Russian invasion of Ukraine in 2022, which led to sanctions that limited the export of oil and gas from Russia. In the medical sector, we experienced supply problems in March and April of 2020, when insufficient face masks, made out of polypropylene which uses oil as a natural resource, were available to protect healthcare staff. The scarcity of these apparently simple products had a direct impact on public health.

Urban mining is the opposite of conventional mining, since it means harvesting resources not from underground sources, but from stocks above the ground. Urban mining extracts raw materials from used products, from buildings or waste.[24] Where great amounts of energy are needed for exploring, extracting, shipping and refining natural resources during conventional mining, this energy is not needed during urban mining, as the raw materials have already been extracted. Using medical waste as raw material means using material that has already been mined, refined and transported over long distances. We can directly mine around us, needing less energy as compared to conventional mining. Furthermore, waste streams are reduced, as waste is used as raw material, which is reprocessed.

A major advantage of the circular economy is that urban mining explores aboveground, in contrast to conventional mines. After all, one of the goals of urban mining is to decrease the high environmental impact of the exploration, extraction, shipping and refining of virgin raw materials.[24] Furthermore, mining in urban environments can be used as a political strategy providing resource security and an independent source of raw materials, not impacted by foreign geopolitical circumstances. Therefore, urban mining is an essential part of the circular economy and a powerful new way of harvesting the raw materials of the future.

Hospital mining

A hospital can be regarded as an urban mining environment. The medical devices used in a hospital are typically made out of high-quality raw materials. Since the number of products, and in particular disposable products, continues to keep growing, this seems an urban mine with great potential. Hospitals and particularly operating rooms generate waste streams with valuable materials, which could be mined with less effort and energy, at lower costs and with a lower environmental impact when compared to geological mining.

The potential depends, amongst other influences, on a number of factors:

- the recyclability of the waste;
- the logistical process to recover and transport the waste;
- the legal possibilities;
- the willingness of stakeholders to co-operate;
- the costs of reprocessing;
- the mechanical properties of the raw material after reprocessing.

24. Muller, F., Lehmann, C., Kosmol, J., Kessler, H., Bolland, T. 2019. Urban Mining – Resource Conservation in the Anthropocene. German Environment Agency.

Current designs for medical devices are often not sustainable. As discussed above, industrial design projects were based on mass production, especially because of technological developments and globalization from the 1980s. Design aimed to produce mass market volumes with a “design for all” solution.[25]

Medical devices followed this trend and many were transformed from reusable to disposable over the years. New technology, such as robot-assisted surgery, was introduced, resulting in even more disposables which were needed to cover the arms and instruments in the operating room. All this led to the creation of a massive “plastic soup” emerging from hospitals. Pandemics such as Covid-19 further stimulated the use of disposables. An 30% increase in medical plastic waste resulted from the Covid pandemic alone.[26] As a result, waste streams from operating rooms increased even further.

Urban mining would have stimulated those plastic to be made from raw material recovered as waste from the same hospitals. The quality of hospital waste can be surprisingly high, as products for hospitals are mostly made from high-quality raw materials. Medical devices undergo strict medical validations and regulatory approvals. Using waste mined from hospitals as raw material means that only a small amount of energy is needed to reprocess, as compared with the amount of energy that is needed to extract natural resources from the earth and the processing of those resources to raw materials.

Urban mining can be used not only to decrease hospital waste streams and the negative environmental effects that are associated with those waste streams. It may also have positive side effects for hospitals, such as reducing the costs they pay to dispose of waste. Furthermore, urban mining may prevent shortages of available raw materials and secure a stable supply of medical products. Therefore, urban (hospital) mining seems a promising method to reprocess waste into new raw material.

However, it is not easy to reduce the use of disposables, since hospital procedures are not easy to change. Furthermore, there may be more pandemics, making hospitals reluctant to reuse their waste. Moreover, the transformation of the medical industry from traditional linear business models to more sustainable circular models needs time. Manufacturers and suppliers of single-use products, who depend on the sales of disposables, will need time to reinvent their product and sales strategies.

25. Hoftijzer, Jw. (2012). Sustainability by Do-It-Yourself Product Design; User Design opposing Mass Consumption.

26. Patricio Silva et al. 2020. Increased plastic pollution due to Covid-19 pandemic: Challenges and recommendations. Chemical Engineering Journal. Doi.org/10.1016/j.cej.2020.126683.

These companies are subject to risk, however, including the scarcity of raw material, as well as global geopolitical insecurity, which may lead to increased prices and longer delivery times for raw materials. Furthermore, there is a global trend towards increased awareness for sustainability. Thus, from the perspective of industrial ecology, there is no other way than using circular economy approaches to reduce waste streams, reduce the use of energy and lower the impact on the environment. Therefore, urban (hospital) mining is expected to become more important. If standardized methods could be developed for hospital mining and be made accessible to hospitals, industry partners and other stakeholders all over the world, we could decrease the risks of supply disruption from other countries. The world would no longer be dependent on a few countries or mines only.

Urban mined Polypropylene blue wrap, ground after melting. Photo by Bart van Straten.

The operating room as a goldmine for raw materials

Hospitals, and in particular operating rooms, are full of valuable waste. High-value materials which are commonly not seen are present in the waste containers of hospitals, including high-quality polymers such polypropylene (PP), polycarbonate (PC), polyethylene (PE), polyethylene terephthalate (PET) and ABS.

Blue wrap, surgical gowns and personal protection equipment is made out of PP, while implant packaging is made out of high-quality PET. Energy-driven complex instruments have handles made out of ABS. Polymers - which include all plastics - consist of chains of building blocks called monomers.

The operating room is full of these. These plastics are used mostly in single-use products and disposed after every medical procedure. These materials are available and ready to be harvested as above-the-ground stock, without the extraction of gas or oil in far-away locations. There's no need to refine the extracted natural resources into ethane and propane, no need for cracking ethane and propane to turn them into ethylene and propylene, and no need for further processing into polymers.

Another category of raw material is iron-based materials in hospitals, such as disposable instruments, mostly made of stainless steel type 304 or 316. They are readily available as raw material when disinfected after use. Stainless steel is a good material to mine in hospitals: it's easy to melt, no material is lost in the recycling processes and it can be melted over and over again without losing its material properties.

Furthermore, there are some medical and diagnostic instruments such as ablation catheters that contain precious metals such as platinum-iridium alloys. These metals are rare and have a high value, and thus are excellent sources of raw material for new products.

Urban mining of disposed medical products requires a sophisticated logistical process with protected transportation, disinfection and disassembly possibilities. Medical waste may consist of multiple types of products, some of which may need to be disassembled before further processing.

Urban mining can save costs, as well as benefit the environment, but requires extensive planning. Therefore, it is very important that new medical devices are designed in such a way that they can be more easily disassembled and reprocessed, with cleaner waste streams.

Examples of urban mined waste consisting of stainless steel, polypropylene blue wrap and complex surgical devices with a variety of valuable components and materials. Photos by Jeronimus van Pelt.

Main takeaways of this chapter:

- Urban mining is the opposite of conventional mining, since it means harvesting resources not from underground but from materials above the ground.

- Urban mining extracts raw materials from used products, from buildings or waste.

- A hospital can be regarded as an urban mining environment. The medical devices used in a hospital are made of high-quality materials.

- High-value materials and components which can be mined from hospitals, and operating rooms in particular, include polypropylene, PET, PE, polycarbonate, ABS, stainless steel types 304 and 316 and platinum.

- Urban mining is an essential part of the circular economy and a powerful new way of harvesting the raw materials in the future.

5

Turning surgical waste into new products

We have paid a high price for global economic growth. As economies grew, governments seemed paralyzed to intervene to counteract the negative effects. Despite decades of scientific evidence, it is striking how few concrete projects are being started to reduce CO_2 emissions. Endless debates have taken place about 'people, profit, planet', but at the same time our consumer and industrial society consumed more and more disposables - without any 'waste embarrassment'. In fact, the export of waste became a lucrative business. Western countries exported waste for money to vulnerable countries. To the west it was out of sight, at least that's what people thought. Ultimately, we get this waste back in the form of microplastics and through pollution of the oceans and air.

An important question remains why this degradation of the ecological environment continues to be allowed. The Covid period seemed to have highlighted that a sense of urgency only exists for short-term risks, while the longer-term risk of environmental degradation is often ignored. Many legal guidelines and laws were set aside for Covid, including the need for CE approval for face masks, while laws that cause a large amount of waste remained in place. As stated before, laws that do not allow the reprocessing of medical waste are still in place, although the destruction of our environment in the longer term accrues much higher risks to life than possible infection through medical waste. Apparently, the perception of sustainability and circularity is different for short- and long-term risks, not only among the public, but also among businesses, governments and politicians.

Nevertheless, in the name of science, we started our work. In the European Union, medical waste from the operating room may not be reused or recycled by law. From plastic packaging and metal tweezers to stainless steel instruments, everything should be disposed of and incinerated. This leads to enormous amounts of waste: per surgical procedure, on average three garbage bags and two containers of waste come out of the operating room. Just the wrapping paper that contains the instruments used in the operating room adds up to 1.3 million kilos of waste per year in the Netherlands, when waste from all 90 hospitals in the country is added up. In the Netherlands, up to 50,000 single-use metal instruments are thrown away per hospital per year.

All medical waste in the Netherlands is brought to Zavin in Dordrecht, where it is incinerated. When capacity there falls short, it is transported to Belgium. The accumulation of waste and incineration leads to potential environmental pollution. Despite this, this cycle of extraction of raw materials, transport, processing, and the obligatory destruction and incineration after a single use continues to be considered normal. These volumes, however, do provide opportunities. From the perspective of urban mining, these volumes offer gigantic quantities of raw materials from which we can make new products. Great capital is destroyed by burning it, while it is an enormously lucrative basis for future raw materials.

Material behavior

The basis of most medical products is oil or metal. It’s a literal waste to burn these materials when they can be recycled or reused.

Of course, the mechanical properties of recycled waste are important. If we want to make new products out of medical waste, the material properties determine the usefulness of the reprocessed material. Therefore, we need to study the material behavior of recycled waste. The material behavior depends on the relation between stresses and strains in the material.

As described above, we carried out a pilot project at Maasstad Hospital in Rotterdam for recycling blue wrapping paper. Our project aimed to collect, transport and melt blue wrapping paper waste from the operating room. During our meetings with the hospital staff, we indeed noticed a mentality of focusing on what was possible. Legal and operational hurdles were considered irrelevant and were not on the priority list. Just do it; take action.

What we hoped, but did not know, was that the recovered blue wrap, which is made from polypropylene, would have characteristics that allowed us to make new products from the recycled material. Literature studies provided hardly any satisfactory results. We found no studies in which medical waste was collected from the operating room, reprocessed into raw material and injection molded into new medical products to be used again.

We decided to concentrate on clean wrapping paper. This wrapping paper is used to wrap instrument sets before sterilization in the CSSD (Figure 1). The blue wrap ensures that a sterile barrier protects the instruments, so they remain sterile and can be transported safely.

Figure 1. Instrument sets wrapped in blue polypropylene, prepared for sterilization. Photo by Tim Horeman.

Maasstad Hospital uses blue wrap made by the manufacturer Halyard. The sets are unwrapped in the operating room in a special area, the so-called pre-operative preparation area. After unwrapping by the OR assistants, the unwrapped sets are transported to the designated operating room. After use, the blue wrap is disposed of in plastic bags. Since 1.3 million kg of blue wrap is used and disposed of by hospitals in the Netherlands each year, this is an interesting potential to urban mine.

The energy for making this raw material has already been used during primary production, so we would only need to use energy to collect and melt the polypropylene. This would partially – or perhaps completely – level out with the energy needed for transporting and incinerating the blue wrap.

Therefore, we wanted to make a new medical product out of this material, preferably a product which could be used again in the same hospital. This would require CE validation, according to the Medical Device Regulation (MDR). The MDR is an EU regulation on requirements for medical devices. Just like the FDA in the USA, the EU requires technical documentation including verification and validation of the product and production processes before it enters the market.

This, we knew, would be hard to achieve, as we wanted to use 100% recycled blue wrap as the raw material. The CE validation requires technical specifications of the raw materials, our case we became the raw material supplier as well as the product manufacturer. The raw material was not purchased as granulate but recycled by us. Our purpose was, furthermore, to avoid the use of additives, as is usually the case with plastics. Therefore, we conducted toxicity tests on the material, mechanical tests on the material behavior and we tested the raw material in a CSSD in worst case conditions in order to build a database with all specifications.

Additives are added to plastics to enhance the polymer properties and extend their lifetime, but these potentially harmful chemical substances can be released during the recycling and melting process.[27] The emissions during incineration of plastics can also be dangerous for the environment. Although additives might be part of the existing blue wrap and its recycled granulate, we did not want to add additives once the material was melted.

We used a special oven for melting the blue wrap, which we converted to match our experiments (Figure 2). A KOS electric crucible oven, series 219029, was placed at TU Delft faculty of Mechanical Engineering. The furnace was fitted with special plating and extraction to extract the gases from the materials that were melted down. In addition, special constructions had to be built to melt materials under pressure, but also to be able to cast materials directly into molds. After modification of the oven, we started the experiment. Science is a matter of trying, failing and trying again. In other words, persistence is paramount. Einstein already said ‘a person who never made a mistake never tried anything new’. With this in mind, we were ready for the next mistakes and started the pilot in collaboration with Maasstad Hospital.

27. John N. Hahladakis, Costas A. Velis, Roland Weber, Eleni Iacovidou, Phil Purnell. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling, Journal of Hazardous Materials, Volume 344, 2018, Pages 179-199, ISSN 0304-3894, https://doi.org/10.1016/j.jhazmat.2017.10.014.

Figure 2. Dedicated melting oven, modified for our experimental purposes. Photo by Bart van Straten.

Melting, testing and even more testing

The first batch of blue wrap from the operating room was transported to the oven at TU Delft. The sheets were sorted upon arrival and checked for potential contamination and the presence of undesired debris.

We started to melt the blue wrap at 200 °C, 250 °C and 300 °C in a stainless steel tube with a diameter of 100 mm (Figure 5.3). The melted bars were granulated into 8 mm particles (granules) and injection molded. Injection molding is a technique where the granulate is heated above its melting point and injected under pressure into a mold. In our case, we used a mold in the shape of a standardized dog bone. A dog bone (Figure 3) has a standardized design with two shoulders at both ends and a smaller part in the middle.

A grinding mill was used to granulate the melted bars into small particles. These particles were used as 100% recycled granulates, and mixed with virgin polypropylene granulate in different ratios: 75% recycled, 50% recycled and 25% recycled. We did not add additives. One set of dog bones was made with polluting elements, such as stickers and tape, still in the granulate. The next step was the injection molding of dog bones from the different mixing ratios. The dog bones were then tested and compared with each other and with 100% virgin polypropylene.

In order to investigate material behavior, the dog bones are subject to tensile testing. The dog bone is gripped at each end (this is why the end shoulders are wider than the inner part) in a tensile test machine and pulled apart until it fails. This is regarded a fundamental test in materials and engineering science. The ultimate tensile strength, breaking strength, maximum elongation and reduction in a specific area are derived. Having retrieved this data, properties can be calculated such as Young's Modulus, Poisson's Ratio, yield strength and strain-hardening characteristics.

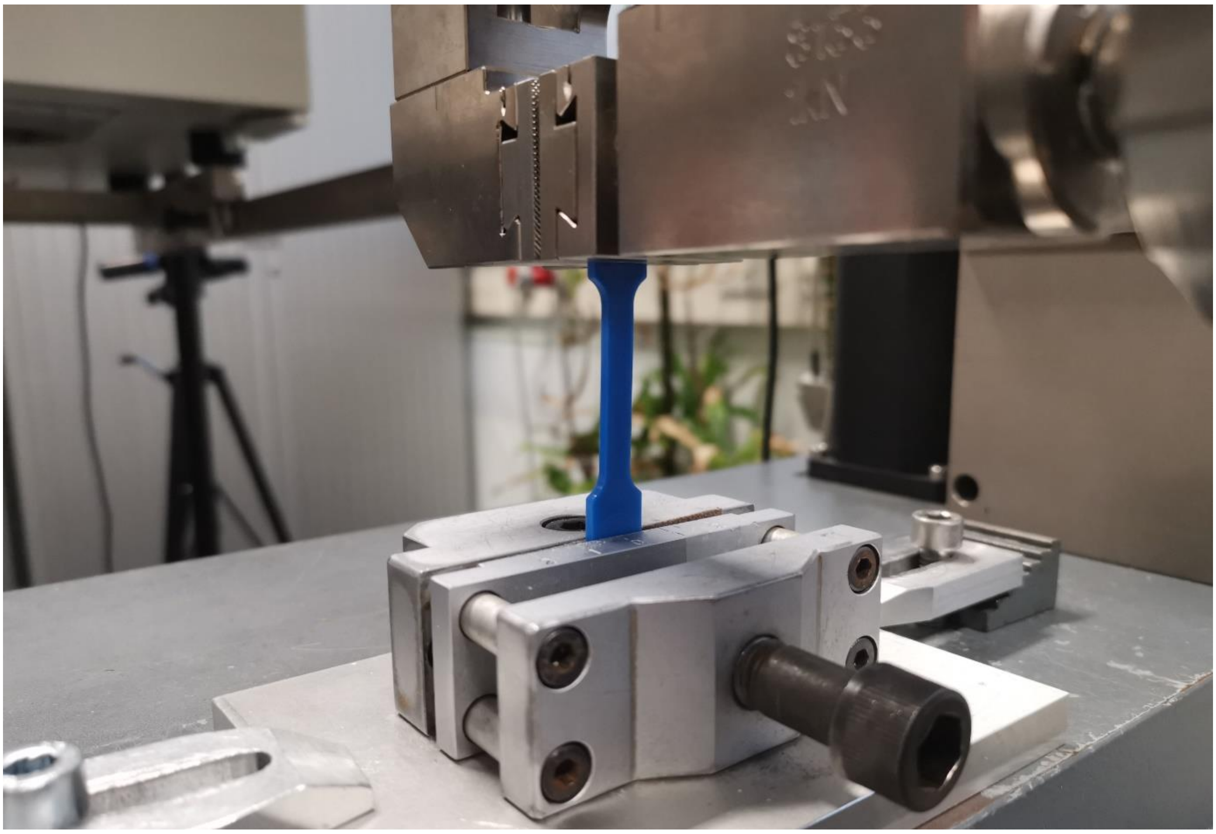


Figure 3. Dog bone injection molded from blue wrapping paper waste in the tensile machine, Delft. Photo by Bart van Straten.

Analysis

Tensile strength tests are commonly done to evaluate the mechanical properties of certain material compositions. We analyzed the Young's Modulus, in other words the stretch ability or elastic behavior of the material. The Young's Modulus is calculated by relating the strain to the tension by $E = \frac{\sigma}{\varepsilon}$.

We wanted to know how by much the recycled blue wrap could be stretched, also known as the elongation at break. This number is displayed as a percentage of its original dimensions. We also wanted to test how the recycled dog bone would perform regarding ultimate tensile stress (UTS), i.e. what load the material could bear when stretched before it breaks. These tests were necessary because we wanted to know if the products made of recycled material would withstand chemical processes in hospitals.

Medical products, used in the operating room, need to be disinfected and sterilized by the CSSD of the hospital. Disinfection is typically carried out on 90^0C using disinfection agents. Sterilization is done under vacuum in an autoclave on 121 or 134 ^{0}C. As these processes may also influence material behavior, it is important to test the materials by using dog bones which are treated with these kinds of chemical and thermal cycles.

The test results from the dog bones, molded in the different mixing ratios, showed surprising outcomes. The values of the ultimate tensile stress (UTS) were all, with the exception of the polluted mix, above 30 MegaPascal (MPa). One MPa equals one million Pascal (Pa). A Pascal is one newton of force per square meter, meaning that one MegaPascal is one million newtons per square meter. A higher MPa means that the material is stronger. The UTS of the recycled material was 31.5 MPa for the dog bone made out of virgin material, rising to 36.5 MPa for 100% recycled polypropylene (Figures 4 & 5). We considered this a good strength, at least good enough to justify making new products from this recycled material. On the other hand, the strain of the dog bone made out of recycled material was 6% lower than for virgin propylene, meaning it could be stretched 6% percent less. The mechanical properties of the recycled material appeared to be stronger, stiffer and harder, but also more brittle.[23]

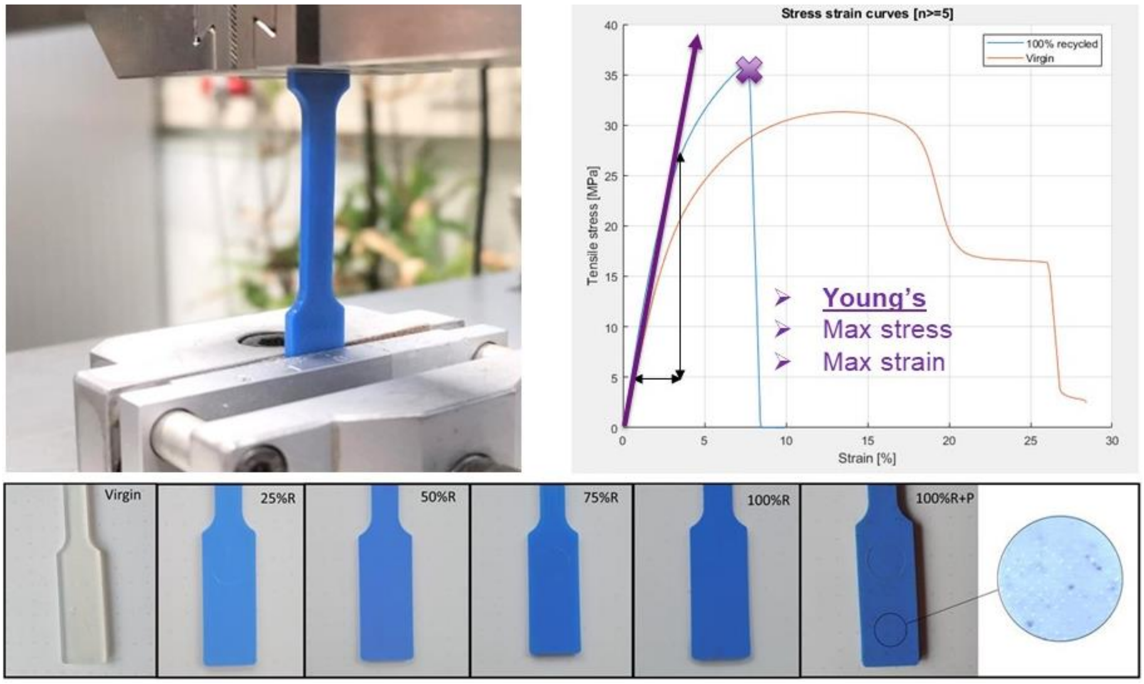


Figure 4. Dog bone test. Recycling means that the material becomes stronger and harder. Photo by Tim Horeman.[23]

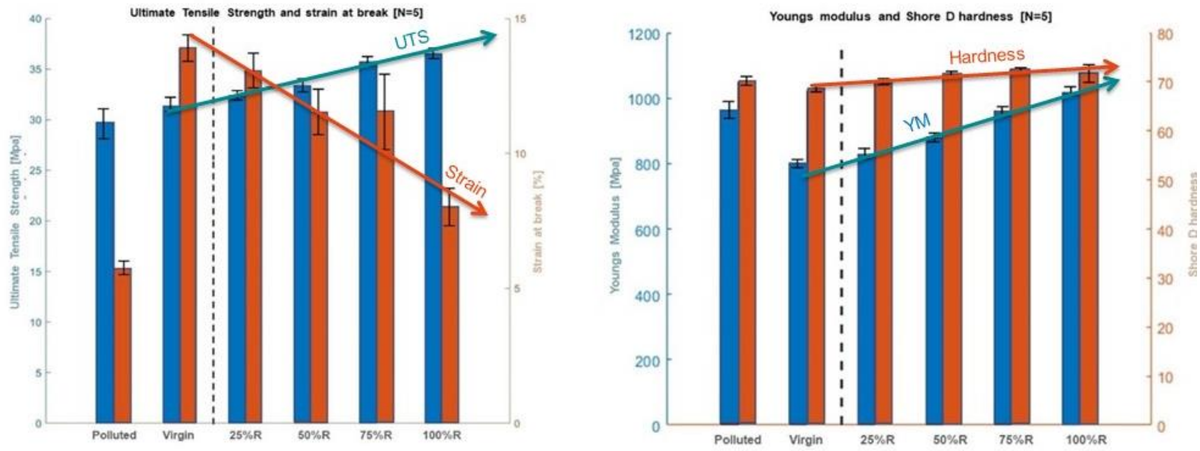


Figure 5. Mechanical properties of polluted and virgin polypropylene in the left-hand graph, showing various mixing ratios. Right graph showing the hardness. Figure by Tim Horeman.

The positive results of the experiments provide a basis for urban mining (figure 6) of medical waste and for potential product designs using recycled surgical waste as source of raw material.

Figure 6. Urban mined polypropylene from Maasstad Hospital, used to melt into polypropylene granulate, which is used to injection mold dog bones and other products. Photo by Bart van Straten.

Designing products out of medical waste: an example

Our goal was to design and make an instrument opener. An instrument opener is used to keep hinged instruments open during washing and disinfection. These openers are usually made from stainless steel, an expensive material. It takes a relatively high number of steps to make an instrument opener from steel, making it too expensive for this kind of application. Apparently, several hospitals use tile crosses instead, which are bought at hardware stores. Tile crosses are used to keep tiles in place after they are laid and need to dry. These products are of course not medical products and certainly not validated or CE-certified. However, creative solutions must found, given the lack of alternatives - even though these tile crosses melt around the instrument at higher temperatures.

We designed an instrument opener suitable for different-sized of instruments. The opener needed to be developed so that a hinged instrument would be kept in an open position at all times. Just like a car jack, we wanted to create a design that would be suitable for all hinged instruments. We came up with a design as shown in Figure 7, with a cross at the front and a solid shape at the back, that fits into an open instrument.

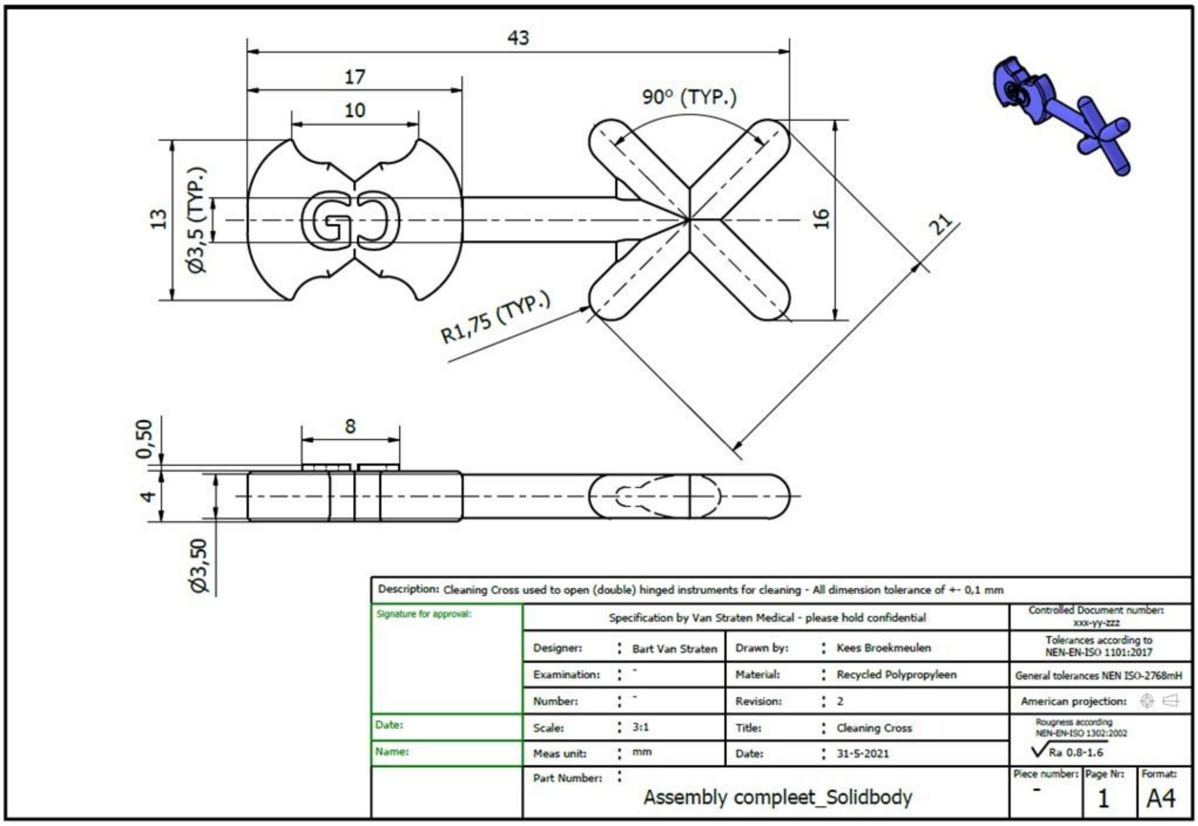


Figure 7. Drawing of the Go Jack instrument opener. Drawing by Bart van Straten.

After designing the instrument opener, a Finite Element Analysis (FEA) was performed (Figure 8). An FEA is a software method which can be carried out using a CAD program. It can be used to calculate how a product reacts to forces that are applied in daily practice. The FEA is a simulation in order to determine whether a product will break or wear out, and whether it works the way it was designed.

The next step was to make injection molds in the shape of the instrument opener. Once the molds were ready, we used them to injection mold the first series. We made different batches of instrument openers, from various mix ratios: 100% recycled blue wrap granulate, 75%, 50%, 25% and 10% mix ratios.

The first instrument openers were tested in the CSSD of CSA Services and Maasstad Hospital. The first results showed that the instrument opener functioned well. This was a good basis to start writing the CE application according to the MDR.[28]

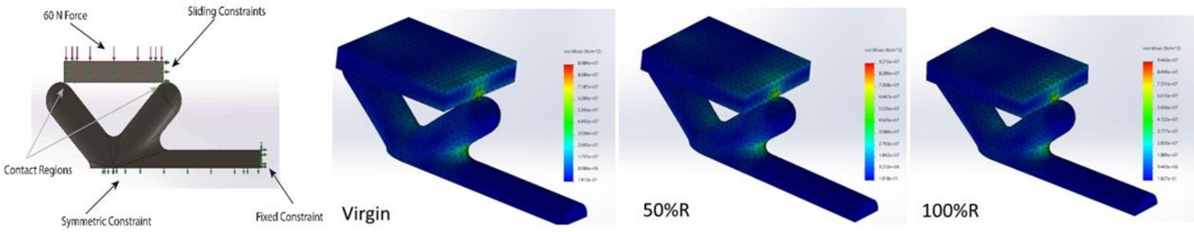


Figure 8. Screenshots from the FEA software showing the relevant sections of the instrument opener with the hinge interaction of the opened instrument. The colored areas show the spots of highest tensile and compression stress.[23]

28. OJ L 117. Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on medical devices, amending Directive 2001/83/EC, Regulation (EC) No 178/2002 and Regulation (EC) No 1223/2009 and repealing Council Directives 90/385/EEC and 93/42/EEC. 2017 May 05. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017R0745

The instrument opener was named ‘Go Jack’, a brand name derived from a car jack because it lifts or pushes apart a hinged object. The letters GO represent GreenCycl, with the O as an inverted C, because the instrument is made from recycled waste, and thus ‘green’. Remarkably, designing Go Jack, milling the molds and injection molding the first 1.000 instrument openers took us just six weeks, while writing and submitting the CE technical documentation took one year! Despite this long certification period, we were thrilled to have designed the first surgical product made from 100% recycled surgical waste that obtained an MDR CE validation.

The packaging of the instrument opener was designed to be made from grass carton, a pulp-based product which, apart from virgin fiber from wood and recycled paper, contains a significant proportion of grass fibers. Due to the organic water and grease barriers, packaging made of grass is primarily used for corrugated cardboard trays for fruit and vegetables. Taking the Butterfly Diagram in consideration, we had to focus not only on the mechanical recycling part but also on the biological part, i.e. the left-hand side of the Butterfly Diagram.

Finally, the instrument openers made from recycled PP are recycled again once they reach their end-of-life after being used in the process for minimal 50 times. We designed a collection box, made from recycled medical waste, in which they could be deposited after use. Thus, they could be collected and added to the polypropylene waste flow before being granulated again and to be used as raw material to make new instrument openers. Maasstad Hospital became the raw material supplier for its own instrument openers. In our opinion, this example of a circular business case can be applied to many other products.

The results of this study were published in the *Journal for Cleaner Production*,[23] showing to the world that surgical waste can be reprocessed into new medical products.

Main takeaways of this chapter:

- The material behavior depends on the relation between stresses and strains in the material.

- In order to investigate material behavior, dog bones can be used to perform tensile testing. The results regarding the mechanical properties are a good indication in order to select which product to make out of recycled materials.

- A grinding mill can be used to granulate melted waste into small particles.

- The concept of circularity can be enhanced by using sustainable packaging, such as grass board, for recycled products.

6

Reprocessing metal waste from hospitals

The world's crude steel production has grown tremendously since early 2000. The global hunger for steel needed for buildings and infrastructure, leading to ever-growing economic wealth, has brought iron ore production to the highest levels in history. Iron ore is mined as rocks and minerals from which metallic iron is extracted in order to produce steel.

The use of steel products has also grown exponentially in hospitals in the last decades. Many small surgical procedures are now carried out with disposable stainless steel instruments, although they had always been performed with reusable instruments in the past.

Disposable stainless steel instruments such as needle holders, tweezers and scissors are used in hospitals in many departments. Single use is presented as cheap. Disposable instruments are always sterile, as the supplier supplies each instrument in single packaging, do not have to be cleaned and re-sterilized. The numbers of single-use instruments used grew significantly, as environmental impact considerations did not play any role.[29] Apparently, we used to favor luxury over sustainability. Nowadays, many hospitals are using over 50,000 disposable stainless steel instruments per year, which are, moreover, flown in from production locations around the world. They are used only once, and then immediately disposed and incinerated, so that enormous amounts of metal were disposed on a daily basis by hospitals. However, at the same time there is increasing scarcity of iron ore as a natural resource.

It is important to note that there is a distinction between ferrous and non-ferrous metal types. Ferrous metals contain iron; non-ferrous metals do not contain iron, at least not in in appreciable amounts. Basically, non-ferrous metals are non-magnetic (due to the absence of iron), they are highly resistant to corrosion, and they do not rust – that's why copper pipes are often used in corrosive environments – but they have a lower tensile strength and durability than ferrous metals.

29. F. McGain, S. McAlister, A. McGavin, D. Story. 2021. The financial and Environmental Costs of Reusable and Single-Use Plastic Anaesthetic Drug Trays. Anaesthesia and intensive care, 38. P. 538-544.

The research group of the authors decided to see if it was possible to collect, recycle and use metal-based waste and use it as raw material for new medical products or components. There were hardly any studies to be found in the literature which described the reprocessing of metal surgical waste into raw material used as input for new medical products.

This seemed a perfect starting point for a study; the next step was selecting a medical device that we wanted to recycle. Preferably, it would be an instrument that was used in the operating room in large numbers. An anesthesiologist from the Amsterdam University Medical Center drew our attention by pointing out that his hospital used disposable laryngoscope blades, although there is also a type of blade available that is reusable. Laryngoscope blades are used in high quantities to intubate patients before surgery, but the anesthesiology department could not prevent the hospital from purchasing disposables. The type of laryngoscope blade used in this hospital was made of Zamak.

Zamak is a lesser-known, non-ferrous metal. The initials of the name Zamak stand for the four main components Zinc, Aluminium, Magnesium and Copper (using the German spelling K for Kupfer). It’s a very useful material with good physical and mechanical properties that is used in jewelry lines but also in the car and furniture industry, where it is used for door handles and decorative strips. In short, it a high-quality material with casting potential.

The Amsterdam University Medical Center used and disposed 7,000 of these blades per year (Figure 1). If the hospital were to use a reusable version, it would only need a few hundred. It seemed we had found our product: a medical device made out of a high-quality material, consumed by hospitals on a daily basis, with high costs to have them collected and disposed. The supplier of the product, a US-based company, manufactures these blades in China and sells them around the world. The company had already seen a rise in hospitals asking for its sustainability agenda. We agreed with this supplier that it would support us in setting up recovery programs with hospitals to collect the blades after use.

Figure 1. Left: Zamak laryngoscope blades. Right: Collection of disposed laryngoscope blades. Photo by Bart van Straten.

Virgin Zamak has a melting temperature of 390 ^{0}C. After melting and during solidification, the material tends to shrink, which is known as solidification shrinkage and occurs as the alloy changes from a liquid to a solid. The solidification shrinkage of Zamak is 1.2 %. This is an important aspect when casting products, as it can lead to weaknesses in the material. Zamak has an ultimate tensile strength (UTS) of 280 Mega Pascal (MPa), which makes it roughly seven times stronger than polypropylene and approximately 2.2 less strong than stainless steel. Zamak has a yield strength of 210 MPa. After this point the material will deform and not return to its original state. The Young's modulus, a measurement of stiffness, is 86 GPa. A low Young's modulus value means a material is elastic. A high Young's modulus value means a material is inelastic or stiff. The Elongation at break of Zamak – the measurement of how much the material can be stretched – is 11 %.

It was interesting to find out what the properties would be when we would melt blades which are used in the operating room. We wanted to find out whether we could recycle disposable Zamak laryngoscope blades into new medical products by using a new "all-in-one" affordable reprocessing setup as alternative for the common Zamak die-casting.

In total 48 kg of disposable Zamak laryngoscope blades were collected as waste from two hospitals: Spaarne Hospital, Hoofddorp, and Amsterdam University Medical Center, Amsterdam. The operating room team placed the waste in special plastic containers with a lockable lid.

After receipt of the containers, we opened and disinfected the laryngoscope blades at 90 ^{0}C. The easiest set-up was to make a stainless steel bowl with a funnel and a mold underneath the funnel (Figure 2). The whole set-up could be placed in the melting oven. The set-up was made from stainless steel, as this type of steel has a melting temperature of 1.400 ^{0}C or higher, far above the melting point of Zamak.

Figure 2. Cleaning, disinfection, melting and casting Zamak. Left: the cleaning and disinfection machine. Middle: the melting oven. Right: the casting set-up. Photo by Bart van Straten.

The laryngoscope blades are coated with an epoxy-polyester coating which had to be removed. The bake-off method can be used in these situations to turn the coating layer into ashes. This method requires a temperature of 340 ^{0}C to 400 ^{0}C,[30] when the coating starts flaking and forming cracks. The aim was for the Zamak to flow into the mold once the coating degraded enough.

A temperature of 420 ^{0}C seemed to be the best melting temperature to reduce the oxidation rate. Oxidation leads to gases and debris, which in turn can be absorbed by the liquefied Zamak. This may create defects and porosity during casting, which may lead to weaknesses in the cast material. This may result in lower ultimate tensile stress and yield strength and a lower Young's modulus. As a result, the material could break more easily.

During casting the melted material decreases in volume when it solidifies; i.e. the casting shrinks. This phenomenon can be explained by the fact that particles are pulled into the direction where the solidification starts. It tends to start at the walls of the mold, as this area cools down first. As a result, holes may appear in the material if there is not enough melt available to compensate for the loss of volume. This is called shrinkage porosity[31] and should be prevented.

To prevent shrinkage porosity, we chose to design the mold with a riser. A riser is an extra space on top of the mold, functioning as a reservoir in which more cast Zamak accumulates. The melted Zamak in the riser solidifies last, meaning that the material in the mold pulls liquid Zamak material from the riser towards the areas where cavities emerge.

An "all-in-one" melting process takes three hours' melting time and another hour to be sure that the cast material has cooled down.

30. GizmoPlans. (2018, December 5th) How To Remove Powder Coating (4 Different Methods). https://www.gizmoplans.com/how-to-removepowder-coating.

31. Han, Q. (2008). Shrinkage porosity and gas porosity. ASM Handbook, 15, 370-374.

The recycled material showed a recovery rate of 93% and looked like a bar of silver after opening the oven. The standard machining experiments showed the cast Zamak material could be machined easily with standard equipment with standard mechanical properties (Figure 3).

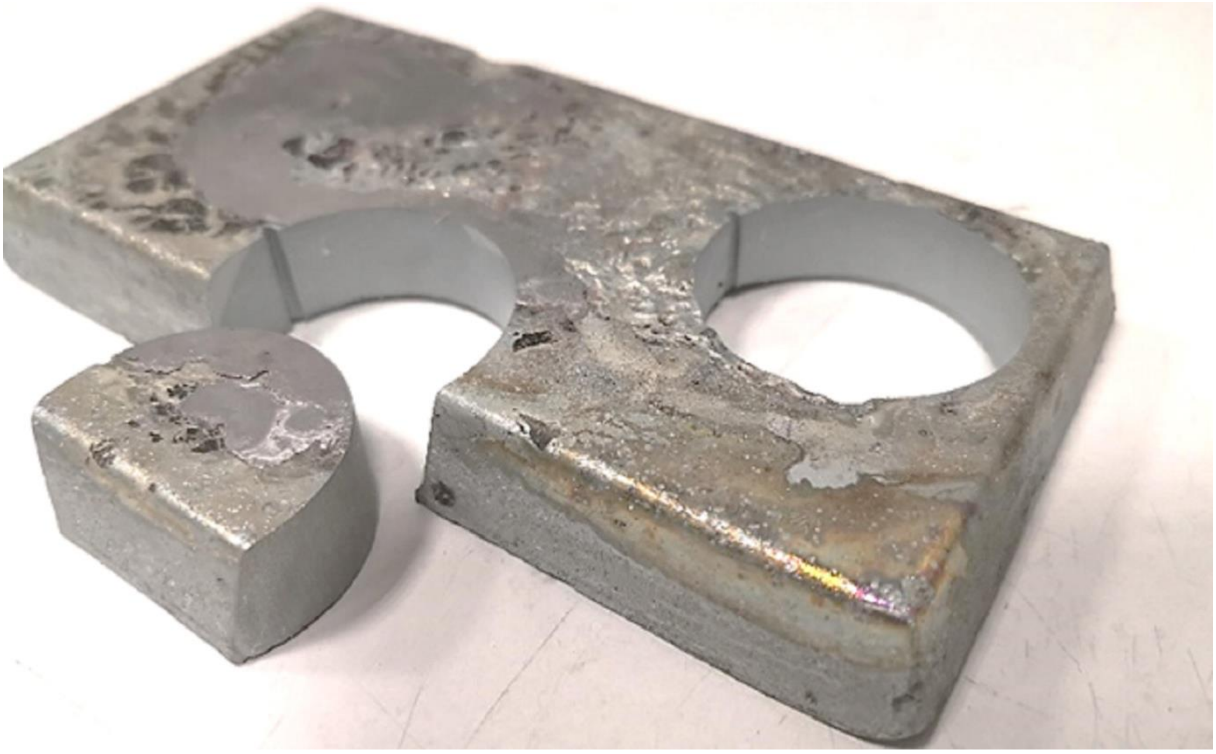


Figure 3. Zamak bar, cast from recycled laryngoscope blades. Round parts were cut from the bar and processed into usable material. Photo by Bart van Straten.

The wisdom lies in measurement

An X-ray fluorescence analysis (XRF spectroscopy) on the recycled Zamak was carried out. This is a method to determine the elemental composition of materials, i.e. to look at the material on an atomic level. The XRF analysis measurements were performed with a Panalytical Axios Max WD-XRF spectrometer at the Department of Materials Science and Engineering at TU Delft. The results were remarkable. Our relatively simple "all-in-one" melting and casting set-up led to good recycling results. Although there were some impurities, the material mainly contained Zinc, as Zamak is supposed to have. The concentrations of Zinc and silicon found in the cast material were higher than in virgin Zamak. The silicon likely came from the plastic parts of the laryngoscope blades which were not removed before melting. The tested samples had a purity of 99.7% and we saw no porosities in the cast material. The riser did its job: it prevented gas and shrinkage porosity and the casting temperature of 420^{0}C appeared to be a good temperature for the "all-in-one" recycling set-up.

The second step was to make dog bones out of the recycled cast Zamak in order to determine the ultimate tensile strength, the yield point and the Young's modulus. While the UTS determines the maximum stress that a material can withstand, the yield strength is often used to determine the maximum allowable load on a mechanical component. It represents the upper limit to forces that can be applied without causing permanent deformation (which is also called the plastic deformation region). Engineers use yield strength when designing products, as it keeps products safe from failure when the maximum load stays below the yield strength. The yield strength is a constant that represents the maximum limit of elastic behavior (Figure 4).

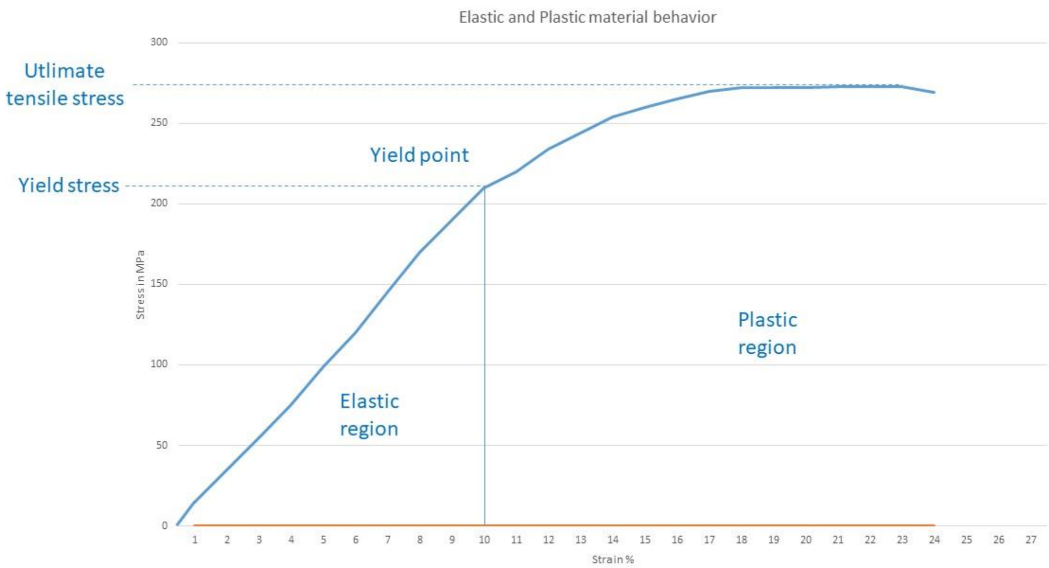


Figure 4. Elastic and plastic behavior of material, ultimate tensile stress and yield stress.

Dog bones made from the cast material (Figure 5) were used to perform mechanical tensile tests. The average UTS of the recycled Zamak laryngoscope blades appeared to be 236 ±61 (MPa) as compared to 280 MPa for virgin Zamak. The average YS of the recycled Zamak was 70 MPa compared to 210 MPa for virgin Zamak. Although the UTS as well as the YS are lower than virgin Zamak, the strength of the recycled Zamak was sufficient to work with.

Figure 5. The material transformation steps from collected Zamak instruments (top) that are cast into blocks (middle) before being turned into dog bones (below) for tensile testing. Photo by Bart van Straten.

After obtaining the results of the tensile testing, the casting of steering wheels was prepared, to design as part of the handle of a medical instrument used for laparoscopy as explained in Chapter 8.[32] A stainless steel mold was made to cast these wheels.

32. Hardon, S. F., Schilder, F., Bonjer, J., Dankelman, J., & Horeman, T., 2019. A new modular mechanism that allows full detachability and cleaning of steerable laparoscopic instruments. Surgical endoscopy, 33(10), 3484-3493.

The casting of the steering wheel was successful. It smoothly released from the mold and there were no damages on the surface. We observed shrinkage of the material, as is common with casting. This varied between 0.0% and 1.2%, which was acceptable. The steering wheel, cast out of recycled Zamak, was assembled on the SATA instrument and tested (Figure 6). Thus, like with the instrument opener made from blue wrap, we managed to make a new component from Zamak waste. In short, we succeeded in making reusable components out of disposable products.

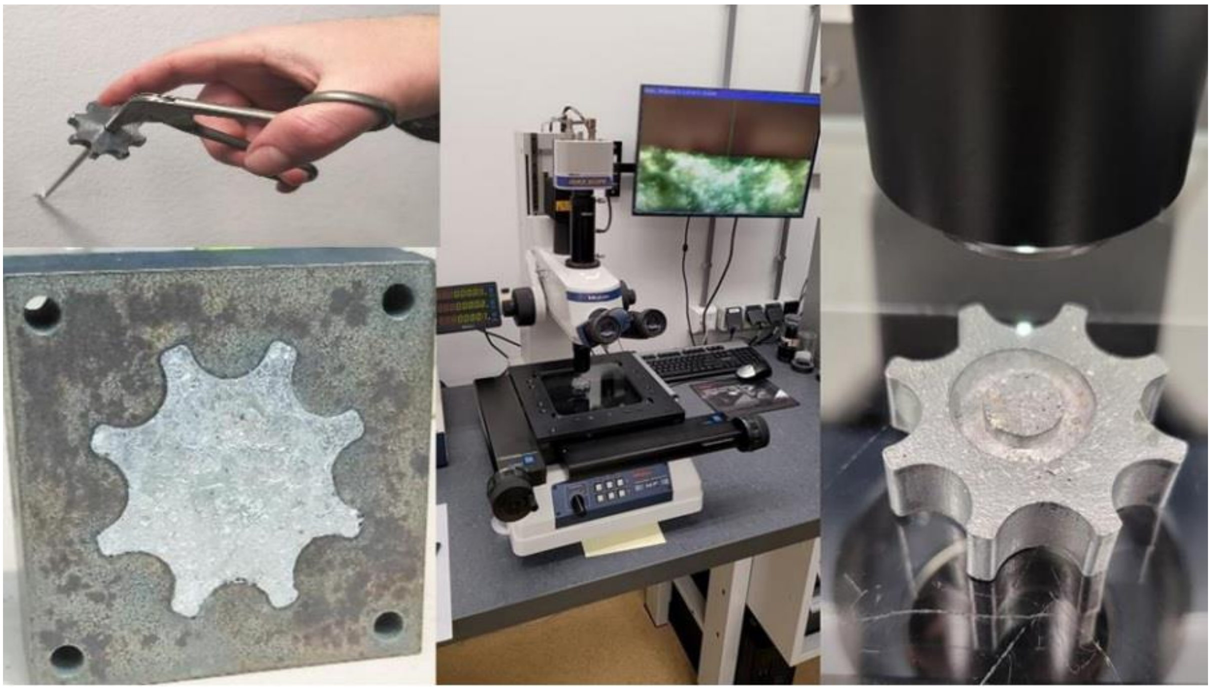


Fig. 6. Left: mold with cast steering wheel component. Middle: measuring shrinkage. Right: a finalized wheel fixed on the instrument. Photo by Tim Horeman.

Despite the limitations and changing mechanical properties, the results indicated that is feasible to reprocess disposed medical instruments into usable raw material and new medical parts.[33]

Reducing waste within the circular economy can be done in different ways. Changing from the use of disposable instruments to reusable instruments in order to reduce medical waste is a good option to consider when setting up circular strategies. After all, keeping products and materials in circulation instead of disposing them is the objective of the circular economy. These circular strategies help to reduce CO_2 emissions and contribute to a circular healthcare economy. Another option, apart from the recycling of non-ferrous metals such as Zamak, is the recycling of ferrous metals (Chapter 7), which clearly has benefits for the environment. It results in less extraction of raw materials from the earth and helps to reduce carbon emissions.

33. Bart van Straten, Brian Tantuo, Jenny Dankelman, Nicolaas H. Sperna Weiland, Bendiks Jan Boersma, Tim Horeman, Reprocessing Zamak laryngoscope blades into new instrument parts; an 'all-in-one' experimental study, Heliyon, Volume 8, Issue 11, 2022, e11711, ISSN 2405-8440

Main takeaways of this chapter:

- Iron ore is mined as rocks and minerals, from which metallic iron is extracted in order to produce steel.
- Large amounts of metal are discarded in hospitals on a daily basis.
- Recycling of ferrous and non-ferrous metals has benefits for the environment. It means less extraction of raw materials from the earth and helps to reduce carbon emissions.
- There are two types of metal: ferrous and non-ferrous. Zamak is a little-known, non-ferrous metal. The name Zamak stands for the four main components Zinc, Aluminum, Magnesium and Copper. Like other metals, Zamak is recyclable.
- A temperature of 420 ^{0}C seems the best melting temperature for Zamak, in order to reduce the oxidation rate. Oxidation leads to gases and debris, which in turn can be absorbed by the liquefied Zamak. At this temperature the coating is removed, called the ‘bake-off method’. The molten material turned out to be good raw material for making new products.

Part III

A sustainable market

7

Climate change as a business case

The circular economy is gaining more and more interest around the world, meaning that it can be considered as a growing business model. Circular business models aim to reduce the extraction and use of natural resources and to prevent waste streams. They represent the transition to a sustainable economy. But to change from a traditional model to a circular model, courage, vision and risk-taking are needed.

Some visionaries may be regarded as dreamers, but their vision says what their business will look like in the future. They present a clear image combined with passion and perseverance. Despite many objections and obstacles, they continue. And then there are the followers: those who join in if it turns out that the market is indeed moving in the direction the visionaries foresaw. The more people, organizations, politicians and policymakers join the circular vision, the faster the transition will take place. Sustainability has now grown into profitability. If you are not sustainable, you will no longer be relevant. This also increasingly applies to hospitals.

As we have seen in chapter 1, the global growth of medical waste has been the result of the growing global population. Also of the growing number and size of hospitals as well as the increase in use of disposable products resulted in growing waste streams.[34] Some studies report that up to 8.4 kg of waste is generated per patient per day.[35] Roughly 5.9 million tons of hazardous waste (15% of the total) and non-hazardous medical waste (85% of the total), is disposed by USA hospitals each year.[36] Hospitals in the USA account for 8% of the total CO_2 emissions in the USA,[37] which equals the emissions by hospitals in all EU countries, including the Netherlands.

The challenge is to use these environmental damaging aspects to set-up an evidence-based way to growing new successful circular initiatives, using commitment, resources, knowledge, and confidence as ingredients for success.

34. Mohee R., 2005. Medical wastes characterization in healthcare institutions in Mauritius. Waste Management 25: 575–581.

35. Kane, Grace & Bakker, C.A. & Balkenende, R., 2017. Towards design strategies for circular medical products. Resources, Conservation and Recycling. 135. 10.1016/j.resconrec.2017.07.030.

36. Yazdani, Morteza & Tavana, Madjid & Pamucar, Dragan & Chatterjee, Prasenjit, 2020. A Rough Based Multi-Criteria Evaluation Method for Healthcare Waste Disposal Location Decisions. Computers & Industrial Engineering. 106394. 10.1016/j.cie.2020.106394.

37. Voudrias, E. A., 2018. Healthcare waste management from the point of view of circular economy. Waste Management 75: 1-2.

For our study, we investigated the feasibility of reusing medical instruments and stainless steel extracted out of hospital waste streams. We wanted to study not only the technical and logistical aspects of recycling, but also to see whether recycling of hospital waste could constitute a positive business case. After all, the circular economy is increasingly becoming a suitable business model in a market where the demand for sustainability is growing. This would mean that an attractive proposition would have to be formulated for hospitals. Our research question for the business case part of this study[38] aimed to investigate if financial benefits for hospitals could be realized by applying circular strategies: Can cost savings be realized when using repair, refurbishing and recycling as methods to reach a concept of closing the circular loop in a hospital environment?

During the last decades, various business models have emerged, such as e-commerce business, pay-per-use, open-source applications, shared concepts and environmentally-friendly business models. Circular business models will be the next big step and may be seen as a disruptive model in some cases. Disruptive innovation creates new markets and might eventually displace established market-leading firms.

A circular business model applies circular economy principles, where products and processes are designed for reuse, repair, refurbishment, remanufacturing and recycling. The European Commission supports the transition from linear to circular by the establishment of a “right to repair”. For now, this “right to repair” only applies to products in the consumer market. It means that consumers will have the right to ask for the repair of products, also after the warranty period, as this results in lower costs, fewer greenhouse gas emissions and less energy consumption. Despite the fact that it might take a while before this also applies to the business market, it is a good example for suppliers of medical devices. In fact, it may serve as an example for manufacturers to take social responsibility and a good starting point for new sustainable and circular business models: ‘climate change as a business case’.

38. 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.

Particularly for stainless steel there is a good business case to make for reuse. Disposed instruments and stainless steel medical waste consist of valuable materials, which can be reused. They have a good resistance against corrosion, especially medical and surgical instruments. Stainless steel consists of iron (Fe)-based alloys, containing Chromium (Cr), Nickel (Ni), Molybdenum (Mo), carbon and silicon.

Surgical instruments are mostly made of stainless steel type 316 (SS316). Stainless steel type 304 (SS304) is typically used for disposable instruments and instrument transport mesh baskets. Stainless steel has a 100 percent recyclability and has good properties after melting. Stainless steel products should therefore never become waste at the end of their useful life. Instead, they should be structurally separated, melted and led back into the manufacturing of new products.

Our experiment was focused on collecting stainless steel waste from hospitals, which consisted of disposed single-use instruments (Figure 1) and other disposed stainless steel waste such as mesh baskets and other accessories. Three Dutch hospitals were included in the study: Haaglanden MC in The Hague, Maasstad Hospital in Rotterdam, and Amsterdam University Medical Center (AUMC, location VUmc).

Figure 1. Collected stainless steel (SS) disposable instruments. These instruments are typically made in Pakistan and shipped throughout the world to be used once, after which they are disposed of and often incinerated. This type of stainless steel is generally SS304. Photo by Bart van Straten.

Methods

The business case started with collecting discarded reusable and disposable instruments and other stainless steel waste from the operation rooms during a period of 6 months (25 September 2018 – 12 February 2019). We used the facilities at our company Van Straten Medical in De Meern-Utrecht, the Netherlands, which is equipped for processing and repairing medical instruments.

The collected waste was disinfected at the supplying hospital sites in disinfectors using standardized disinfection programs at 90 °C. The waste consisted of several stainless steel waste streams, including used disposable instruments which were disinfected in a thermal disinfector which was acquired second-hand.

We contacted a metal recycling company that collected the recyclable stainless steel material from our facility, after disinfection by us. This company melted the materials into new sheet metal. We then transported the sheet metal from the company and used it to manufacture new components, mainly mesh baskets and other stainless steel components needed to create instrument mesh baskets. The sheet metal plates were processed on a water jet cutting machine to cut the components for the mesh baskets.

The retrieved instruments were absorbed in the mass of metal, making it impossible to determine whether the collected plates contained any old instruments. Nevertheless, we considered this a circular loop, as no material waste was generated during the process.

In this business case we decided to focus on the savings that hospitals make by not having to pay waste disposal costs, which vary per hospital. The costs for hospital waste collection by a waste processing company hospitals consists of a price per kg waste, plus costs for use of special waste containers, consultancy and handling costs. Furthermore, we created revenues and value through reprocessing hospital metal waste.

Our costs included costs for electricity, costs for overhead and transportation costs, costs of repair and parts that were needed to repair and remanufacture old instruments into instruments in 'new manufacturing's condition', which equates to the quality of new products. The revenues were aimed at getting a price per kg for the recycled instruments as well as charging a price for instruments which could be repaired. This led to further savings for the participating hospitals, because repairing these instruments was much cheaper than buying them new. The instruments which could not be repaired because of too much damage were recycled, for which we received a revenue per kg. The melting of the steel was done via a steel manufacturer who offer a price per kg. Stainless steel revenues are dependent on the current market price for stainless steel and vary per period. However, due to geopolitical circumstances at the time of this study, the raw material prices (and supplying times) for stainless steel were increasing.

In this study, the focus was on three main cost cycles in hospitals with regard to stainless steel waste:

(1) Disposed instruments, which could be repaired. The price of repair was compared with the price of a new instrument.

(2) The revenues from recycling stainless steel instruments which could not be repaired.

(3) Savings of costs for waste handling, which the hospitals no longer had to pay since we collected the waste.

All costs were related to units equivalent to 1,000 kg (ton).

Results

During our experiment we collected a total of 1,380 kg waste from the three participating hospitals. The waste consisted of all kinds of different instruments, ranging from instruments used for basic surgery to instruments used for specialized surgery (Figure 2). Furthermore, stainless steel trays and mesh baskets were collected. Twenty percent of the collected waste consisted of instruments that could be repaired.

Figure 2. Left: Two carts with mesh baskets filled with instruments from Maasstad Hospital. Right: Bin with discarded instruments at Van Straten Medical. Photo by Bart van Straten.

A total of 50 kg consisted of disposable instruments which had been used only once. These were collected in a closed container, as they had to be disinfected first before they could be used. The other 1,330 kg consisted of reusable instruments disposed for various reasons, and disposed mesh baskets (Table 1). From this, 20% (approximately 266 kg) seemed to be repairable, meaning that they could be processed into "new manufacturing condition" after refurbishment. All stainless steel instruments and mesh baskets consisted of stainless steel types 316 and 304. If the instruments could not be repaired, the steel was melted and recycled into sheet material. The total amount of waste per hospital category is provided in Table 2. The distribution per type of waste (refurbished and recycled) per hospital is provided in Table 3.

Table 1. Collected instruments.

Collected	Material specification	Collected weight (kg)
Reusable instruments and mesh baskets	Mixed SS304/SS316	1,330
Disposable instruments	SS304	50
Total		**1,380**

Table 2. Collected waste types and distribution per hospital category.

Hospital	Type of hospital	Type of waste	Waste collected (kg)
Maasstad, Rotterdam	Large peripheral	SS baskets, containers, discarded instruments	717
Haaglanden MC, The Hague	Peripheral hospital consisting of Westeinde, Bronovo & Antoniushove	SS baskets, discarded instruments, used disposable instruments	209
AUMC, loc. VUmc, Amsterdam	Academic Hospital	SS instruments, baskets	454
Total			**1,380**

Table 3. Circular processed waste.

	Collected (kg)	Refurbished (kg)	Recycled mixed SS304/316 (kg)	Disinfected & recycled SS304 (kg)
Maasstad	717	71	646	
Haaglanden MC	209	120	39	50
VUmc	454	46	408	
Total	**1,380**	**237**	**1,093**	**50**

In total, 945 instruments were repaired and refurbished into new manufacturing condition: 282 instruments from Maasstad Hospital, 478 from Haaglanden MC and 185 from VUmc. The average weight of each instrument was 251 g, adding up to 237 kg in total.

The revenues of collecting one kg of metal waste which was recycled at the market price for stainless steel appeared higher than the costs to collect, disinfect and handling, leading to a positive business case (Table 4).

Table 4. Costs and savings per 1.000 kg for recycling stainless steel instead of disposing.

Costs	**(€ per 1,000 kg)**
Transportation costs	100
Collection bins	70
Handling costs	10
Disinfection costs	150
Overhead costs	10
Total logistical costs	**339**
Savings	
Steel revenue	**910**

The revenues in the business case were further increased by the 237 kg of collected instruments which could be refurbished. The savings for the hospitals are shown in Table 5., as compared to the costs of replacing them with new instruments.

The average costs of refurbishment were € 39 per 250 g. The average sales price of a new instrument was estimated at € 80, based on the average sales price of a total of 16,912 medical instruments available in the market, gathered from price lists at Van Straten Medical. For the business case this meant a saving of € 41 per instrument (€ 164 per kg) for the hospital and € 39 in turnover per instrument for those selling it. It goes without saying that a facility is required where instrument repairs can be carried out in accordance with medical requirements. Furthermore, this business case is focused only on cost savings and positive returns, not on CO_2 savings.

Table 5. Total savings realized by refurbishing/repairing instruments which could be repaired.

	Refurbished instruments (kg)	**Savings from refurbished per instrument kg (€)**	**Savings from refurbished instruments as compared to new (€)**
Maasstad	71	164	11,644
Haaglanden	120	164	19,680
VUmc	46	164	7,544
Total	**237**		**38,868**

A total of 1,143 kg of stainless steel was collected by a metal recycling company at an average price of 0.91 €/kg, resulting in a revenue of € 1,040.

For the hospitals the savings that are realized by using refurbished instruments, leading to reduced waste processing costs, are shown in Table 6.

Table 6. Net gain for the participating hospitals.

	Direct hospital savings on waste costs (€)	**Savings from refurbished instruments as compared to new (€)**	**Total gain for hospitals (€)**
Maasstad	143	11,644	11,787
Haaglanden	82	19,680	19,762
VUmc	91	7,544	7,635
Total	**316**	**38,868**	**39,184**

Climate change as a business case

The world needs sustainable solutions. Our economic systems will have to change from linear to circular. Growing market demands for circular products and services will support this change. Activist shareholders are increasingly pushing for environmental change. Corporate Social Responsibility programs are emerging as management concepts to offer environmentally-friendly products and services. In short, sustainability sells. Many companies realize that if they don't come up with sustainable solutions, they will miss out on market demand, as they are challenged by individuals and organizations who are intrinsically motivated to take action to save ecosystems, but do not financially gain from their actions. The business case outlined in this chapter shows that there is a financial incentive for hospitals to participate in the circular economy and that it is possible for new business models to emerge.

Healthcare waste demonstrated to have negative impacts on the environment, which may be limited by handling waste in a circular way.[39] This business case showed that instruments for general surgery and specialized surgery can be repaired and brought back into circulation. The costs associated with repair and refurbishment amounted to 49% of the average purchase (replacement) costs. Such business cases could also be set up for other products used in hospitals which are normally not recycled. Circular projects such as this study are generally received with enthusiasm by hospital staff and provide new insights into the potential reusability of medical waste.

39. Viani, Costanza & Vaccari, Mentore & Tudor, Terry. 2016. Recovering value from used medical instruments: A case study of laryngoscopes in England and Italy. Resources, Conservation and Recycling. 111. 1-9. 10.1016/j.resconrec.2016.03.025.

A circular business case can be made from different perspectives. From a business perspective, the circular economy can maximize profits or point to new products or markets. From the perspective of a hospital, it is profitable to save costs, and enables the hospital to set up a green agenda. A persuasive circular proposal describes a clear definition of the problem and the solution. A strong proposal allows decision-makers to make a decision based on the benefits, disadvantages, costs, risks of the current situation and the future vision.

The Butterfly Diagram can be used as a basis for a circular proposal by prioritizing the inner loops over the outer loops (share/maintain/repair – reuse/redistribute - refurbish/remanufacturing – recycling). The loops as shown in Figure 3 represent cost savings to hospitals and businesses. They make keep products and materials in circulation, rather than purchasing new products.[40] Our experiment emphasized the importance of the repair and recycling strategies in the Butterfly Diagram.

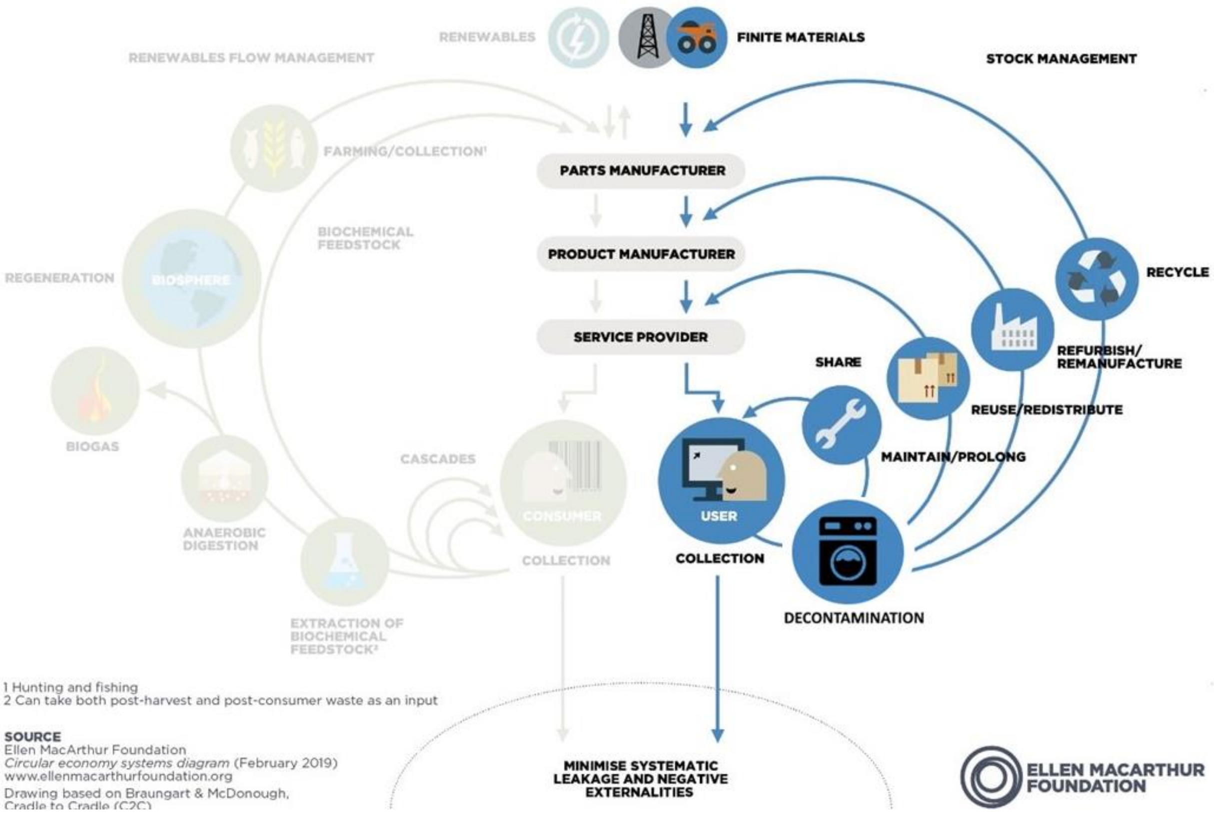


Figure 3. Butterfly Diagram with added decontamination step. From inner to outer loops, each loop shows increased costs and energy usage. Source: the Ellen MacArthur Foundation, modified by Tim Horeman.

In short, climate change as a business case can result in cost savings for hospitals and generate revenues for businesses at the same time. Using waste as source of income and as a source of raw material to make new products as circular strategies can create new business models. Even more important is that we use these new business models to stop the degradation of our planet.

40. The technical cycles of the Butterfly Diagram. Ellen MacArthur Foundation. (2022). Retrieved from https://ellenmacarthurfoundation.org/articles/the-technical-cycle-of-the-butterfly-diagram

Main takeaways of this chapter:

- The circular economy faces growing interest around the world, meaning it can be considered a profitable business model.
- Circular business models aim to reduce the extraction and use of natural resources and to prevent waste streams. They represent the transition to a sustainable economy.
- Climate change as a business case can lead to improved protection of our ecosystems.
- The Butterfly Diagram can be used as a basis for a circular proposal by prioritizing the inner loops over the outer loops, i.e. focusing on share, maintain, repair and reuse, rather than refurbish and recycle.
- The loops of the Butterfly Diagram represent cost savings to hospitals and businesses. They can make use of products and materials already in circulation, rather than investing in making or buying them new.
- Waste can be used as a source of income and as a source of raw material to make new products.

8

Eliminating waste by design: A Design by Dissection - Component Interaction analysis (DD-CIA)

Engineering design for a circular economy means a fundamentally different way of developing and producing products and services. As the circular economy is gaining more and more interest, we will see the emergence of new technologies and waste-preventing products and services like the initiative of GreenCycl to design waste into products (Figure 1). Engineering is about solving problems. Not only engineers, but all other stakeholders in the circular economy can have a significant impact on sustainable development. Basically, anyone who helps to engineer a circular product or service helps to create a better world.

Circular engineering principles can be seen as engineering principles that are aligned with the principles of the circular economy. They harmonize the engineering principles “ideas and concepts that are used to solve an engineering problem” with the circular economy principles as defined by the Ellen McArthur Foundation: [32] designs which eliminate waste and pollution, circulate products and materials and regenerate nature.

Circular engineering principles can be applied in product design and in process design, by using design requirements for the circular strategies of sharing, maintenance, reuse, repair, remanufacturing and recycling. Thus, a circular product is created, which requires designing towards zero waste. In other words: products, components and materials continue to circulate in the economy.

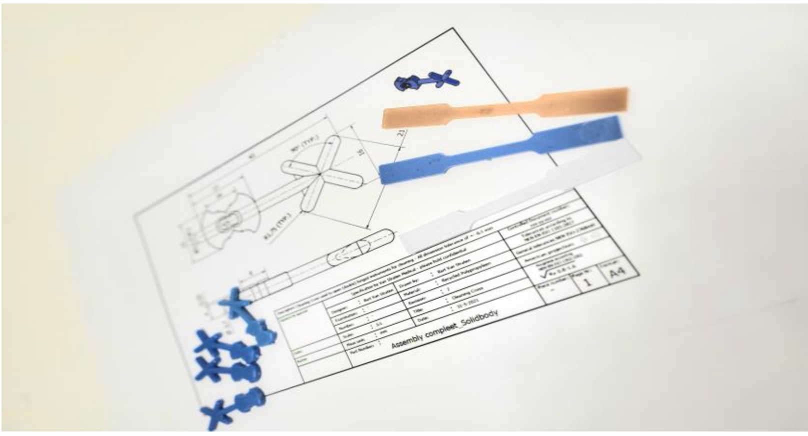


Figure 1. GreenCycl initiative: Designing waste into products.
Photo by Bart van Straten.

Taking the circular loops of the Butterfly Diagram into consideration, we can aim to design products in a different way than traditional products. This means designing them to last longer and to be re-used, by:

- Choosing high-quality and strong materials that prolong durability.
- Minimalistic design, with fewer parts, preferably using the same materials for all parts, and less complexity.
- Facilitating ease of maintenance and repair, for instance by limiting the number of steps that is needed to access parts that must be replaced, and by ensuring that few tools are needed – ideally no tools at all, but in any case standard tools that are easy to find.
- Using recycled materials.
- Standardizing parts and lubricants.
- Simple modular design, with replaceable modules.
- Making the product easy to clean and avoiding small holes or cavities where dirt can accumulate.
- In the choice of materials, making sure that all parts are able to withstand the same detergents and temperatures.
- Making heavily used surfaces able to withstand mechanical cleaning.
- Making the product easy to disassemble (non-destructive), e.g. by limiting the use of glue.
- Making it easy to replace components that wear out or can easily break, such as tires.
- Designing reusable or bio-based (degradable) packaging.

Processes

Besides products, processes can also help to become more circular by:

- Providing a repair service to the customers (thereby creating revenue and ensuring satisfied customers).
- Sales of spare parts and spare parts kits.
- Providing a market distinction for products that are easy to repair.
- Collecting packaging after use in an exchange process.
- Collecting products at the end of life and reprocess or recycle.
- Pay-per-use service.
- Good, easy-to-find online documentation for maintenance, repair and disassembly.
- Eco-friendly transportation of the product.

The level of circularity maybe determined by the environmental impact an object or process has on the environment.

In the previous chapters mainly strategies related to existing product designs were discussed. We learned how material choices and component structures have their influence on the functionality as well as on the cleaning of the device and its life cycle.[41]

However, an assembled complex product or device can be seen as the result of an extensive design process in which essential decisions are made regarding the looks, feel and functioning of a device and their interrelations.

Therefore, it makes sense that sustainability requirements have a tremendous influence on the eventual footprint of a device and should be dealt with on a higher design level.

41. Ecochain Technologie. Life Cycle Assessment (LCA) – Complete Beginner's Guide. 2022. https://ecochain.com/knowledge/life-cycle-assessment-lca-guide/

The design and manufacturing methods of surgical products have a large influence on the complexity of the design and thus on energy consumption and sustainability. Therefore, a smart design approach with focus on well-embedded and integrated functionality can help to make a “greener” product. Particularly in the field of surgery, the conventional approach, namely to design multifunctional surgical devices, often means that complex instruments are designed, with many components.

These devices are sometimes difficult to use in the operating room or to handle on the CSSD department. A redesign is needed in this case to improve functionality or ease of use. In many cases, redesign is needed due to changes in legislation, procedures, finances or use, although there is nothing wrong with the devices’ primary function.

Conventional design approaches

In 1993, a V-model was initially published by Bröhl[42] for the structured development of software applications; this found its way into the development of technical systems.[43] Thereafter, the model was further developed for mechatronic systems in the VDI guideline 2206 by Gausemeier and Moehringer in 2002 (Figure 1).[44]

In general, all models that are based on this structure are divided into three main components: the system design, the domain-specific design and the system integration. The input to the system design component consists of the requirements of the product to be designed. These requirements are defined after the problem analysis and after breaking down the goal of the design problem to be solved.

These input requirements also represent what the final product needs to achieve. The design process contains verification steps that allow the user to make changes to either the required characteristics of the future product, the details of the sub-functions or the requirements.[45] In the domain-specific phase, the selected solution concept is worked out in detail with the necessary calculations of the elaborated design, followed by a comprehensive functional performance that is presented with respect to the most critical functions. In the system integration part of the process, the results are integrated regarding various domains. Using the validation process, the specified solution is checked against the requirements defined in the beginning. This is done to make sure that the obtained characteristics of the final product are the desired ones. The result of this phase at the end of the system integration process is the final concept or product.

42. Adolf-Peter Bröhl. Das V-Modell: Der Standard für die Softwareentwicklung mit Praxisleitfaden. Oldenbourg, 1993.

43. Iris Gräßler. A new V-Model for interdisciplinary product engineering. Universitätsbibliothek Ilmenau, 2017.

44. J Gausemeier and S Moehringer. Vdi 2206-a new guideline for the design of mechatronic systems. IFAC Proceedings Volumes, 35(2):785–790, 2002.

45. Moritz Neukirchner. Establishing Sufficient Temporal Independence Efficiently: A Monitoring Approach. Cuvillier Verlag, 2014.

Specific design methods and guidelines exist that can help designers to create surgical devices that meet the broad requirements of all stakeholders while taking recycling and reprocessing at the end-of-life into account. For assessment of a device development both Barbero and Pereno et al. used three assessment methods: 1. the disassembly analysis, 2. the accessibility analysis and 3. the input-output analysis.[46] Disassembly analyses are shown to be useful for healthcare equipment, as they allow the researcher to fully understanding the equipment, identifying components that are easy or difficult to disassemble and defining the material composition of the equipment, in order to understand the ease of separation of different materials at the end-of-life.[45] The accessibility and interaction analysis is useful to get insight into, for example, the ease of maintenance. Barbero and Pereno et al. highlight the importance of showing ease of access for different users, like maintenance technicians, healthcare staff and patients or, in case of surgical instruments, CSSD workers, technicians and waste processors. The guidelines of Pereno et al. for Complex Handheld Surgical Devices (CHSD) and circular design are related to narrowing, slowing down and closing the design development loop. They suggest how to promote circular design in the categories information communication, product life cycle, usability, technology embedding and flexibility in use.[47]

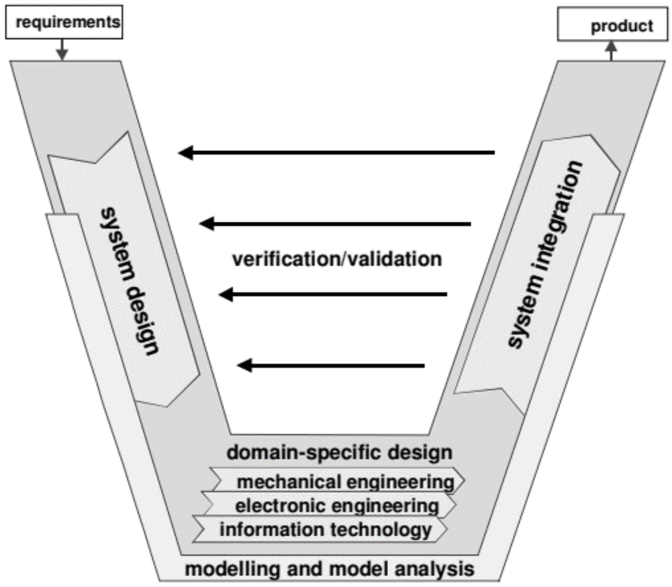


Figure1. V-shaped models show the steps that should be taken in a very abstract matter. Figure by Tim Horeman.

Romli et al. 2015 suggest that inspiration for redesign ideas can be gathered from other instruments, in order to prevent spending unnecessary time in finding already-existing solutions for a problem.[48] Koppella et al. 2013 present a method for redesigning the product architecture for improved critical part retrieval for reuse with two medical devices as case study.[49] Regarding the end-of-life, the work of Kane et al. describes design guidelines based on value and criticality that help choose the best strategy.[50] These results show that a throughout systematic analysis of the current design with interacting components is essential before any circular strategy can be proposed.

46. Barbero, S., Pereno, A., & Tamborrini, P. (2017). Systemic innovation in sustainable design of medical devices. The Design Journal, 20, 2486–2497. https://doi.org/10.1080/14606925.2017.1352763

47. Pereno, A. (2017). Design for sustainable behaviour. Routledge Handbook of Sustainable Product Design, September, 127–144. https://doi.org/10.4324/9781315693309

Based on the relatively high value and high criticality of CHSD, reprocessing is advised as the best recycling strategy. When the device can no longer be reused due to for example functional or regulatory obsolescence, then recycling is presented as the final end-of-life option. Kumar 2020 indicates "design for" strategies that make possible the recovery of materials, with a strong focus on specific design guidelines for the cleaning process of surgical devices.[51]

This work describes the importance of identify potential economic barriers throughout the design process. Moreover, it suggests to take regulations into considerations, as these give practical barriers for certain recovery strategies. Especially regulations linked to decontamination can cause a well-designed part, that can be easily reprocessed and reused, to end up as incineration or landfill part (Figure 2). Ferraresi et al. 2014 suggest to ensure differentiation of materials and to use compatible materials.[52]

Moultrie et al. 2015 implement circular design in the early stage of the design process. Hanson & Hitchcock 2009 suggest to use circular assessment tools to set up appropriate redesign requirements based on a thorough understanding of the device and to integrate circularity throughout the design process. Mann et al. 2018 emphasize that we should not forget the practicality and feasibility of sustainable design,[53] while Beeftink et al. 2019 show that the normal design process can still be used, with a circular aspect integrated within each phase in order to keep the process orderly and lean.[54] Finally Barbero et al. 2017 suggest that it is preferable to change the device as little as possible from current designs, as every change requires new medical testing and approval.[55]

48. Romli, A., Prickett, P., Setchi, R., & Soe, S. (2015). Integrated eco-design decision-making for sustainable product development. International Journal of Production Research, 53(2), 549–571. https://doi.org/10.1080/00207543.2014.958593

49. Koppella, K. V. M. (2013). Critical Parts Retrieval and Profit Maximization for Medical Sustainability using Design for Disassembly and Modularity. https://digitalcommons.utep.edu/open_etd

50. Kane, G. M., Bakker, C. A., & Balkenende, A. R. (2018). Towards design strategies for circular medical products. Resources, Conservation and Recycling, 135, 38–47. https://doi.org/10.1016/j.resconrec.2017.07.030

51. Kumar, P. (2020). EcoDesign for Medical Devices.

52. Ferraresi, M., Nazha, M., Vigotti, F. N., Pereno, A., Giorgio, D. Di, Gatti, G., Bevilacqua, R., Cagnazzo, M. L., Cassetta, M., Denti, B., Grimaldi, G., Monterossi, G., Barbero, M., & Piccoli, S. (2014). Ecodialysis: first strategiest to limit damages and reduce costs. http://porto.polito.it/2570340/

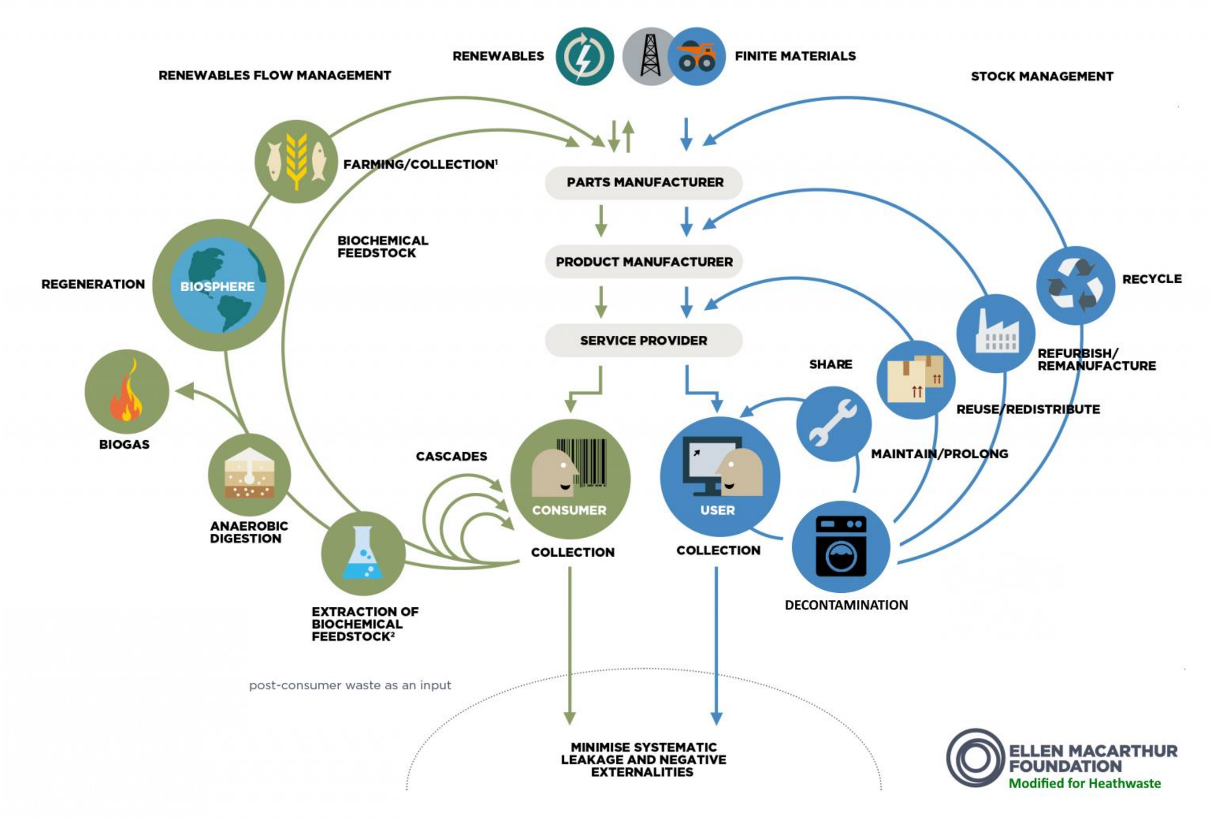


Figure 2. Hypothetically updated Butterfly Diagram for decontaminated medical devices.[12]

53. Mann, H., Mann, I. J., & Gullaiya, N. (2018). A case in medical equipment design for strategic sustainability. South Asian Journal of Business and Management Cases, 7(2), 111–119. https://doi.org/10.1177/2277977918774647

54. Beeftink, F. (2019). The redesign of CPAP supplies for the Circular Economy.

55. Barbero, S., Pereno, A., & Tamborrini, P. (2017). Systemic innovation in sustainable design of medical devices. The Design Journal, 20, 2486–2497. https://doi.org/10.1080/14606925.2017.1352763

Design by Dissection-Component Interaction Analysis

Due to the complex nature of surgical procedures and the limited time the surgical staff has to elaborate on the problem, it is likely that essential information is missed or misinterpreted by the development team. Moreover, it should be understood that the way a surgical team performs a surgical procedure highly depends on the knowledge of the surgeon. Therefore, the skills and surgical approach depend on where and how a surgeon was educated and can differ highly between hospitals. Finally, financial pressure often dictates surgeons to work long hours on an irregular basis, leaving them with less time to fully explore the problem that needs to be solved or to investigate whether potential solutions exist. Therefore, a methodology is needed to overcome these limitations and prevent that the obtained information is too limited or too subjective when solving a problem with surgical devices.

Minimalistic design

Winter et al. found that, to gain acceptance of a technical innovation at a low-resource setting, a different design approach is required that fosters the development of intuitive and maintenance-friendly devices.[56] Although the focus of Winter et al. was on low-resource settings, his suggestion is important: to find ways to reduce complexity by actively looking for alternative technology or mechanisms within the device without changing its basic functioning as soon as the cost price becomes too expensive. Due to the additional requirements the context of surgery brings to surgical technology design, in combination with the desire to keep the mental load during device interaction to a minimum, the design of surgical technology is challenging.

Within the synergy phase of the design process, the morphological chart (Figure 3) is often used to split the design of a device into partial sub-functions. For each of these sub-functions potential solutions are found that can all be combined into feasible concepts. Depending on the source, these concepts are translated into "proof of concepts" and assessed based on a set of criteria with the help of an assessment matrix such as the "Harris Profile".[57] Although this is a very structural way to create a design out of existing elements, it is doubtful whether this method motivates designers to create a fully integrated system, instead of ways to combine existing ones into a functional prototype by the use of additional supporting structures or components. It is possible to increase awareness for the importance of having an integrated design when combining the sub solutions with a specific mindset (e.g. most affordable, most comfortable or fastest developing time etc.) into desirable concepts. To further motivate designers to redesign surgical devices to better fit a new context or to solve a functional problem, a new approach is presented to investigate the problem on a component level and to remove problem-causing components from the device without compromising its function.

56. Winter A, Govindarajan V (2015) Engineering reverse innovations: principles for creating successful products for emerging markets. Harv Bus Rev 93(7–8):80–89

57. Van den Hoven, J., Vermaas, P. E., & Van de Poel, I. (2015). Handbook of ethics, values and technological design. Handbook of Ethics, Values, and Technological Design.

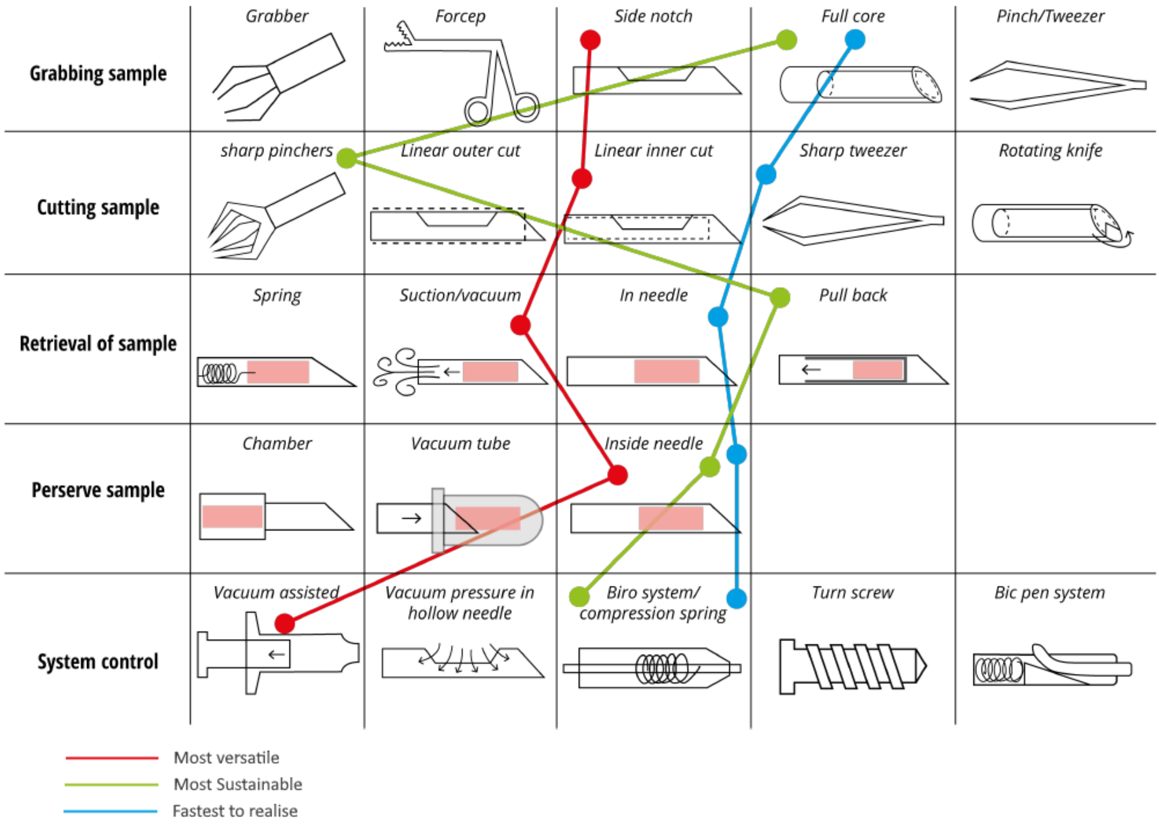


Figure 3. Updated example chart for the design of an automated spring loaded biopt needle, indicating how sub-functions are combined to facilitate a certain predefined mindset like "most versatile", "most sustainable" and "fastest to realize" (illustrated by red, green and blue lines). Figure by Tim Horeman.

Many papers that contain design methods and guidelines for surgical devices focus on specific improvements within the design process. Valuable examples are suggestions like "optimize the volume and shape", "improve the affordability of the product", "design the product so it can be easily customized and renewed without substantially changing the production processes" or "optimize the internal layout of components". However, specific "how to" examples are limited to specific aspects, e.g. the type of material to use, based on its chemical resistance or other properties, or how to make a design modular. Therefore, this study will provide a concrete methodology that allows designers to redesign surgical devices that fit better in the complexity of the operating room.

To help new designers to create smarter instruments, the "Design by Dissection (DD)" methodology has a strong focus on Component Interaction Analysis (CIA) in combination with a step-by-step development and evaluation plan. This development and evaluation plan involves all key users who are relevant to the innovation to create lean functional medical devices. To show its potential, this new methodology is validated below by examples that show how the design was influenced in a concrete way.

Fewer parts with more functions

In many cases, problems related to surgical devices can be related to a single type of critical component. The DD-CIA approach helps the designer to identify these critical components linked to a function. By removing the failing components from the design, designers are forced to think of ways to alter the remaining parts so that they take over the functions of the removed parts. CIA requires the designer to think about all functions the instrument needs to fulfil in terms of energy transmission through the device. Input of energy provided on one side of the device needs to result in output on the other side of the device and vice versa. This type of communication is often facilitated by physical components that have additional tasks, such as providing structure to the system. In addition, these components should also facilitate cleaning and therefore allow for easy disassembly and re-assembly. Furthermore, they should be easy to clean in a sometimes hostile environment for surgical devices with high temperature differences and aggressive chemicals. This generally means that medical or surgical devices benefit from a strong reduction in communicating components.

The DD-CIA method adds to the execution of any standard design process and expands the investigational and constructional phases. The holistic DD-CIA methodology can be integrated in the Design-by-Dissection problem identification method as shown in Figure 4. The Design-by-Dissection method was created to help researchers who develop surgical devices to fully understand the problem of the surgeon or surgical team and to develop devices in a minimalistic way.

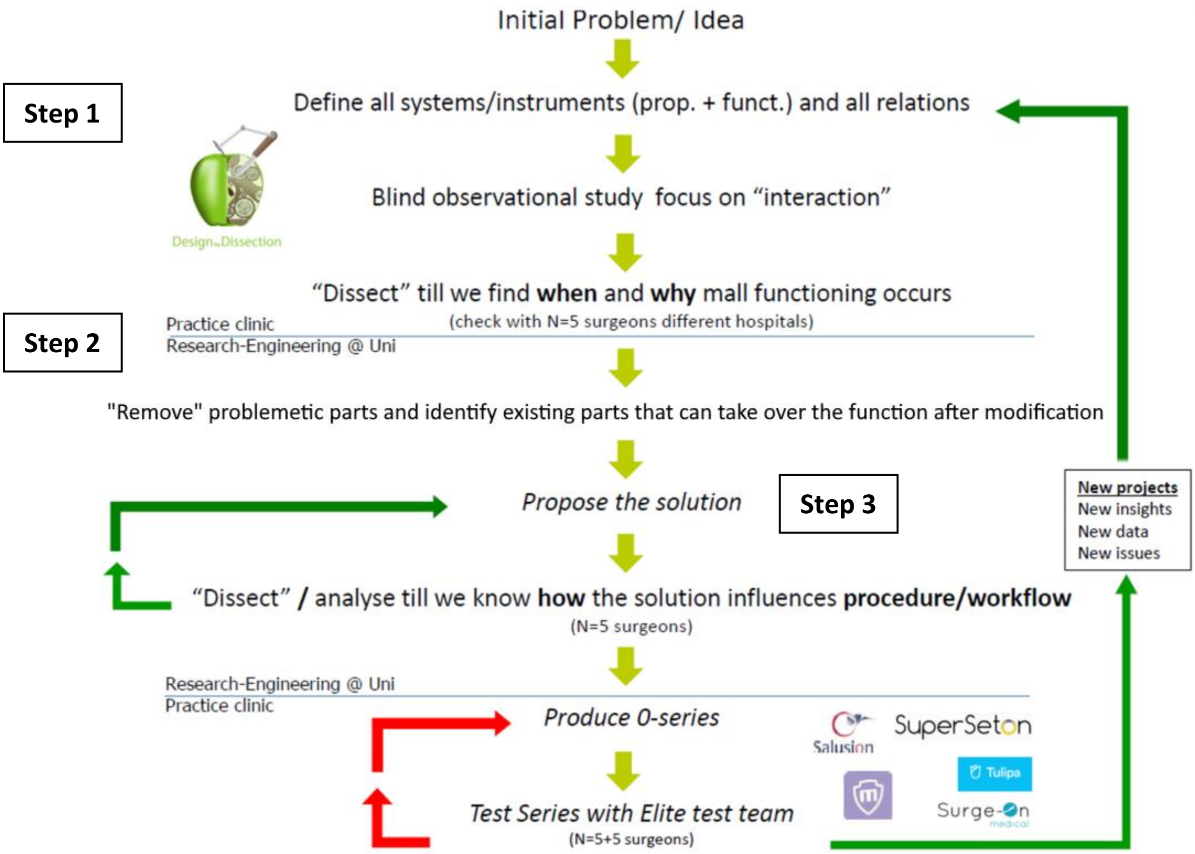


Figure 4. Flow chart for a Design by Dissection and implementation of medical or surgical devices. Figure by Tim Horeman.

In the investigational phase, the current situation of failing equipment is analyzed in **step 1**. This table shows functional component(s) that cause problems and allows the designer to check if alternative components fit better in the context and can be better aligned with the energy transmissions in the remaining components during the overall functioning of the system. In the synergy phase (**step 2**), the components are identified that are related to the problematic procedural steps, and which should be avoided when meeting the overall device requirements for ease of use or cleaning.

In **step 3**, alternative solutions are presented that can be integrated without compromising the functioning of the device. These solutions contain identified alternative or hybrid (modified) components that always aim to reduce complexity. In this step it should be taken into account that energy transmission inside the components of the device (like a certain component motion or force build-up) can be used as input for any of the functions that require a physical action (e.g. decoupling/coupling, monitoring of force/motion or physical state).

The flow as shown in Figure 4 is used to determine all relevant interaction forces, component motions and other energy transmissions. All interactions between components and environment needed for primary functioning, but also secondary use should be included. A structured identification method based on energy flow definitions is created, as shown in Table 1. This Table was fully explained for the first practical example within the model validation paragraph.

Model validation

Between 2010 and 2020, the DD-CIA method focusing on component interaction was used within the research line "Sustainable Surgery and Translational technology" at the Delft University of Technology to improve a series of surgical and medical devices. To validate the DD-CIA, each of the innovations was compared with the existing state-of-the-art. Objective assessment was done based on the number of components, the complexity of the device and the complexity in use.

Only devices were included that made it towards a Technology Readiness Level of 8 (market introduction) and were used in pre-clinical research. From the design process, only the influence of the DD-CIA on the design of the device is described and evaluated here.

Depending on the relevance, the impact of the DD-CIA on the number of parts, complexity, costs and efficiency in terms of procedural time or logistic steps reduction is evaluated. In the following examples it is explained how these steps are integrated into the design process of various surgical devices, including a surgical implant, surgical instruments, a storage system and an isolator system.

Example 1: Expanding the functions of structural components

Ever since the introduction of laparoscopic surgery, researchers have been trying to add steerability to instruments to allow the surgeon to operate with better reach and less tissue interaction force. Using the DD-CIA (Table 1), it was indicated that traditional solutions often use a combination of springs, cables, pulleys and guiding structures, resulting in (semi)-disposable instruments that cannot be properly cleaned and thus are very costly to manufacture and maintain. An alternative was found for the use of cables, resulting in a multi-steerable, cable-less 5-mm instrument line for arthroscopic and laparoscopic surgery, with instruments that operate based on shaft rotations (Figure 5). [58-60]

58. Hardon, S. F., Schilder, F., Bonjer, J., Dankelman, J., & Horeman, T. (2019). A new modular mechanism that allows full detachability and cleaning of steerable laparoscopic instruments. Surgical endoscopy, 33(10), 3484-3493.

59. Horeman, T., Schilder, F., Aguirre, M., Kerkhoffs, G. M. M. J., & Tuijthof, G. J. M. (2015). Design and preliminary evaluation of a stiff steerable cutter for arthroscopic procedures. Journal of Medical Devices, 9(4).

60. Horeman, T., Kment, C., Kerkhoffs, G. M., & Tuijthof, G. J. (2017). Design and stepwise user evaluation of an ergonomic 2 DOF arthroscopic cutter. Cogent Engineering, 4(1), 1410996

Table 1: Structured way to investigate if components that cause problems can be replaced by alternatives in order to increase the lifespan or reduce the number of components to make an instrument more sustainable.

<table>
<tr><td>Function</td><td colspan="5">3D steering of the tip</td></tr>
<tr><td>Problem part (PP)</td><td colspan="5">Tensioned cables that actuate the steering tip components cannot be cleaned, wear out fast and maintenance is not possible.</td></tr>
<tr><td>Energy flow through PP: relevant physical characteristics</td><td><u>Motion</u>
Transmission handle to tip</td><td><u>Force</u>
Transmission handle to tip</td><td><u>Torque</u>
Generation around hinges</td><td><u>Electric</u>
Monopolar
Bipolar</td><td><u>Optics</u>
N.A.</td></tr>
<tr><td>Energy flow presence</td><td>continues</td><td>continues</td><td>continues</td><td>accidental</td><td>N.A.</td></tr>
<tr><td colspan="6">Potential takeover of functions</td></tr>
<tr><td>Solutions</td><td colspan="2">Option 1: Shaft</td><td colspan="3">Option 2: Tissue interaction</td></tr>
<tr><td>Influence on component interactions in design</td><td colspan="2">• handle needs to transmit motion and forces to shaft
• shaft needs to transfer motion and forces to tip</td><td colspan="3">• tip needs to be placed in position by force and motion during interacting with environment
• position of tip needs to be locked and released by handle, which requires force motion transmission in shaft</td></tr>
<tr><td>Required component modification</td><td colspan="2">• multiple thinner shaft tubes that communicate forces and motions by rotation and translation
• wheel levers needed for each tube inside the shaft
• instead of being linked to cables, tip hinges can be linked to tubes</td><td colspan="3">• tip hinge mechanisms at back drivable and stable
• designated shaft or rod motion (different from operation) locks all individual hinges
• instead of being linked to cables, locking mechanism in tip hinges can be linked to shaft or rod</td></tr>
<tr><td colspan="6">Sub-assessment: impact of change</td></tr>
<tr><td>Solutions</td><td colspan="2">Option 1: Shaft</td><td colspan="3">Option 2: Tissue interaction</td></tr>
<tr><td>Environmental footprint</td><td colspan="2">Low</td><td colspan="3">Low</td></tr>
<tr><td>Concessions to energy flow</td><td colspan="2">Low</td><td colspan="3">Medium</td></tr>
<tr><td>Workflow influence</td><td colspan="2">Low</td><td colspan="3">High</td></tr>
<tr><td>Redesign effort</td><td colspan="2">Low</td><td colspan="3">Low</td></tr>
</table>

The focused design question was defined as: *How can relative tube movements within a fully modular instrument translate finger motions towards tip steering in 3D?* A new steering technology was developed accordingly and the assembly and disassembly potential was validated with ten participants, who showed that it was possible to fully dismantle and reassemble the instrument 60 times within an acceptable timeframe. In addition, ten medical students used a laparoscopic grasper with integrated steering technology in the ForceSense box-trainer system on a 3D pick-and-place task (Figure 6), showing good outcomes in control effort based on learning curves for steering errors, task time, instrument path length, and maximum tissue interaction force.[57]

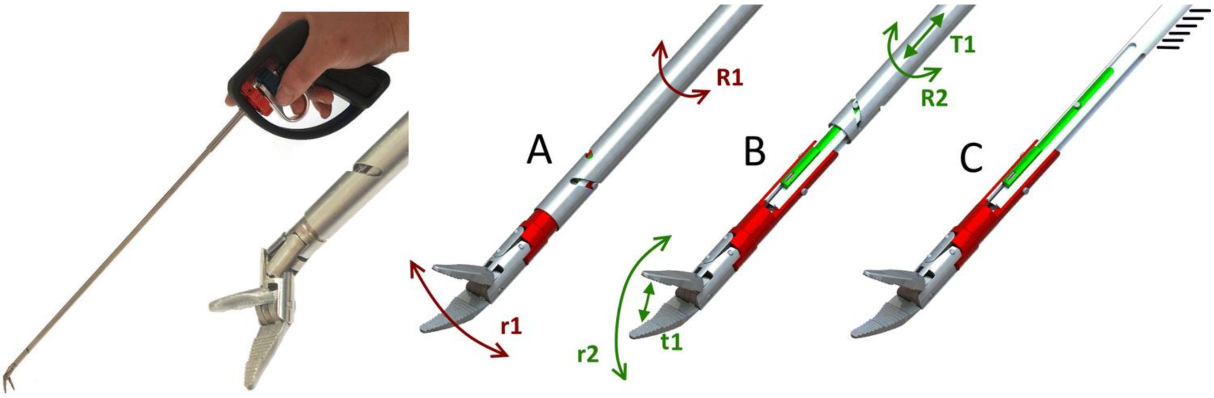
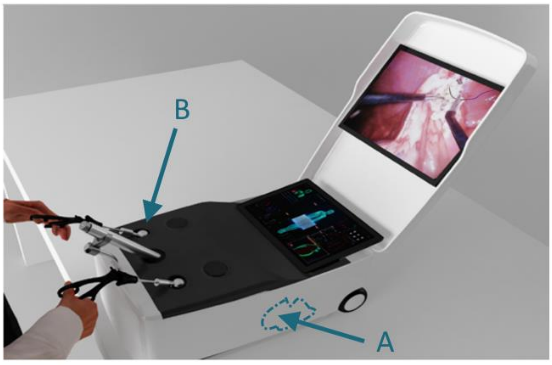


Figure 5. Left: The Shaft Actuated Tip Articulation (SATA) 2DOF instrument and tip. Right: principles of tip actuation. A sideways articulation (r1) is accomplished by rotation of the outer tube (R1), which drives the red sliders. B Beak rotation (r2) and closure or opening (t1) are accomplished by rotation (R2) or translation (T1) of the inner tube, which drives the green sliders. C The inner rod fixed to the handle prevents rotation of all the sliders, while allowing translation. Figure by Tim Horeman.

Example 2: function outplacement

The ForceSense is a set of sensors (Figure 6) that can be used in a so-called box-trainer that allows surgery residents to train their technical skills in laparoscopic surgery. The sensors measure the instrument motion and interaction force that is used to assess performance during training, in terms of efficient instrument use and safe tissue manipulation. The ForceTRAP 3D force sensor was developed for use inside the ForceSense with the DD-CIA approach, as the restriction in instrument diameter (e.g. 5 mm diameter) does not allow for easy integration of sensors. The component interaction analysis conducted on laparoscopic instruments in combination with the complex user context (e.g. should be used with multiple instruments and for training) resulted in a large set of design requirements for implementation of a sensor in the instruments.

This directed any potential solution of measuring forces and motions in laparoscopic instruments away from the instrument. In fact, filling out Table 1 in this case dictated that interaction forces should not be measured in the instrument as seen in the sate-of-the-art in instrument design, but instead the reaction forces should be measured under the training task. This allows for training with any 5-mm instrument, without wear of the measuring elements. The advantage of using real, unmodified instruments for training in surgical procedures led to a series of studies on using the ForceTRAP with and without force feedback on a real cadaver specimen during arthroscopic knee[61], elbow[62] and wrist surgery[63] and training for dermatologic procedures[64] and laparoscopic surgery.[65,66]



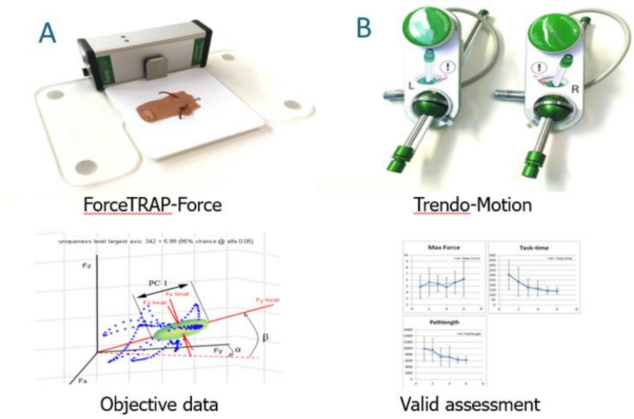


Figure 6. Left: The motion and force sensors integrated in a SMART Boxtrainer. Right: The DD-CIA designs that measure force and motion outside the instruments, allowing surgeons to use standard instruments. Figure by Tim Horeman.

61. Horeman, T., Tuijthof, G. J. M., Wulms, P. B., Kerkhoffs, G. M. M. J., Gerards, R. M., & Karahan, M. (2016). A force measurement system for training of arthroscopic tissue manipulation skills on cadaveric specimen. Journal of Medical Devices, 10(4).

62. Hilgersom, N. F., Horeman-Franse, T., Bleys, R. L., Eygendaal, D., van den Bekerom, M. P., & Tuijthof, G. J. (2018). Force measurement metrics for simulated elbow arthroscopy training. Journal of experimental orthopaedics, 5(1), 1-9.

63. Obdeijn, M. C., van Baalen, S. J., Horeman, T., Liverneaux, P., & Tuijthof, G. J. (2014). The use of navigation forces for assessment of wrist arthroscopy skills level. Journal of wrist surgery, 3(2), 132.

64. Marsidi, N., Vermeulen, S. A., Horeman, T., & Genders, R. E. (2020). Measuring Forces in Suture Techniques for Wound Closure. journal of surgical research, 255, 135-143.

65. Horeman, T., Rodrigues, S. P., Jansen, F. W., Dankelman, J., & van den Dobbelsteen, J. J. (2010). Force measurement platform for training and assessment of laparoscopic skills. Surgical endoscopy, 24(12), 3102-3108.

66. Hardon, S. F., Horeman, T., Bonjer, H. J., & Meijerink, W. J. (2018). Force-based learning curve tracking in fundamental laparoscopic skills training. Surgical endoscopy, 32(8), 3609-3621.

Example 3: Create new sub-functions by removing material

One of the risks related to tissue manipulation in laparoscopic surgery is that distorted haptic feedback causes high pinch forces that can damage soft internal tissues during manipulation. Standard solutions consist of complex decoupling mechanisms, system actuated ratchets and end-stops that increase the handle dimensions or break parts that damage after overloading[67], causing the user to get a new instrument and dispose of the damaged one. Filling out Table 1 showed that similar functionality can be reached by using the tension build-up in the main push-pull rod that drives the tip. To create a locking mechanism out of an existing component (Figure 7), a standard push-pull rod was machined with a single manufacturing wire cutting machine that eroded a specific shape in the rod, allowing it to deform under loading. When the pulling force reaches a predefined threshold, the rod deforms and locks itself inside the instrument shaft, preventing high actuation at the handle side which could result in dangerously high pinch forces in the beak that could damage delicate tissue. This simple mechanism reduced the number of extra components related to the functionality overloading protection to zero.[66]

Figure 7. Top: A force-limiting shaft (green box) that expands when overloaded and thus prevents damage to tissue. Below: Pulling on the rod results in a movement and mechanical lock of the flexing element. Photo by Tim Horeman.

67. Steinthorsson, A. T., & Horeman, T. (2022). U.S. Patent No. 11,376,029. Washington, DC: U.S. Patent and Trademark Office.

Example 4: Temporary structural support to facilitate multiple sub-functions

Perianal fistulas are a common and incapacitating problem. Many patients are treated by seton drainage to prevent recurrent abscess formation. For centuries, a vessel loop or suture has been used for seton drainage. The knot (or suture) that is necessary to tie both ends together often causes complaints interfering with the patient's quality of life. When removing the knot, it became evident that it is best to directly connect the distal ends of the seton wire in line with each other for a smooth result. Due to the nature of the seton, the material needs to be very flexible in order to prevent tension build-up during contact with the very sensitive inflamed wound or fistula track. The DD-CIA analysis on load cases and the way components are interacting during the different stages based on their material properties showed the need for a strong connection that allows a high tension when components are connected with each other. It also showed the need for low overall stiffness to reduce pain and discomfort. Instead of using additional components, modifications or material combinations that facilitate this firm connection, the analysis using Table 1 dictates using the seton silicone component to facilitate more of the required sub-functions. Thus, one flexible tube was made that can be cut to the required length and does not cause discomfort due to high tension in the material by making it hollow and adding an internal connection rod.

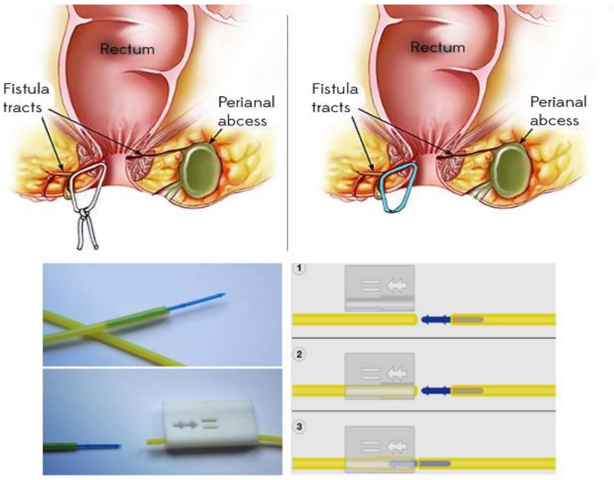


Figure 8. Top left: Old seton solution. Top right: New seton solution used to keep a fistula track open. Below: The functional parts that establish a strong connection in a very flexible seton: 1 applier, 2 insert, 3 drainage tube. [68]

The challenge became to create a high tension/friction connection after closure of the ring, as the material buckles and deforms when one tries to establish this connection. The DD-CIA analysis of this interaction problem indicated that it is desired to temporarily restrict the expansion direction of the material by inserting it with an "applier" (Figure 8). After connection, the applier, which provides temporary stiffness and rigidity, must be removed. Thus, the established pre-tension within the seton wall is high enough for the seton ring to remain functional for up to 3 months. A validation study conducted in 50 patients where a knotted seton was replaced by the knotless seton showed a significantly decreased discharge ($P = 0.005$) and pain ($P < 0.001$) [68].

68. Stellingwerf, M. E., Bak, M. T., de Groof, E. J., Buskens, C. J., Molenaar, C. B., Gecse, K. B., ... & Bemelman, W. A. (2020). Knotless seton for perianal fistulas: feasibility and effect on perianal disease activity. *Scientific Reports*, *10*(1), 16693.

Furthermore, 71% of patients reported fewer cleaning problems compared to the knotted seton, indicating the feasibility of the knotless seton design with promising short-term results. This valuable study allowed the creation of a startup that fostered the technology into the certification process and first sales.

Example 5: Use of suture tension to measure force

During suturing, tension is applied to the suture ends to bring wound edges together or to create a high-quality knot. In many cases, like wound closure after a laparotomy or during reconstructive or cosmetic surgery, it is important to know the tension in the wound as an indicator for a proper healing process.

When force sensors are used, the output of the force-sensing element can be related to the thread tension by making a connection between sensor and wire, placing the measurement unit in between the different parts of the wire. However, especially in case of multiple stitches in a suture or tying a knot, it is time-consuming or costly to place a force sensor between the surgeon's hands and the suture, or to modify an instrument. Moreover, the surgical site is very small in size and most sensors are too large and bulky to place between the wound edges in order to measure the wire tension in a continuous or matrass suture during wound closure.

The DD-CIA approach showed that in this case interruption of the wire and the resulting connection of the ends to a sensor should be prevented. Using Table 1 led to the solution in which the path of the wire was altered to create a resulting force around a rotation point without damaging the wire. The changing position of this rotation point can be measured with a tiny hall sensor and a magnet, and is directly related to the wire tension. It can be calibrated to display or indicate the wire tension (Figure 9, left). The researchers demonstrated that this principle can even be used reliably inside a compressed closed wound and can be integrated in a small force-measuring device that gives direct feedback about force levels[69] (Figure 9, right). Therefore, a series of reusable measurement sensors was launched with a reduced mass, size and invasiveness compared to traditional methods.

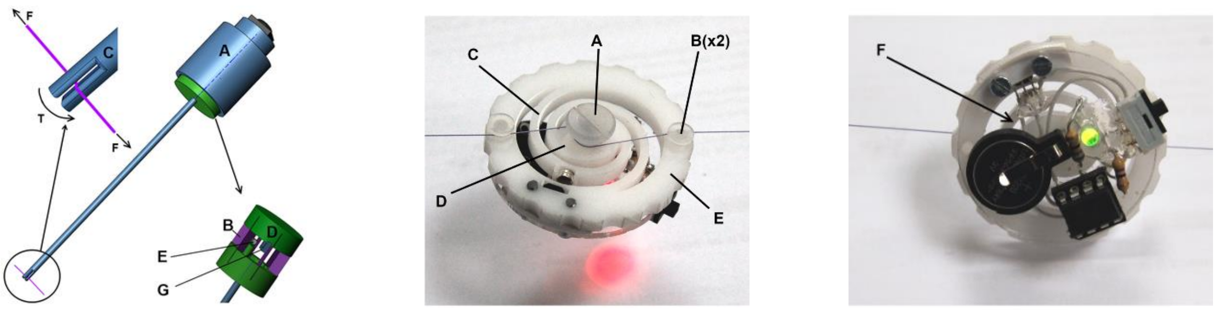


Figure 9. Left: Simple force-measuring concept for transferring the tension in a wire to a measurement element in a non-invasive way. Middle & Right: Through a tiny integrated system with multicolor LEDs, force levels can be communicated to the user.[69]

69. Horeman, T., Meijer, E. J., Harlaar, J. J., Lange, J. F., van den Dobbelsteen, J. J., & Dankelman, J. (2013). Force sensing in surgical sutures. *PloS one*, *8*(12), e84466.

Example 6: Use of component movements in a new safety function

Veress needles are commonly used in establishing pneumoperitoneum in laparoscopic surgery but can result a serious laparoscopic entry complication, like bowel perforation and vascular injury, related to the unintentional overshooting of the needle part after entering the abdominal volume (Figure 10). As these complications are potentially life-threatening, they should be avoided at all costs. Therefore, improving the safety of this action is paramount triggering multiple research teams to add sensory systems and control mechanisms (e.g. attaching a robot arm) to provide as much info and control to the surgeon during placement of the Veress needle. Independent from their potential effect, these systems mainly seem to increase the complexity and costs of the procedure.

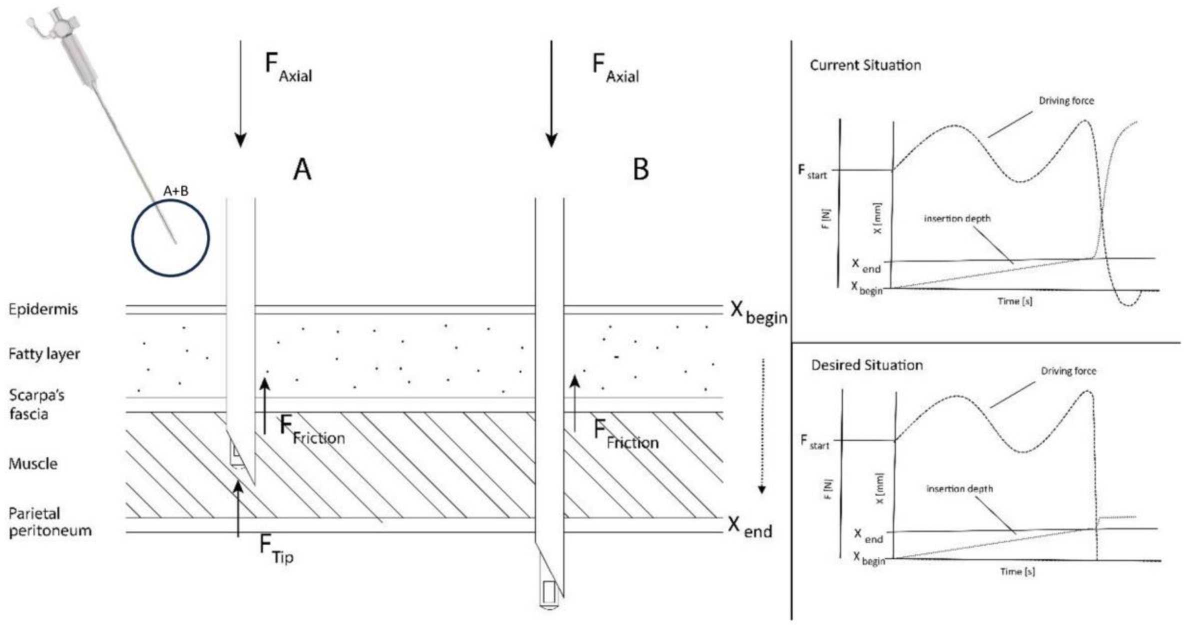


Figure 10. Analysis of the components during overshooting of the needle after reaching the abdominal area. In this load case, the driving force F axial is not immediately removed after passing the last tissue layer with the tip. Figure by Tim Horeman.

Based on the DD-CIA approach, focusing on function expansion of existing components, a new safety mechanism was developed for the Veress needle which decreases the risks of overshooting.

Table 1 helped to identify that the motion characteristics of the inner stylet can be used to decouple the driving force generated by hand and arm inertia. The mechanism works by preventing acceleration of the tip of the needle by decoupling the surgeon's hand from the needle immediately after entering the abdomen.

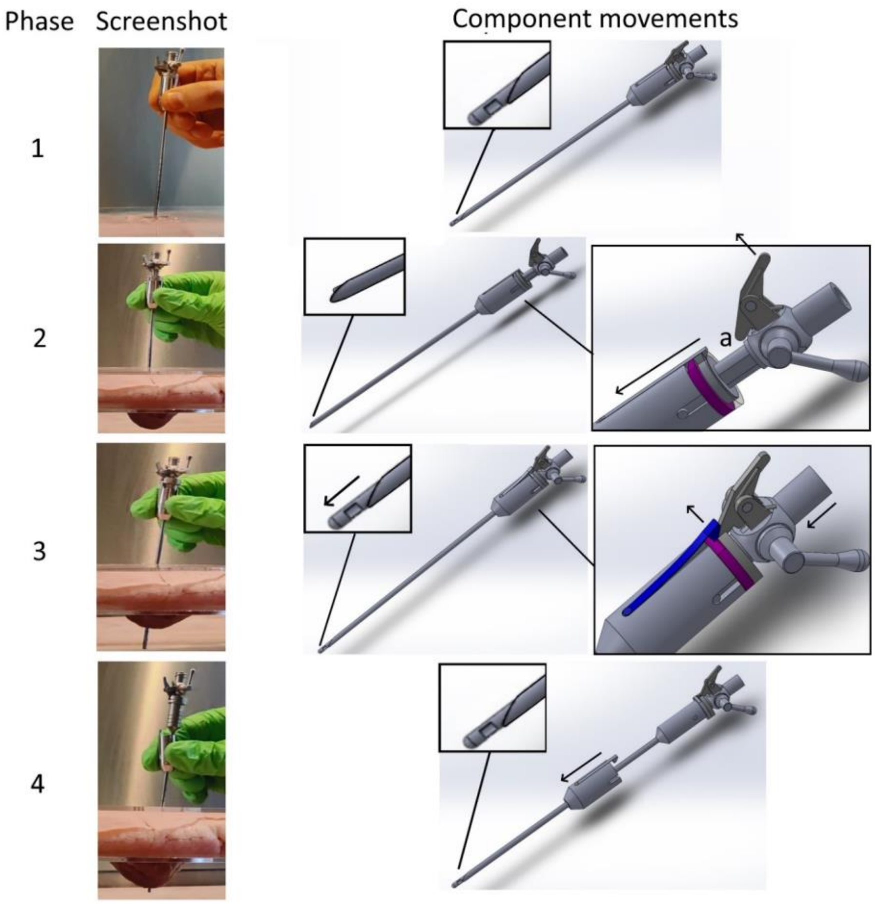


Figure 11. Veress needle PLUS concept with extra safety mechanism that decouples the hand movement from the needle immediately after insertion. The energy in the moving stylet is used for decoupling. [70,17]

In a series of studies, eighteen participants (novices, intermediates and experts) performed a total of 248 insertions in a systematic way with wide- and small-bore versions of the conventional Veress needle and the Veress needle PLUS.[70,71] The insertion depth was measured by recording the graduations on the needle under direct laparoscopic vision. For wider acceptation of the innovation in a lather phase of development, strategic choices can be made to make the experiments as inclusive as possible by comparing as much conditions as possible. In a set of pre-clinical experiments, researchers looked at the general feel of the needles during use in different types of bodies, differences between male and female surgeons, the wear and tear, and different needle sizes. The participants found the procedures conducted with the new needle felt lifelike and agreed that the Veress needle PLUS significantly reduced the insertion depth in all tested conditions. Thus, a completely new safety mechanism was introduced by introducing just three extra parts, by making efficient use of the energy running through the existing design of the standard Veress needle.

70. Postema, R. R., Cefai, Van Straten, B. .... & Horeman-Franse, T. (2021). A novel Veress needle mechanism that reduces overshooting after puncturing the abdominal wall. *Surgical Endoscopy*, *35*(10), 5857-5866.

71. Postema, R. R., Hardon... & Horeman-Franse, T. (2023). Pre-clinical Evaluation of the new Veress Needle+ mechanism on Thiel-embalmed bodies; a controlled crossover study. Experimental research. *Annals of Medicine and Surgery (2012)*, *85*(5), 1371-1378.

Example 7: A cleanroom integrated instrument concept

Airborne particles in the operating room are a concern for both patient and staff. Many complex ventilation systems have been designed to reduce the number of these potentially dangerous particles, microorganisms or viruses inside the operating room (Figure 12, left). However, when trying to execute laparoscopic surgery with an extended range of motion of the instrument handles inside an isolator system, the plastic covering material gives too much friction and limits the surgeon's arm movements.

When following the DD-CIA approach to replace the plastic cover material, it was found to be possible to turn the traditional trocar (e.g. guiding tube for laparoscopic instruments) design into a small, sterile environment around the critical components, instruments and open surgical area, by developing an Isolator System (IS). The system includes a sleeve to protect the instrument shaft and tip and a special balloon to protect the incision and trocar tube[72]. This makes it possible to perform surgery safely inside a non-sterile environment in case a patient is infected with a contagious disease (Figure 12, right).

Within this design direction, the DD-CIA approach shows us that it is important to keep the tip and shaft in the isolator when the instrument is disconnected, allowing the instrument to enter the trocar when the system is locked, ensuring a safe and reliable lock between coupling and ensuring that, when disconnected, both the trocar and the coupling are not leaking. The system works with just a single button that disconnects the coupling, so that the mental load related to instrument handling remains low.

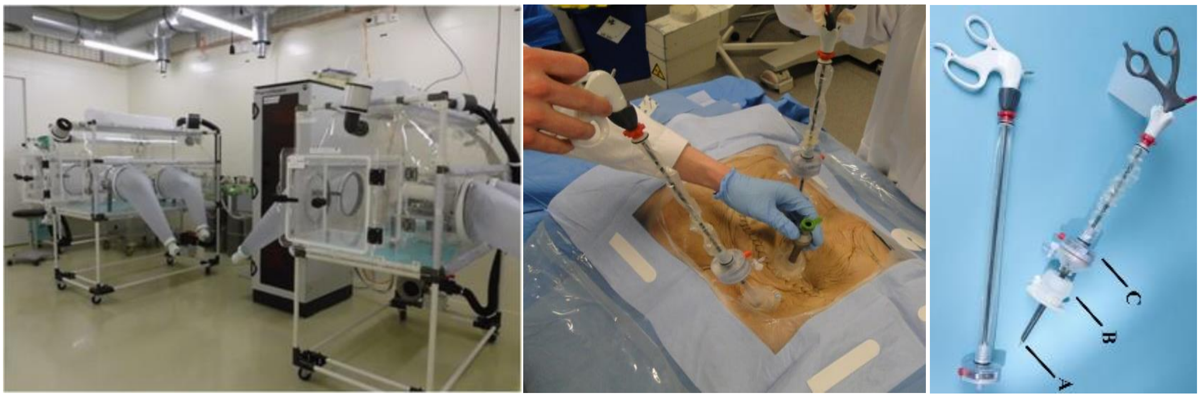


Figure 12. Left: Traditional isolator system for contagious patients. Middle: Instrument with shaft isolator locked on IS-trocars during a laparoscopic procedure. Right: Only when coupled, instruments can pass the IS trocar. A: IS trocar. B: Incision-Port Shield made of silicone. Photo by Tim Horeman.

72. Horeman, T., Jansen, F. W., & Dankelman, J. (2010). An Isolator System for minimally invasive surgery: the new design. *Surgical endoscopy*, *24*, 1929-1936.

When pressing the button to disconnect, the input energy is used to seal off the opening of the now-isolated instrument by expansion of a pin under pressure. Secondly, extra input energy extracted from the same moving button is stored in a deformed spring blade. This energy is used to automatically lock the coupling of the isolated instrument on the trocar after. This simple single button-operated design allows the system to contain up to seven functions by storing and releasing energy in a smart way, ensuring minimal impact on the already complex workflow related to the handing of laparoscopic instruments. Furthermore, this design approach reduces the amount of disposable plastic used by more than 90%.

Example 8: Multifunctional use of gas pressure

Transport of cleaned and sterilized surgical instruments between the sterilization department and operating room takes place both inside and outside the hospital. To make sure that the sterile barrier is not compromised, the instrument tray is packed within a sealed plastic bag; complex sensor mechanisms can be added to measure sterility. Moreover, to ensure that transport boxes are not opened, multiple tie-wraps are used to seal the lid. However, these are time-consuming to remove and generate waste. By removing the sterility sensor and tie-wraps from the system, the DD-CIA approach helped to create a new safe transport container[73] (Figure 13) containing a plastic bag that can be pressurized with sterile air (A) within the cleanroom and can be used for multiple functions. The energy needed to pressurize the bag with gas in the cleanroom is used to form a locking plate (B). When the bag expands, the locking pins (C) move into the corresponding slots (D). This ensures that the lid of the container cannot be removed as long as the instruments are surrounded by sterile air. Moreover, a pressure indicator is created by adding a visual extension on one of the moving parts of the locking plate, allowing a direct observation of the pressure in the box.

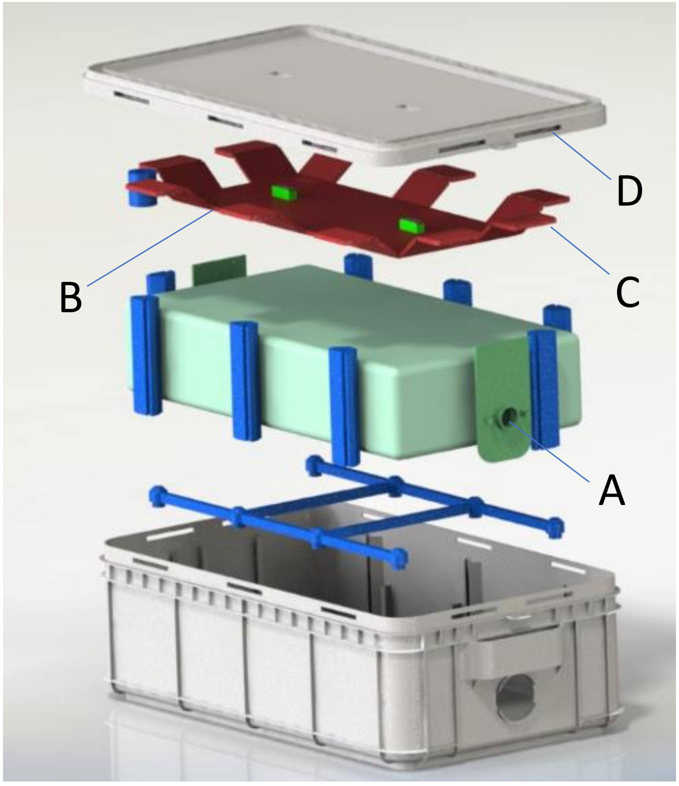


Figure 13. The SteriBox concept. The gas pressure used to create a sterile barrier around processed surgical instruments is used to actuate a locking mechanism that ensures that a box with clean instruments cannot be opened by accident. A: Pressurized gas input. B: Locking plate. C: Locking plate pin. D; Locking plate slot.[73]

73. M. El Mortadi, N. van Straten, T. Horeman, WO2022060222A1, A box for storing and/or transporting surgical items. (2020).

Any loss of pressure due to rough handling results in a change in the visual indicator and a loose lid, providing two indicators that warn the user when the instrument sterility has been compromised. Replacing the disposable sensor and tie-wraps, which both have two individual functions (e.g. indicating contamination and securing the closed lid), by a simple locking plate with pressurized air, the standard transport box not only becomes more sustainable, but also more reliable.

DD-CIA model validation discussion

While using the DD-CIA method in all examples above, it became clear that it is beneficial to describe all functions of all components that cause problems during use of the device in clear technical terms. The examples indicate that a structured design approach with a focus on function expansion of already-existing components often led to interesting new designs. New functions in these designs are fully integrated at minimum costs, resulting in increased sustainability, as the reduction of device complexity by removing system components is always leading. Especially in complex surgical settings, every attempt to reduce complexity increases the chance of successful implementation and adoption by all stakeholders.

In all cases described above, the substantial reduction of components that eventually lead to hospital waste will contribute to a more sustainable healthcare system. For example, the cable-less steering technology allows the instruments to become stronger due to the layered instrument shaft and a much smaller instrument diameter, as there are no cables inside to steer the tip. In this case the DD-CIA design approach worked on multiple levels and ensured a first generation of fully reusable instruments that comply with the guidelines of the FDA in terms of cleanability and inspection, while strongly reducing the number of parts.

The force restrictor needle and force measuring box trainer designs showed that essential new features can be simply cut out of existing components with laser, water or wire cutting relocated outside the intended design framework, by measuring not the grasping force inside the instrument but the reaction force under the training task. Both approaches sharply reduced the complexity in terms of number of parts needed inside the instruments. The Veress needle PLUS and IS trocar designs showed the value of obtaining energy from already moving parts. The moving stylet inside the standard Veress needle was used, with a minimum set of extra components, to trigger an existing mechanism that prevents overshooting in a very reliable way, thus removing the need for very space consuming control devices to limit overshoot like a force-controlled robot arm. The moving button and pin within the IS trocar coupling were equipped with an energy storage spring system that allowed the coupling to lock automatically after being placed correctly above the trocar. Besides leading to very simple designs, the DD-CIA method also directly reduced the interaction complexity by reducing the number of additional systems and interaction/actuation means needed to use a system inside the operating room.

The Steribox concept showed that even gas used to create a sterile field around processed instruments can a constructive component when it is pressurized. Pressurizing the bag just a little more does not require any changes to the already-existing airflow systems as, by nature, pumps always use pressure to create a flow.

This pressure became functional after using it to lift a locking plate mechanism that ensured that the box is always closed when being full and cannot be opened. As a bonus, the pressurized locking plate changes configuration when the inner volume is filled with gas and, in essence, becomes a sensor that directly relates its position to inner sterility. Therefore, this single plate adds two functions within a simple container design.

Besides the impact a design process can make on the costs related to the complexity of a design and the validation and verification process, a significant impact is made on the waste generated by medical devices and in particular disposables. If a more integrated design approach reduces the number of components in a design, less energy is needed for manufacturing of the components and CO_2 emissions will be lower. Moreover, it is likely that fewer parts means that the device will have a lower weight and therefore less mass needs to be incinerated. This adds to the relevance of a smart design process for medical devices.

Main takeaways of this chapter:

- Circular engineering applies to products and processes and can be described as ideas and concepts that solve engineering problems which eliminate waste and pollution, keep products and materials in circulation and regenerates nature.

- The Design-by-Dissection approach helps to fully investigate the impact a redesign solution makes on the complex surgical workflow in order to mitigate risks.

- Using sustainability as a driver to make product designs less complex can be accomplished by using the Design by Dissection strategy by executing a Component Interaction Analysis (DD-CIA).

- The DD-CIA strategy can be used for different types of products and focusses on the possibility of combining functions in single components.

- Functions of components can be seen as energy transmissions defined by combinations of physical actions like force, torque, movements, electricity or light communication. This helps to gain insights into the simplification possibilities of devices.


BARBER SHOP
DRINK
RPM
MOTOR OIL
COVER THE EARTH
SHERWIN WILLIAMS
PAINTS

9

Behind the neurophysiological aspects of sustainability: Neuromarketing and sustainable buying behaviors

New trends in consumer behavior

From the first chapters it became clear that it is essential to create greener products as result of the implementation of more sustainable circular processes. As this topic becomes more important, the marketing power of this kind of terminology from a marketing perspective is increasing. Unfortunately, this can lead to “green” claims that are only made to foster the sales of a product that do not hold any ground from a scientific perspective. The following chapter was written to better understand these phenomena.

The development of the internet and other modern technologies have transformed our lives. The internet has brought down the walls of the world, making a very large offer of services and products accessible to us 24/7, worldwide. Every day, we are seemingly only a few clicks away from millions of products and brands, generating a window of opportunities for us, the consumers.

In time, we have become used to wanting more products, comparing their qualities and characteristics on search engines (e.g., Google shopping), demanding better (usually lower) prices, and sharing our experiences about products and services more widely, e.g. on social media. This all contributes to a society which is more and more characterized by consumption.

While consumption is a generalized process, we cannot presume it is a linear one. It requires a certain degree of adaptation, as not all consumers, companies, sectors and countries are integrated in the system.[74]

74. Vincenzo, G. (2018). New ritual society: Consumerism and culture in the contemporary era. Cambridge Scholars Publishing.

In an ideal world, the increased request for consumption worldwide should benefit both companies and consumers equally. Instead, the growth of consumerism has caused a hyper-competitive environment, which forces firms to manufacture more products than they can sell. To establish a significant local, national or global presence for their brand or products, companies need to find synergies with their customers to scale efficiently and profitably.

It comes as no surprise that the "mortality" of new products is usually very high. According to a recent study, every year about 30,000 new products are introduced to the market, and every year, 95% of them fail to make the cut.[75] In fact, about 75% of consumer goods and retail products make less than $7.5 million during their first year.[76]

This trend is also visible in advertising. Back in 1965, the average buyer was able to remember a major proportion of products and/or ads presented (around 34%); however, a couple of decades later the percentage had dropped to 8%. A survey of 1000 consumers in 2007 found that individuals could remember only a small percentage (2.21%) of ads they had seen throughout their lives.[77] So, the question arises: how can businesses make sense of what consumers need and want in this hyper-competitive environment?

The answer of course lies with the consumers. Understanding consumers' needs and inner desires, and decoding and cracking the shopping behavior consumption code is what companies have aspired to do for a long time. Despite the advancement of modern technologies, many concepts, methodologies and techniques used to study consumer behavior have remained untouched for a long period of time.

For instance, self-reports, surveys and interviews are still the most common techniques used in marketing to investigate consumers' preferences for products and services. However, these techniques provide a limited understanding of why and how people make decisions about product and services.

This is due to how the information is collected, such as asking consumers to explain, describe or recall specific information or experiences they had with a brand, product or service. For instance, consumers might not be entirely aware of their reasons for their answer due to loss of memory or even boredom. Implicit and explicit bias might also be present; for instance, respondents are not always encouraged to give accurate answers, or they might not feel comfortable giving an answer which pictures them in an unfavorable manner.

75. Forbes (2019). Retrieved from: https://www.forbes.com/sites/shamahyder/2019/10/17/how-to-launch-a-new-product-or-service-what-the-latest-research-teaches-us-about-successful-launches/?sh=2c737e7d412a

76. Harvard Business Review (2011). Retrieved from: https://hbr.org/2011/04/why-most-product-launches-fail

77. Lindström, M. (2010). Buyology: Truth and lies about why we buy. Crown Business.

Given the difficulty of achieving competitive advantage using traditional marketing methods, researchers and companies have realized that marketing can benefit from integrating and combining theories and tools from other disciplines. At the beginning of the 21st century, a novel approach arose for studying consumer behavior by integrating neuroscience tools, psychological methods and marketing theories. This has led to the rise of a new and interdisciplinary field of study: Consumer Neuroscience, a.k.a. neuromarketing.[78]

The popularity of neuromarketing has rapidly increased in the last two decades (see Figure 1).

Neuromarketing research focuses on investigating the physiological and neurophysiological mechanisms that support and affect consumer behavior. The application of neuroscience tools to study consumer behavior aims at investigating which physiological and neurophysiological responses are involved and affected while consumers process marketing stimuli. Once these areas are identified, researchers try to associate them with cognitive and psychological processes underlying the consumption process. Compared to more traditional marketing techniques (e.g. surveys), neuromarketing tools can be used to understand implicit processes that are usually impossible to examine due to the unwillingness of consumers to answer questions, or the inability of consumers to explain their own behavior. Thus, the application of neuroscience tools allows marketing researchers to study both physiological and neural processes of consumers' decision-making processes, rather than only psychological mechanisms.

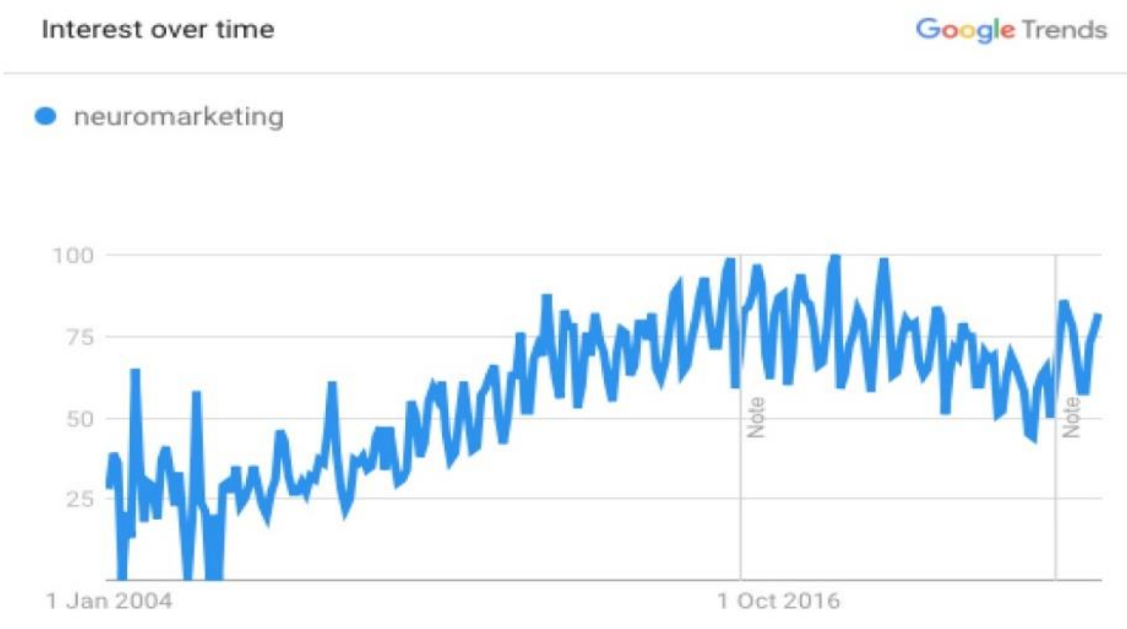


Figure 1. Google Trends data for the keyword 'neuromarketing'

78. Alvino, L., van der Lubbe, R., Joosten, R. A., & Constantinides, E. (2019). Which wine do you prefer? An analysis on consumer behaviour and brain activity during a wine tasting experience. Asia Pacific Journal of Marketing and Logistics, 32(5), 1149-1170.

Neuromarketing tools can be used to support the study of consumer behavior in several context, such as branding, advertising, pricing and product assessment.[79]

Firstly, neuromarketing can help companies study the impact of ads on consumer behavior (e.g., satisfaction, liking) and cognitive processes (e.g., engagement, memory), but also emotional responses (positive or negative). Similarly, neuromarketing tools can help companies to investigate neural processes involved in memorizing a brand's name or logos, but also the reward mechanisms linked to brand loyalty. Neuromarketing tools are also used to study the impact of price on consumers' expectations (positive, neutral or negative).

Finally, neuromarketing tools can be used to analyze how consumers evaluate the quality, design or eco-friendliness of products or services. Neuromarketing aims to understand individual preferences for products and, consequently, understand how and when the human brain processes the information it received about a brand. In fact, certain neural mechanisms can be triggered several milliseconds before the stimulus is presented. This suggests that consumers are often already processing information about a product or service, before being aware of it.

Overall, neuromarketing research focuses on neuronal and cognitive process during marketing-relevant behavior, and in the moment that directly precede or follow such behaviors.[80]

This contributes to building models that improve the predictions of purchasing behavior.[81] However, the type of information that we can retrieve and analyze using neuroscience depends on the type of tools used. The next section describes the neuroscience tools currently used in neuromarketing research.

79. Alvino, L., Pavone, L., Abhishta, A., & Robben, H. (2020). Picking your brains: Where and how neuroscience tools can enhance marketing research. Frontiers in Neuroscience, 14, 577666.

80. Alvino, L. (2018). *Consumer Neuroscience: New directions in predicting consumers' behavior and their preferences for product characteristics*. Doctoral dissertation

81. Plassman, H., V. Venkatraman, S. Huettel, and C. Yoon (2015). Consumer Neuroscience: Applications, challenges, and possible solutions. In: Journal of Marketing Research 52, pp. 427–435.

Neuromarketing tools

There are a variety of tools or methods that can be used for neuromarketing research. These tools can be divided into two classes: physiological and neurophysiological tools.[82] Physiological tools measure the autonomous functions of the body, such as breathing, pupil dilation, sweating, blood pressure and heart rate. Thus, these tools allow us to study all human reactions that originate in the brain, but they do not reflect our brain activity. The autonomous functions of the body are usually not under a person's intentional control; therefore, they cannot be biased like self-reports or surveys. Tools used to measure physiological reactions are eye-trackers (ET), electrocardiogram (ECG), galvanic skin response (GRS) and facial expression recognition software (fEMG) [83] (see Table 1).

An eye tracker is a non-invasive tool that allows measurement of eye movements, fixations and pupil dilation. Eye tracking can be portable (e.g., through glasses) or non-portable (e.g., a bar fixed below a computer screen). Changes in the speed, direction and number of fixations usually provide information about consumers' visual attention and interest and the attractiveness of a product, image or website. Similarly, pupil dilation could provide information about excitement and fear.

Eye tracking outputs results in measurements (maps or paths) of consumers' visual attention behaviors (e.g., heat maps, focus maps and scan paths). Each of these measurements gives different information about where and for how long consumers focus their attention on a stimulus. Eye tracking has several applications in marketing, for instance measuring consumers' preferences for billboards, TV and YouTube videos, or different versions of product packaging or websites. For this reason, eye tracking is a very popular tool in neuromarketing research.

Secondly, the electrocardiogram is a very simple, portable, non-invasive tool which enables researchers to measure the electrical activity of the heart. This tool thus gives information about the emotional state of consumers, as changes in a person's hearth rate may be correlated with increasing levels of stress and/or excitement as a response to certain triggers. Researchers usually use ECGs to measure consumers' arousal or preference for different version of TV commercials or videos.

Thirdly, galvanic skin response is used to measure the electrical conductance and temperature of the skin. This indicates the level of arousal of consumers, as a result of the level of awareness and excitement towards a product or service. Its most common use is in detecting preferences for different versions of movie trailers and social media posts.

Finally, facial expression recognition software is used to match a consumer's facial expression with their emotions, as facial expressions are important codes of emotional reactions (positive, neutral or negative). Thus, this software can be used to measure consumers' emotional reactions to different marketing stimuli, such as preferences for different versions of YouTube videos, and their product experience (e.g., candy testing).

82, 83. Alvino, L., Pavone, L., Abhishta, A., & Robben, H. (2020). Picking your brains: Where and how neuroscience tools can enhance marketing research. Frontiers in Neuroscience, 14, 577666.

Neurophysiological tools can help us identify when and where neural activity in the brain is associated with the ability to perform a particular cognitive task.[84] Thus, these tools can be used to measure cognitive processes involved in product consumption and decision-making process for product or services (e.g., brand recollection). Neurophysiological tools can be divided into two groups: tools that measure electrical activity (electroencephalography), and those that measure metabolic brain activity (functional magnetic resonance imaging).

Electroencephalography (EEG) "is a non-invasive medical imaging technique that records the extra-cellular electrical activity of the brain, generated by the action potentials of neurons".[85] EEG is one of the most-used tools in neuromarketing research as it enables researchers to measure changes in brain activity linked to product preferences, in-store experience or promotion strategies.

Functional magnetic resonance imaging (fMRI) measures the neural activity through the increasing of blood flow and metabolic activity in a specific area of the brain.[86]

Thus, fMRI can detect changes in the brain activity due to the increase in blood flow.[87]

fMRI can be used to study consumer preferences for products, visual stimuli (e.g., specific videos or images), brand preferences and loyalty. fMRI can also be used to study several cognitive phenomena (e.g., engagement, memory, reward and valencies), but it is more expensive and the procedure takes longer than EEG.

Table 1 shows the different tools used in neuromarketing research. *Adjusted from Alvino et al. (2020).*

Tool	Type of tool	Measurements
Eye Tracking	Physiological	Eye movements Pupil dilatation Fixations
Electrocardiogram	Physiological	Heartbeat Blood flow
Galvanic skin response	Physiological	Skin moisture level
Facial expression recognition software	Physiological	Facial expressions
Electroencephalography	Neurophysiological	Brain Activity
Functional magnetic resonance imaging	Neurophysiological	Brain Activity

84. Bunge, Silvia A and Itamar Kahn (2009). Cognition: An overview of neuroimaging techniques. In: Encyclopedia of neuroscience 2, pp. 1063– 1067.

85-86. Bhang, P. A, B. W. Gawali, and S. C. Mehrotra (2016). Introduction to EEG-and speech-based emotion recognition. Academic Press.

87. Buxton, R. B. (2013). The physics of functional magnetic resonance imaging (fMRI). Reports on Progress in Physics, 76(9), 096601.

Neuromarketing and sustainability

Our planet's sustainability and its preservation have become important issues. Nowadays, significant efforts are made to promote sustainable consumption by increasing the production of green products and services (e.g., pesticide-free products, reusable, etc.) and generating more government supports and tools (e.g., education, subsidies, taxes, communications campaigns). In the past few decades, these policies have had direct or indirect effects on how consumers make decisions about products and services. On the one hand, companies are pushing green products and services into the market to attract the attention of customers and being more sustainable in their missions. On the other hand, consumers' increased awareness about sustainability is forcing companies to act upon these issues, meaning they have to show more commitment to sustainability and more transparency (e.g., tracking all the steps of a product's life cycle) and accountability (e.g., how organizations acknowledgement responsibility for their actions, decisions, etc.) about their environmental impact.

Transparency and accountability are particularly important for consumers in order to avoid greenwashing or propaganda.[88] Greenwashing can be the result of intentional or unintentional false claims or misleading information about green product/services or a company's overall commitment towards sustainability. Thus, companies must gain insight into the decision-making process and behavior of consumers towards sustainability issues.[89]

Thus, companies, as well as governments, alike aim to understand:

Which factors affect sustainable consumption? What actions are consumers taking to develop a more sustainable lifestyle? Which consumers are more sensitive to greenwashing activities? How can consumers recognize greenwashing propaganda?

Despite the increased use of new and more sophisticated technologies to promote and distribute product and services, self-reports, surveys and interviews are still the main ways of studying how consumers assess the environmental actions of companies and approach sustainable consumption. As discussed before, these tools have limitations, as consumers are often reluctant or incapable to explain their choices about products or services. Instead, applying neuroscience techniques can help understand the cognitive and emotional aspects involved in sustainable behavior and green actions.

88. Gopalakrishnan, R. (2012). Accountability, Transparency and Sustainability in Governance: Can Rural Broadband be a Game-changer?. IIM Kozhikode Society & Management Review, 1(1), 51-54.

89. Dangelico, R. M., Alvino, L., & Fraccascia, L. (2022). Investigating the antecedents of consumer behavioral intention for sustainable fashion products: Evidence from a large survey of Italian consumers. *Technological Forecasting and Social Change*, *185*, 122010.

Neuromarketing supports existing marketing theories by identifying hidden mechanisms or unconscious processes that drive consumption and purchasing behavior for green products (e.g., coffee, clothing).[90] Neuromarketing tools can help understand which brain areas are active during product assessment and evaluate cerebral activation in the presence of environmental elements (e.g., message, tag). Thus, they can identify when and how implicit biases and unconscious processes steer "rational" decision-making processes.

A specific application of neuromarketing tools in sustainability could be to identify how individuals' environmental bias affects cognitive processes (e.g., memorizing logos), emotions (e.g., high or low excitement for sustainability) and decision-making. Consumers more sensitive to environmental issues might behave differently than those not predisposed to sustainable consumption behaviors. Using neuroscience tools, we can test if these ideological dissimilarities can produce diverse physiological responses and changes in our brain activity.[91]

Hence, it might help identify the relevant psychological and neural mechanisms that explain sustainable conception and pro-environmental behavior.[92]

For instance, one neuromarketing experiment shows that green consumers (e.g., people who try to protect the environment by selectively purchasing green products or services) have dissimilar brainwave responses as non-green consumers when exposed to green products. Using EEG, researchers measured an increase in the brain activity (frontal areas) of green consumers in response to environmentally-friendly advertisements and products,[93] e.g., higher levels of delta, theta and beta waves (Figure 2).

90-91. de Quevedo, A. S., Quevedo, D. M., Figueiró, P. S., & Fernandes, E. K. (2020). Neuromarketing as an Environmental Awareness Tool: The Sustainable Consumption. Anthropological Approaches to Understanding Consumption Patterns and Consumer Behavior, 404-426.

92. Leeuwis, N., van Bommel, T., & Alimardani, M. (2022). A framework for application of consumer neuroscience in pro-environmental behavior change interventions. Frontiers in human neuroscience, 16, 886600.

93. Lee, E. J., Kwon, G., Shin, H. J., Yang, S., Lee, S., & Suh, M. (2014). The Spell of Green: Can Frontal EEG Activations Identify Green Consumers? Journal of Business Ethics, 122(3), 511–521. doi:10.100710551-013-1775-2

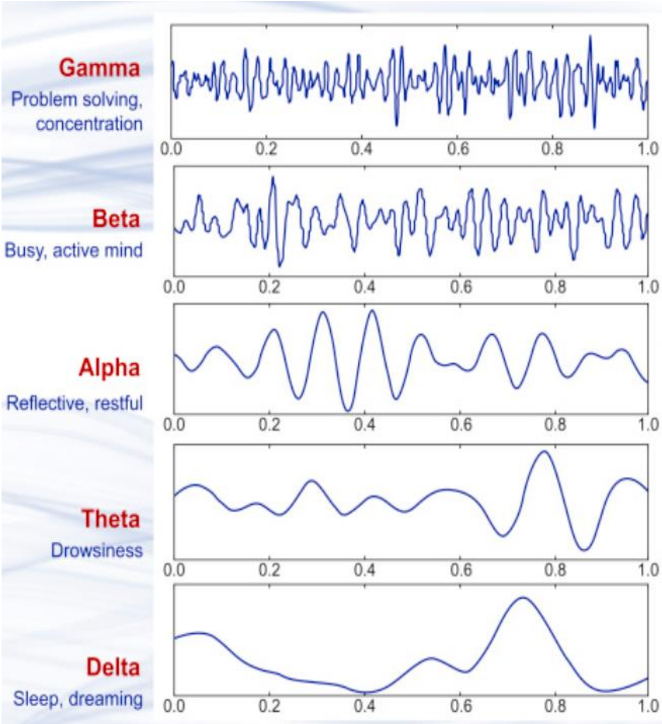


Figure 2. Different types of brainwaves, representing different emotions. From Abhang (2016)[94]

Neuromarketing tools can also be used to maximize the effectivity of "green" advertisement and to encourage sustainable consumption. We can use these tools to assess how distinctive ads and messages are processed by consumers (e.g., positively or negatively). When designing an advertisement for green products, we need to consider how different types of messages will trigger distinctive emotional responses. For instance, messages designed with a gain-frame (i.e. they emphasize the benefits, e.g., "*if don't buy fast fashion, you won't pollute our planet*") are usually found to be more effective than messages designed with loss frame (i.e. they emphasize the costs, e.g., "*if you don't buy natural products, you won't help yourself stay healthy*").[95] This suggests that companies should focus on defining the best frame to effectively convey messages to their audience.

Finally, neuroscience tools can help manufacturers and retailers to define how to anticipate on sustainable consumption. In fact, neuroscience tools and methods can be used to nudge consumers into behaving more sustainably. For instance, retailers can influence consumer behavior by providing relevant information about the eco-friendly nature of their products, by expanding the number of "green" products on offer, and by putting eco-friendly products in prominent places in the store.

94. Abhang, P. A. (2016). Chapter 2-Technological Basics of EEG Recording and Operation of Apparatus (PA Abhang, BW Gawali, & SCBT-I. to ES-BER Mehrotra.

95. Fiestas, M. M., Viedma, M. I., Fernández, J. S., & Rios, F. J. M. (2015). A Psychophysiological Approach For Measuring Response to Messaging How Consumers Emotionally Process Green Advertising. Journal of Advertising Research, 55, 192-205.

Tools like eye tracking can be used to measure consumers' visual attention to green products in the store. In fact, the positioning of a product and the type of information displayed can affect how consumers look and select products in a store. Neuromarketing research finds that higher visual attention mechanisms to green products are connected to higher willingness to pay a premium for these products.[96]

In addition, studying visual attention helps defining which information or elements impact how consumers choose green products. For instance, the color green can affect a consumer's visual attention mechanism, due to its association with the natural or organic properties of a product. Thus, anything that is green (e.g., price tag, label) should help consumers to easily spot sustainable products.

However, companies might also use colors to trick consumers into believing they are buying sustainable products, even when they are not (a.k.a. greenwashing). A neuromarketing study found that these greenwashing practices might considerably reduce visual attention towards "real" green products.[97]

Additional point-of-purchase (PoP) information about the type of product (fair-trade, organic, etc.) can be used to signal green products to consumers. Using eye-tracking, we can measure how easily consumers spot PoP information. PoP information influences a consumer's visual attention towards green products. On average, consumers spend more time looking at green products if PoP information is present than when it is absent. Based on this, neuromarketing shows how retailers could use both colored price tags and PoP information to signal green products to consumers and give additional information about these products. By orienting consumers' visual attention towards these green products, retailers can nudge consumers to acknowledge and eventually buy these products. These actions should be aimed to support consumer choices about green products and prevent greenwashed practices that obstruct consumers from finding green products.

Overall, joint efforts of individuals and companies alike to be more eco-friendly and sustainability-minded can help the preservation of environmental resources and ensure a better quality of life for us and the planet at large. In the last two decades, advances in neuroscience tools have led to neuromarketing, a new approach to study sustainable consumption and green behavior.

96-97. Guyader, H., Ottosson, M., & Witell, L. (2017). You can't buy what you can't see: Retailer practices to increase the green premium. Journal of Retailing and Consumer Services, 34, 319-325.

Neuroscience tools like EEG, fMRI, ET, ECG, GSR and fEMG can be used to develop green marketing practices and strategies. These tools can offer us different insights into how green messages, product characteristics and displays affect consumers’ preferences and buying behaviors. Neuroscience tools in sustainability issues can be applied to three different areas:

1) understanding consumer individual differences
2) improve green advertisement effectiveness and
3) nudging sustainable consumption behaviors.

Both manufacturers and retailers can play an important role in driving consumers towards sustainable practices, and neuroscience is the “secret weapon” that can help shaping sustainable consumption behavior.

Main takeaways of this chapter:

- General consumption habits and challenges for companies have changed over the past decades due to the internet and other modern technologies.
- Neuromarketing is a new field of study at the intersection of three disciplines: marketing, neuroscience and psychology.
- Neuroscience tools can be divided in two categories based on the type of measurements: 1) physiological and 2) neurophysiological.
- There are several neuroscience tools used in marketing research, such as EEG, fMRI, ECG, ET, GSR and fERS.
- Neuromarketing tools can be used in several marketing domains, such as advertising, branding, pricing, product development and user experience.
- Neuromarketing can be used to study sustainable consumption and green behaviors.
- Neuromarketing can be applied to three different areas: 1) understanding consumer individual differences, 2) improve green advertisement effectiveness and 3) nudging sustainable consumption behaviors.


Nattraby
Pressen

10

Reflection

The population on our planet has grown tremendously: from one billion humans in 1800 to over 8 billion in 2022. As a result of this large growth, the amount of greenhouse gases emitted by human activities - especially carbon dioxide - has grown as well.

The golden age of capitalism in the post-war period led to global expansion of economic growth and globalization. Growing wealth in combination with the rapid growth of the population resulted in a mass consumption society. The economy worked with a linear model based on a “make – use – dispose” principle.

After decades of severe natural resource depletion, it was realized that this linear model is not sustainable. In its place, the circular economy was introduced, based on the “make – use – reuse” model. In this system, the product life cycle is extended and waste is minimized or reused.

Hospitals use a standard way of working, focused on single-use products. Therefore, it is a challenge to implement circular strategies. Concepts such as ‘pay-per-use’ or sharing of capital goods between hospitals, or reuse, product repair, maintenance and refurbishment, are rather often not (yet) considered in the healthcare sector.

Climate change as a business case can lead to cost reduction, new business opportunities and better protection of the earth’s ecosystems. Urban mining may provide a growing harvesting resource, where materials are not mined underground, but from stocks above the ground. From this perspective, the operating room can be considered a goldmine of valuable raw materials.

Yet, a circular healthcare economy is possible, as this book has aimed to show. The circular healthcare economy aims to reduce hospital waste streams by defining specific waste as new resource material and remove them from the waste flow before incineration (Figure 1). More and more evidence for this kind of reprocessing technology foster the circular healthcare economy as a movement followed by a growing interest around the world for new circular business models. This was the starting point of the new “Hospital Mining™” movement.

Figure 1. The operating room at Maasstad Hospital, Rotterdam, the Netherlands. The OR offers valuable materials such as high-quality polypropylene, PET and stainless steel 304 and 316 that can be urban mined. Photo by Jeronimus van Pelt.

The circular model builds economic, natural and social capital on three principles, driven by the three design principles: [98]

- Eliminate waste and pollution.
- Circulate products and materials (at their highest value).
- Regenerate nature.

The circular economy is an opportunity to solve many challenges. It is a method to combat climate change and realize growth of the economy at the same time. New circular business models will emerge which will introduce sustainable solutions, create jobs, develop new technology and create ecological stability.

The leaders of tomorrow need to embrace circular economy principles, create new ideas, refuse polluting products and processes, develop sustainable technology, start new projects, connect with others and inspire people to take action.

98. Ellen McArthur Foundation. 2023. What is a circular economy? Retrieved from: https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Change is needed. In the new circular economy, materials will never become waste or pollution, whether they are plastics or metal-based materials. Circular design will ensure that the new products are reusable, re-manufacturable, recyclable, or compostable.

Using circular engineering to design out waste in our future products and processes will help to eliminate waste and pollution and keep products in circulation. The circular engineering principles can be applied in future designs with circular strategies such as reuse, repair, remanufacturing and finally recycling for both products and processes.

Specific design methods, guidelines and strategies like the DD-CIA methodology can be created for the design and re-design of products that do not comply anymore to the changing world. The sooner sustainability becomes part of any creative phase within a design approach, the more likely it has a larger effect on the environment during the product's lifetime.

Consumer behavior is changing towards increased sustainable solutions, creating greater support for circular design. We can use neuromarketing to study sustainable consumption and stimulate "green" behavior.

In addition to raising public awareness and developing new sustainable technologies, it is highly important to anchor circular engineering in our educational system and to teach the managers and politicians of tomorrow how they can apply circular strategies. Whether or not we want to be circular is a choice. Technically, it is possible to have an entirely circular economy. Whether you are an engineer, policymaker, hospital staff member, student or industry representative: look for the opportunities that circular economy can bring and apply the principles in your daily practice.

If we combine our efforts to take action, we can support the next generations by designing sustainable products and processes which make the world more circular.

Why should we apply circular economy principles?

Everyone seems to be talking about sustainability. But why should we care? Is it because we feel guilty? Because we have to hand over the world properly to our children? Are we doing it for our own peace of mind? Or does it provide new products and services from which we can earn?

It's about us having a choice. A choice to be sustainable or not. From the philosophical perspective, making choices gives us freedom and freedom makes us think. Aristotle argues that making choices contributes to character building. And that characterizes us as authors to fully commit to sustainability and circular principles.

We acknowledge, just like the Ellen MacArthur Foundation, that the current take-make-waste industrial model is no longer sustainable. It should be replaced by a circular economy which aims to redefine growth and aim to realize positive society-wide benefits with less waste. We quote the Ellen MacArthur Foundation by stating that circular "economy principles" entails gradually decoupling economic activity from the consumption of finite resources, and designing out waste from products and processes". This should be supported by a transition to renewable energy sources.

For the authors, this is a vision in which they believe. A vision that can be realized in collaboration. A collaboration between governments, industry, hospitals, consumers and science ideally directed by Academia and education. Academia (Figure 2) should play a leading role in this development through research and education. Circular economy principles offer a range of benefits that make them highly valuable for both the environment and the economy. Some compelling reasons to adopt and promote circular economy principles are:

Resource Efficiency: The circular economy aims to minimize waste and optimize the use of resources by promoting practices such as recycling, refurbishing and remanufacturing. This reduces the need for extracting raw materials and prevents resource depletion.

Waste Reduction: Circular economy principles prioritize reducing waste generation, landfill usage and incineration. By designing products with longer lifespans and encouraging repair and reuse, less waste ends up in landfills or in incineration, reducing environmental pollution.

Environmental Preservation: By keeping products and materials in use for longer periods, circular economy principles help to mitigate environmental degradation, including deforestation, habitat destruction and pollution. This contributes to the preservation of ecosystems and biodiversity.

Climate Change Mitigation: Circular economy principles reduce the need for energy-intensive processes involved in extraction, manufacturing and disposal of products. It also lowers the greenhouse gas emissions that are associated with waste management.

Economic Growth and Innovation: Circular economy principles can stimulate economic growth by creating new business opportunities in areas like recycling, refurbishment and remanufacturing. It fosters innovation in product design, materials and manufacturing processes.

Job Creation: Circular economy practices can lead to the creation of new jobs in various sectors, such as recycling facilities, repair shops and design firms focused on sustainable products.

Resilience to Supply Chain Disruptions: A circular economy reduces dependence on scarce or volatile raw materials, making supply chains more resilient to disruptions caused by factors like geopolitical tensions or natural disasters.

Consumer Engagement: Circular economy principles encourage consumers to be more conscious of their consumption patterns, promoting responsible purchasing decisions, repair and reuse. This can lead to a shift towards a more sustainable consumer culture.

Reduced Environmental Pollution: Circular economy practices help minimize pollution caused by waste disposal, landfill leakage and incineration, which can have detrimental effects on soil, water and air quality.

Long-Term Cost Savings: Circular economy practices can lead to cost savings for businesses through reduced material procurement and disposal costs, as well as energy savings from more efficient resource use.

Regulatory Compliance and Reputation: As governments and consumers increasingly demand environmentally responsible practices, adopting circular economy principles can help businesses comply with regulations and enhance their reputation as sustainable and socially responsible entities.

Global Sustainability Goals: Circular economy principles align with various global sustainability goals, such as those outlined in the United Nations' Sustainable Development Goals (SDGs), including responsible consumption and production, climate action and preservation of life on land and below water.

Circular economy principles offer a holistic and forward-thinking approach, promoting a more sustainable, resilient and equitable future for current and future generations.

Figure 2. Industry participation in education and research: TU Delft students presenting their new sustainable product designs in front of an expert jury panel. The next generation are the future leaders of circular design. Companies may facilitate this by offering their facilities and input on student projects. Photo by Bart van Straten.

Author’s notes

By Bart van Straten

Writing this book was of a personal nature. An eye-opener for me was a special day with my children and the Dutch astronaut Andre Kuipers. An afternoon was organized by my children's primary school. We had arranged the location and were therefore an hour earlier, just like Andre Kuipers. It was breathtaking to observe how Andre explained to my children about his stay in the International Space Station ISS. He shared his experience in a special way, describing how fragile the atmosphere looks at an altitude of 400 km comparable to an egg and its shell. A moment when I realized that we borrow the Earth from our children and we owe them to take action. Another memorable moment was on June 18, 2018, Bruno, Minister for Health, Welfare and Sports, received an instrument mesh basket from me. We had made this instrument basket, partly from recycled stainless steel. What I couldn't foresee at the time was the impact this handover would bring. In fact, this moment can be seen as the start of my research period, a Field Lab and integration of circular economy principles in education.

By Letizia Alvino

"Unlocking the potential to change the world commences from within, catalysed by a single neuron, nurtured by a solitary thought, and propelled forward with each deliberate step." What motivated me to write about sustainable consumption is the unwavering belief in the unexploited potential within each of us to address the pressing sustainability challenges of our time. As a consumer, a pivotal awakening occurred during a chilly winter in Italy when I embarked on what I thought was a simple quest to find a pair of trousers made from ethically sourced wool. The journey revealed the formidable obstacles that stand in the way of sustainable choices in our everyday lives. Despite the best intentions and deep motivation, sourcing clothing crafted from organic, natural fabrics proved a formidable challenge. As a researcher, I have dedicated years to unravelling the complexity of factors influencing sustainable consumption. This book bridges the two worlds I have inhabited—the world of consumers striving for ethical choices and the world of researchers seeking to understand the intricate mechanisms that shape those choices.

By Tim Horeman

Although I am working on the prevention of surgical disposables by using sustainable design principles to create more modular reusable alternatives since 2015, the real intrinsic motivation to do something against the linear healthcare economy came during covid times in April 2018. After developing a reprocessing and testing method for FFP2 face mask when the market was collapsed and surgical procedures were postponed due to safety risks, our team in Utrecht received thousands of masks per day, which were send to us, for reprocessing. When Boxes, containers and bags were stuffed with used Personal Protection Means (PPM's) and brought or send to us from all corners of the Netherlands, we realised that all this material that was filling our reprocessing facilities was normally incinerated. From every 100.000 FFP2 face-masks that were send in, only 25.000 appeared good enough for reprocessing while the rest needed to be disposed.

This enormous increase in waste that now moved from the hospitals and other caretakers to our team in Utrecht needed to be addressed and forced us to investigate responsible possibilities to deal with this waste stream in a sustainable way. Amongst others, this led to the new mechanical Polypropylene reprocessing and testing methods and facilities for surgical (blue) wrap that is made from the same kind of materials.

General notes:

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 or are even outdated. Furthermore, we 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.

Creating a circular healthcare economy

Circular strategies for a sustainable healthcare

Our world is the only planet, as far as we know, which harbors life. The number of humans on our planet has grown tremendously. In 1800 one billion humans occupied our earth; on 15 November 2022, this number reached 8 billion. After the Second World War humanity witnessed gigantic global economic development with great technological improvements. A result of this growth, the primary greenhouse gasses emitted by human activities drastically increased. As the economy developed, our consumption grew apace. In this book, Van Straten, Alvino and Horeman present their findings on creating a sustainable healthcare economy by introducing different circular strategies. In 9 chapters, they present a wide variation of studies as practical cases to show what strategies and actions can be taken to implement sustainable strategies for a circular healthcare.

This book was written in line with the courses they developed at TU Extension School, the open online education edX platform of Delft University of Technology/ TU Delft. A leading university in science and technology and recognized for conducting world-class research. This book is a manual for everyone who follows the online courses ‘Circular strategies for sustainable healthcare’ but certainly also for those who want to discover more about circular strategies, the principles and practices of the circular economy and urban mining. This book is suitable for students, researchers, policymakers, and practitioners in the fields of healthcare sustainability, management, business and economics

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.

Letizia Alvino is an expert on neuromarketing and is affiliated with the Faculty of Behavioural Management and Social Sciences at the University of Twente.

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.

TU Delft

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Cover image disposed single-use medical instruments by B. van Straten