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Carbon footprint reduction of the operating room: tools to mitigate the environmental impact of surgical practice

Friedericy, H.J.

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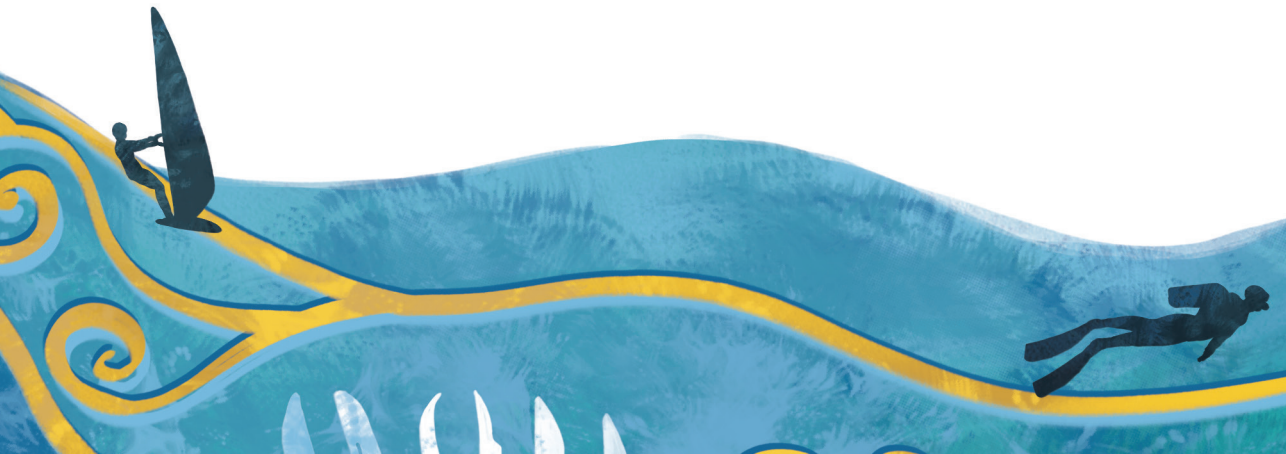
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CHAPTER 8

**General Discussion, Future
Perspectives and Conclusion**



General Discussion

Our research has focussed on the low-hanging fruit, sources of greenhouse gas (GHG) emissions that have the greatest impact on the carbon footprint of the OR. In doing so, we are contributing to the WHO goals of increasing environmental sustainability in healthcare facilities and the Dutch Green Deal 3.0 goal of reducing GHG emissions in healthcare by 55% by 2030 and becoming climate neutral by 2050.^{1,2}

The results are discussed in the framework of the GHG Protocol, which divides emissions into three scopes: direct emissions (Scope 1), indirect emissions due to energy consumption (Scope 2), and indirect emissions due to procurement of goods and waste generation (Scope 3) (Figure 3, Chapter 1).³ Part II of this thesis allows us to distil twelve practical solutions for reducing carbon emissions in the OR. Therefore, we used the evidence-based mitigation measures from the SCALE auditing tool in **Chapter 7** and the results of the HSMEA (**Chapter 6**) to discuss carbon footprint mitigation strategies for the OR. To this end we used the 10R Framework, a model for transitioning from a linear to a circular economy based on hierarchical measures.⁴ This comprehensive model is a refinement of the 3R concept (Reduce, Reuse, Recycle) to preserve value in a circular economy. The 10R Framework has three main objectives: avoiding waste, extending product life and recycling waste, listed here in order of preference. Figure 1 shows which R strategies lead to these three main objectives and explains the strategies. Finally, in the chapter on future perspectives, we will discuss follow-up questions arising from this thesis and indicate the direction in which OR sustainability research should proceed.



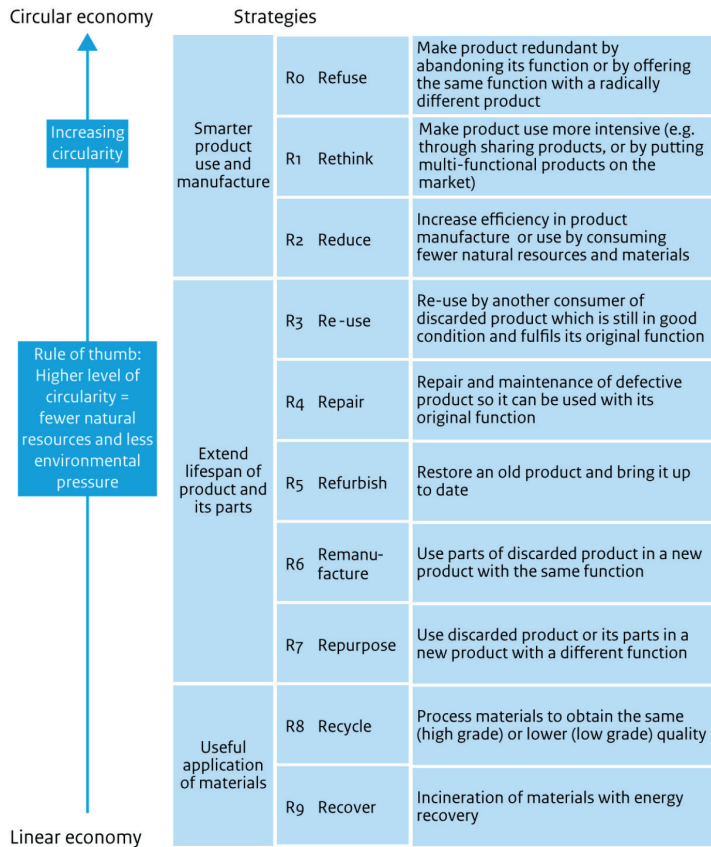


Figure 1. 10R strategy to increase circularity⁵ The higher the strategy is on the ladder, the higher the degree of circularity.

Main results

In Part I of this thesis, reduction of the major determinants of Scopes 1, 2 and 3 of the OR are investigated: inhalation anaesthetic use, energy consumption due to air treatment, waste generation resulting from widely used sterilisation packaging material for surgical instruments and in addition the reduction of the carbon footprint of an aortic valve replacement procedure.

Our results show that direct emissions from volatile anaesthetics (VAs) (**Scope 1**) in the Netherlands are relatively low due to the fact that desflurane is hardly used and that 70% of Dutch anaesthesiologists use propofol as their first choice for general anaesthesia.

However, we did observe that nitrous oxide remains a significant source of Scope 1 emissions, despite there being much less need for its clinical use.

Indirect emissions resulting from energy consumption (**Scope 2**) account for 35% of the carbon footprint of an aortic valve replacement in our study, due to HVAC, sterilisation and electronic devices. In our findings into surgical site infections (SSI) in open heart surgery, the use of an energy-efficient TMA airflow system does not lead to more sternal wound infections or mediastinitis compared to the use of a high flow UDAF airflow system.

The LCA on aortic valve replacement shows that, regardless of the method used, more than 50% of the carbon footprint of these procedures is attributable to single-use items (**Scope 3**). Our LCA of packaging methods for surgical instruments shows that replacing blue wrap, a major contributor to OR waste, with rigid reusable containers reduces the carbon footprint of sterilisation packaging by 85%.

The practical tools presented in Part II of this thesis provide data on where and how to reduce the carbon emissions of the OR. The HSMEA presents a structured way to reduce emissions and is easily applicable in practice for a variety of surgical procedures (**Scope 3**). The SCALE auditing tool for OR complexes demonstrates that just six of the eighteen evidence-based interventions implemented together in Dutch ORs account for 95% of the model's calculated carbon footprint reduction potential of 730 kg CO₂-eq/week/OR (Figure 3, Chapter 5) (**Scopes 1,2, and 3**).



Interpretation of main results and mitigating 'R' strategies

Scope 1

Volatile anaesthetics

Volatile anaesthetics are potent GHGs and responsible for 0.004% of all GHG emissions emitted globally each year.⁶ In **Chapter 2** our results show that annual emissions from VAs in the Netherlands with 0.22 kg CO₂-eq/capita are relatively low. The average per capita emissions of VAs in 2023 for all high-income countries was 1.03 kg CO₂-eq/capita, with Japan and South Korea at the top of the list with 2.51 and 2.28 kg CO₂-eq/capita respectively.⁶ Desflurane, with a global warming potential measured over 100 years (GWP₁₀₀) of 2,540 greater than CO₂, accounted for 70% of total global VA emissions.

Our 2019 bottom-up consumption data showed that only 4.1% of the purchased volume of VAs in the Netherlands was desflurane. Worldwide, the use of desflurane is considerably higher, particularly in countries with high incomes.⁶ Awareness among anaesthesiologists of the harmful effects of desflurane has already led to a reduction of GHG impact due to desflurane of 52% over the past 10 years in these high-income countries. However, a trend was observed whereby middle- and low-income countries actually showed an increase in GHG impact due to desflurane in that period.

Internationally, steps have already been taken to phase out desflurane (*Ro, Refuse*), with the EU strictly limiting its use from 2026 onwards. Given its more favourable overall risk-benefit ratio, it is preferable to choose sevoflurane over desflurane if inhalation anaesthesia is opted for.⁷ Simulations have shown that if anaesthetists worldwide had used only sevoflurane as VA, global GHG emissions from VAs would have fallen by 73% over the past decade.⁶

Choosing propofol over VA for general anaesthesia by anaesthesiologists will reduce Scope 1 emissions (*R3, Reduce*). Unlike VA, the intravenous anaesthetic propofol has virtually negligible GHG emissions.^{8,9} Our results of **Chapter 2** show that 70% of anaesthesiologists in the Netherlands prefer the intravenous drug propofol as their first-choice agent for general anaesthesia, which partly explains the relatively low GHG impact of inhalation anaesthetics in the Netherlands compared to other countries.

When using VA, it is not only important to opt for sevoflurane instead of desflurane, but also to use sevoflurane responsibly (*R3, Reduce*) in order to limit its GHG impact. Two important technical developments are available for this purpose: automated low flow target administration (Et Control) and vapour capture technology (VCT). The former ensures economical administration of VA, while the latter allows part of the exhaled sevoflurane to be captured before it is vented into the atmosphere.^{10,11} In **Chapter 7**, we used the SCALE auditing tool to show that VCT, the capture of VA before it enters the atmosphere, is the second most important factor in reducing the carbon footprint of Dutch ORs. Once VAs have been captured, it is technically possible to recover them (*R8, Recycle*) for re-use in humans which is already permitted under the regulations in Canada, Austria and Germany.¹¹ Although the technique undoubtedly has potential, there is currently controversy in the literature about how much of the administered VA can be recovered. Future multi-centre studies will have to demonstrate its value in daily practice.¹¹

We believe that there is no longer any place for desflurane in anaesthetic practice, but that sevoflurane should remain part of the anaesthesiologist's armamentarium, as the intravenous drug propofol is the only other option available for general anaesthesia. In this context, we have to consider that during the COVID-19 pandemic, a shortage of propofol occurred, and it became clear that an alternative was needed. In addition, the administration of VA requires a unique expertise in daily practice that would otherwise be lost to future anaesthesiologists. When sevoflurane is chosen for general anaesthesia, it is mandatory that administration takes place via Et Control administration and that VCT is used to capture sevoflurane, so that the amount released into the atmosphere remains minimal. Manufacturers must equip their ventilators with these modifications as a standard feature.

Nitrous oxide

Although there is a decreasing need for anaesthesiologists to use nitrous oxide (N_2O), its low potency, which means it must be administered in high concentrations, combined with its atmospheric lifetime of 109 years and resulting GWP₁₀₀ of 298, makes it a significant source of medically attributable GHG emissions. Exact figures are not known, but rough estimates suggest that 1-3% of global N_2O emissions originate from healthcare.^{12,13} This would correspond to 0.1% of total global GHG emissions, which is 25 times the above-mentioned figure for VAs.¹⁴ In accordance with these estimates we found in **Chapter 2** that emissions of medical N_2O in the Netherlands were twice as high as those originating from VAs. These figures correspond to countries such as Ireland and Austria, where N_2O accounts for more than 80% of emissions due to inhalation anaesthetics.^{15,16}

Phasing out (*Ro, Refuse*) N_2O from the anaesthesiologist's armamentarium would be an effective measure to reduce the carbon footprint of the OR. For the administration of general anaesthesia, N_2O has traditionally been used in combination with older VAs to reduce their side effects and speed up induction and recovery. However, with the introduction of sevoflurane in the 1990s, this role of N_2O became redundant. Furthermore, a recent study demonstrated that the use of N_2O had no effect on post-operative mortality or most morbidity outcomes.¹⁷ In addition, it has become clear that widespread large-scale losses of N_2O occur due to leaks in centralised systems which can be prevented by using portable cylinders (*R2, Reduce*).¹⁴

Societies for Anaesthesia must make it clear to their members that N_2O is obsolete in modern anaesthesiology practice, and hospitals must ensure that N_2O connections in operating rooms are dismantled to prevent accidental leaks.



Scope 2

Energy consumption in ORs is high due to the stringent requirements for air quality and the extensive use of electronic equipment. A recent systematic review of the carbon footprint of surgical procedures demonstrated that energy consumption (together with anaesthetic gases) was the main source of GHG emissions.¹⁸ However, the environmental impact of Scope 2 emissions is highly dependent on the type of electricity used. Moving away from (*Ro, Refuse*) electricity generated by burning fossil fuels has a major impact on reduction of the carbon footprint of the OR. In **Chapter 7**, we demonstrated that more than 90% of the calculated reduction potential of Dutch hospitals could be achieved if only energy from renewable sources was used.

Air treatment by HVAC systems accounts for 90-99% of energy consumption in operating rooms.¹⁹ However, these systems often consume energy unnecessarily when they are left on after working hours or when they are not in use during the day. Our results in **Chapter 7** show that applying HVAC setback strategies during unoccupied periods is one of the five most effective evidence-based measures for reducing the carbon footprint of the OR. Setback strategies are an accepted method of reducing energy consumption (*R2, Reduce*).²⁰ Research has shown that this energy-saving strategy can reduce energy consumption by up to 70%.^{21,22} Also in **Chapter 7**, we demonstrate that heat recovery (*R3, Reuse*) from the exhaust air of the HVAC is an important evidence-based method for reducing the carbon footprint of the OR. Fresh outside air is drawn in by a HVAC system and then conditioned (temperature, humidity) before being distributed into the OR. After the air has left the OR again, it is expelled either completely or partially to the exterior. The heating energy can at that moment be recovered and used to pretreat the newly incoming fresh air so that less energy is required to achieve the desired OR temperature. In a case study on the suitability of different air distribution strategies the potential energy savings of heat recovery strategy were twice as high as those of a setback strategy.²³

In addition, the energy consumption of HVAC systems is highly dependent on the degree of air cleanliness.^{23,24} In **Chapter 3**, our results show that, for open-heart surgery, ultra-clean air conditions created by unidirectional airflow ventilation (UDAF) does not reduce the incidence of SSI and that consideration should be given to choosing more energy-efficient systems for these operations (*R2, Reduce*). The use of ultra-clean air to prevent SSIs has been a topic of debate in the scientific community for decades. The low incidence and multifactorial causes of SSIs make it difficult to demonstrate a causal link between the two and has resulted in conflicting results. One possible explanation for this is that much of the research has been conducted using large databases (registries)

involving large patient groups, but without controlling for confounding factors that may also influence the risk of SSI. In our study, air cleanliness was the only variable for the risk of SSI. The only other study with the same study design similarly showed that UDAF did not reduce the risk of SSI, in this case in total joint arthroplasty.²⁵

In conclusion, hospitals must decarbonise their electricity supply and prioritise energy efficiency. Societies of medical specialists must ensure, through guidelines, that unnecessarily high standards regarding clean air in ORs are not imposed if there is no scientific evidence to support them. Facilities Management Departments in hospitals must ensure that HVAC systems are energy efficient by implementing measures such as air recirculation, setback strategies, and heat recovery.

Scope 3

Emissions from the supply chain belong to scope 3 and include hidden emissions from upstream activities such as purchasing goods and generating waste (figure 1, Chapter 1). A carbon footprint assessment of the National Healthcare Service (NHS) in England showed that 62% of total healthcare emissions were attributable to the supply chain.²⁶ ORs are known for their use of large quantities of disposable items and the associated waste production resulting in large Scope 3 emissions.¹⁹ Our results from **Chapter 6** show that in 57% and 53% of respectively SAVR and TF-TAVI the carbon footprint was attributable to disposable items. These outcomes are consistent with the findings of a systematic review of surgical procedures, which found that more than 50% of the carbon footprint of operations is due to Scope 3 emissions.¹⁸

Surgical gowns

Our SCALE auditing tool from **Chapter 7** demonstrates that the most significant Scope 3 reduction can be achieved by replacing disposable surgical gowns with reusable ones (*R3, Reuse*). This measure has been shown to lead to a 64% reduction in energy consumption, a 66% reduction in GHG emissions, an 85% reduction in water consumption and an 84% reduction in waste production.²⁷ A performance comparison showed that reusable surgical gowns offered better protection and performance than disposable gowns.²⁸ User experience shows that reusable gowns are perceived as superior in terms of comfort, ventilation and temperature control, functionality and barrier function.²⁹ Despite these clear advantages of reusable surgical gowns, a study into their implementation revealed a number of obstacles. A global survey of perioperative professionals in 134 countries showed that financial constraints were a particular barrier to implementation. In high-income countries, there were in addition



institutional barriers such as resistance to change and changing working methods. In lower and lower-middle income countries, the sterilisation process was a particular barrier due to inadequate or poor sterilisation facilities and/or lack of clean water.³⁰

Disposable sterilisation packaging

Another major contributor to OR waste is the disposable packaging of surgical instrument trays (blue wrap), thus presenting an opportunity to reduce Scope 3 emissions.³¹ In **Chapter 4**, using an in-depth life cycle assessment, we found that replacing blue wrap with a reusable rigid sterilisation container (RSC) reduced the carbon footprint of sterilisation packaging by 85%.

Carbon footprint estimates of steam sterilisation and packaging of reusable surgical instruments by Rizan et al. yielded conflicting results with ours. In that study, the carbon footprint of blue wrap was lower than that of aluminium RSCs.³² There are a number of possible explanations for these differences. First of all, our results are based on 5,000 usage cycles of the RSC, as opposed to 1,000 in Rizan et al. This will result in an increase in the carbon footprint of the RSC, as four additional containers need to be manufactured and destroyed. In addition, a different type of blue wrap was used, for which 40% less polypropylene was modelled than in our study. Instead, paper was used as a second layer, resulting in a lower carbon footprint for blue wrap. The method used to determine the carbon footprint can also influence the results. To this end, we used three different indicators in our study (carbon footprint, ReCiPe and eco-costs), with all three methods a lower environmental impact was demonstrated for RSC.

Scope 3 emissions can thus be reduced by switching from blue wrap to RSC (*R₃, Reuse*). Aluminium containers are ideally suited as a circular solution for packaging surgical instruments. The containers can be manufactured from recycled aluminium and, at the end of their life, can be used as raw material for new containers. The two packaging systems are comparable in terms of patient safety.³³ However, switching to RSC may have financial and practical consequences. Research shows that the total cost of ownership of the two systems is quite similar, but the implementation of RSC requires long-term investments, which can be an obstacle.³⁴ In addition, additional physical space is required for storage of containers and washing machines.

Operating room waste

Operating rooms produce large quantities of waste, mainly because of the extensive use of disposable items. There are two main waste streams in ORs: hazardous and non-hazardous. For the former, only incineration is possible given the regulations for hazardous infectious waste. The non-hazardous waste stream, on the other hand, is

comparable to household waste. This allows for the reutilising (*R8, Recycle*) of packaging materials in particular, while the remainder is either incinerated or landfilled. The HSEMA tool from **Chapter 6** can be used to identify recyclable waste in the OR, create separate waste streams for it and calculate the carbon footprint reduction by doing so. Applying the HSEMA to waste from 18 orthopaedic operations in a Dutch university hospital showed that of the average amount of 7.8 kg of waste, 23% was non-recyclable. The remaining 77% recyclable portion consisted of plastic, paper, cardboard, and aluminium.³⁵

When the non-recyclable surgical waste is incinerated, heat can still be recovered from the burning process (*R9, Recover*). However, destruction of materials is not in line with the principles of a circular economy and should therefore be seen as a last resort. Table 1 provides an overview of all the above-mentioned practical implications.

In order to reduce the large amounts of concealed CO₂ emissions and waste from consumables in the OR, the purchasing department must include the sustainability of products in tenders, in addition to price. Preference should be given to reusable products such as surgical gowns and rigid sterilisation containers instead of disposables. Staff on the work floor must be vigilant about wasting materials, water, and energy, as this is where the greatest gains can be made in terms of reducing GHG emissions. Finally, the infection prevention department must ensure that no unnecessarily strict hygiene requirements are imposed if there is no scientific evidence to support them, this allows for significant savings in personal protective equipment usage.



Table 1. *Overview of practical implications.*

Main objective	Scope	Strategy	Subject	Method
Avoiding waste	1	<i>Ro Refuse</i>	Desflurane	Use sevoflurane or propofol
	1	<i>Ro Refuse</i>	N ₂ O	Phase out from anaesthetic practice
	1	<i>R2 Reduce</i>	VA emission	Prefer propofol or use Et Control + VCT
	1	<i>R2 Reduce</i>	N ₂ O	Prevent systemic losses
	2	<i>Ro Refuse</i>	Fossil fuel energy	Use renewably generated energy
	2	<i>R2 Reduce</i>	HVAC energy demand	Implement setback strategies
Extending product life	2	<i>R3 Reuse</i>	HVAC heat recovery	Install exhaust air heat exchanger
	3	<i>R3 Reuse</i>	Surgical gowns	Reusable instead of disposable
	3	<i>R3 Reuse</i>	Sterilisation Packaging	RSC instead of blue wrap
Recycling waste	1	<i>R8 Recycle</i>	VA	VCT
	3	<i>R8 Recycle</i>	Surgical waste	Plastic, paper, cardboard, aluminium
	3	<i>R9 Recover</i>	Surgical waste	Incineration

N₂O, nitrous oxide; VA, volatile anaesthetic; HVAC, heating ventilation, and air conditioning; RSC, rigid sterilisation container; VCT, vapour capture technology

Strengths & limitations

In our research, we use carbon footprinting as the main method for quantifying environmental impact. An important reason for doing so is that this measure is now widely used for this goal and also because it is familiar to the general public. This method has proven to be very effective in making healthcare more sustainable by: 1) establishing baseline values and monitoring changes; 2) identifying carbon hotspots that offer opportunities for substantial improvements; 3) enabling comparisons between products; and 4) optimising processes.³⁶ However, there is significant heterogeneity in the various methods, which means that caution should be exercised when comparing the absolute outcomes of studies with different methods. In addition, when comparing studies, it is important to consider whether there are any differences in the functional unit, system boundaries and included life cycle stages.³⁷ A recognised limitation of the carbon footprint is that it is a measure of climate change and not of all other forms of environmental impact, such as human and eco-toxicity, acidification, resource depletion, and so on. This carries the risk that the focus on reducing the carbon footprint could shift the problem to other environmental impacts, as the carbon footprint and other impact categories often do not correlate.³⁸

Future perspectives / research

In order to contribute to the global goal of zero GHG emissions by 2050, the healthcare sector must also take its responsibility as indicated by the WHO. In this thesis, we demonstrate that it is possible to significantly reduce GHG emissions from ORs. Both Scope 1 and Scope 2 emissions are largely influenced by hospitals and can therefore be reduced to virtually zero with the right measures. However, Scope 3 emissions are estimated to account for over 71% of the emissions of the entire healthcare sector.³⁹ These are the concealed emissions contained in the products and services as a result of upstream and downstream activities and are therefore difficult to measure and influence by the healthcare sector.⁴⁰ The main sources of Scope 3 emissions in the OR are disposables, equipment and pharmaceuticals. The majority of items used in ORs today are single-use. In this thesis (**Chapter 5**), we demonstrate that in both types of aortic valve replacement, 99% of the materials used are disposable and account for more than 50% of the carbon footprint of the procedure. It is crucial for future research to focus on reducing Scope 3 emissions in healthcare.

The most important way to achieve this is through the transition from a linear to a circular economy. A circular economy aims to preserve the value of products, materials and resources for as long as possible (Figure 2). This not only results in less raw material consumption, but also lower CO₂ emissions because fewer materials and products need to be manufactured, which means less energy consumption for production. In addition, less waste is produced, which also results in a reduction in GHG emissions due to incineration or landfill. Hence, a circular economy and decarbonisation are intrinsically intertwined. We will discuss two areas that have not yet been sufficiently researched: refurbishing single-use devices and the concept of product as a service.

Reprocessing single use devices

One way to reuse single-use devices (SUDs) is through reprocessing. This involves the regulated cleaning, testing, sterilisation and repackaging of SUDs so that they can be reused by hospitals. In Europe reprocessing has been legally authorised since 2021 but is subject to strict (national) regulations to ensure patient safety. Although several medical devices can already be reprocessed, there are many more that cannot, as is the case with many laparoscopic instruments and instruments for robotic surgery. Future research should focus on circular product design for medical applications. Product manufacturers must collaborate with technical researchers and healthcare professionals to design durable products that are easy to disassemble, repair and reprocess, with features such as modularity, adaptability, and versatility.⁴² Examples include laparoscopic instruments, robotic instruments, and endoscopes.



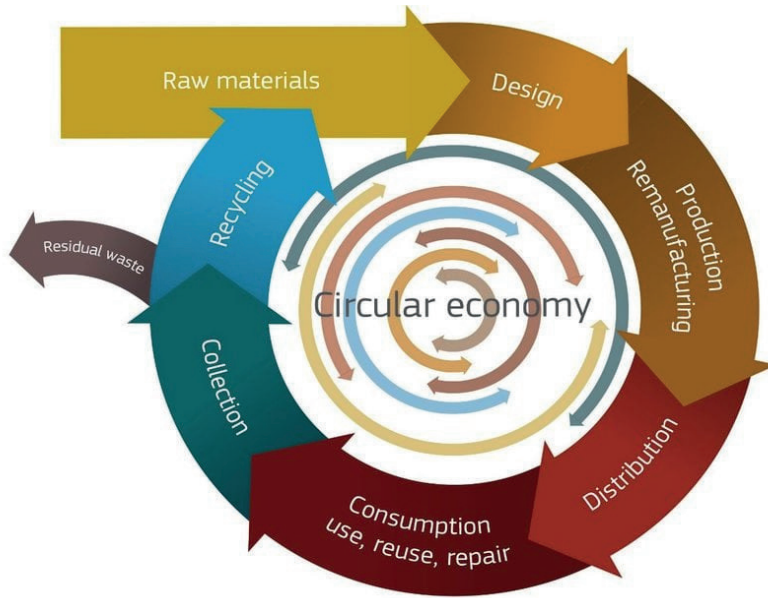


Figure 2. Simple circular economy model.⁴¹

Product as a service

In a linear economy, original equipment manufacturers (OEMs) benefit from high volume consumption, which is why products are designed with characteristics such as: rapid obsolescence, a short lifespan, difficulty in dismantling and poor cleanability.⁴² However, it is sometimes also possible to supply a product as a service, also known as 'servicisation'. An example of this is Philips supplying light as a service rather than light bulbs as a product (Circular Lighting). In this concept, the supplier remains the owner of the product and pays for the electricity, maintenance and end-of-life disposal. As a result, Philips has innovated the lamps so that they have the longest possible lifespan, are energy efficient and have a modular design.⁴³ All characteristics that align with a circular economy. There are also opportunities for servicisation in healthcare, where consumers receive high-quality medical devices that are durable and easy to clean, and where use is facilitated by technical support and product servicing.⁴⁴ This concept provides OEMs with a new revenue model based on usage rather than ownership.⁴³

Future research by technical researchers, healthcare professionals and financial experts, in collaboration with product manufacturers should investigate the possibilities for servicisation in the OR, where many devices could be eligible, such as ventilators, defibrillators, electrocautery devices and operating lights.

Conclusion

To meet the Green Deal 3.0 target of reducing CO₂ emissions in healthcare by 55% by 2030 and ultimately to zero by 2050, the OR has a potential contribution. To achieve considerable reductions in carbon emissions in the short term through quick wins, our results show that significant effective reductions are possible in all three scopes with practical implications based on the 10R strategy. However, given the scale and complexity of Scope 3 emissions, there is still much to be gained to ultimately achieve a zero-emission, circular healthcare economy. Future research should focus on OR circularity, with Reuse, Repair, Refurbish, Remanufacture and Repurpose strategies playing an important role in extending the lifespan of, what are currently mainly disposable, products.

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