Mitigating the carbon footprint of products used in surgical operations

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Abstract

The healthcare sector generates 4.4% of global greenhouse gas emissions, with 10% of the National Health Service carbon footprint in England associated with medical equipment. Here, a ‘carbon footprint’ is defined as the estimation of GHGs directly or indirectly associated with a product or process, converting GHGs to carbon dioxide equivalents (CO_2e) based on their global warming potential, allowing summation. Surgical operations are resource-intensive, but little evidence existed for mitigating their associated carbon footprint. This thesis begins with a systematic review of sixteen studies evaluating carbon footprint of surgical operations, finding major contributors were single-use products, energy consumption, and anaesthesia. The aim of this research was to identify major sources of greenhouse gas emissions (hotspots) associated with products used in common operations, and to evaluate their mitigation.

The carbon footprint of products used for five high volume operations was estimated, finding mean average for carpal tunnel decompression was 12.0 kg CO_2e (carbon dioxide equivalents); 11.7 kg CO_2e for inguinal hernia repair; 85.5 kg CO_2e for knee arthroplasty; 20.3 kg CO_2e for laparoscopic cholecystectomy; and 7.5 kg CO_2e for tonsillectomy. Across the five operations, 23% of product types were responsible for ≥ 80% of the operation carbon footprint. Greatest contributions were associated with production of single-use products (54%), reusable instrument sterilisation (20%), and waste disposal of single-use products (8%).

Single-use laparoscopic clip appliers, scissors, and ports were responsible for 19% (mean average) of carbon footprint of products used for laparoscopic cholecystectomy. The term ‘life cycle assessment’ can be used to describe the evaluation of a range of environmental impact categories associated with a given product or process, and this approach was used to compare the environmental impact of these single-use products to hybrid (predominantly reusable) equivalents, finding the latter was associated with 60% (mean average) reductions in 17 out of 18 midpoint environmental impact categories.

Carbon footprint of reusable instrument sterilisation was evaluated, finding this could be optimised by 31-42% through processing instruments in sets rather than individually, maximal loading of sterilisation machines, and recycling sterile barrier systems, with further reductions associated with low-carbon energy sources.

The carbon footprint of alternative healthcare waste streams was estimated, finding a 50-fold difference between recycling (21 kg CO_2e - 65 kg CO_2e per t of waste), compared with high temperature incineration (no energy recovered from waste) (1,074 kg CO_2e per t).

Finally, life cycle assessment was used to evaluate the role of repair, finding the carbon footprint of reusable scissors (70 g CO_2e per use) could be reduced by 20% through repairing instruments onsite (56 g CO_2e per scissors use).

Strategies for mitigating the carbon footprint of products used in common operations include switching single-use products to predominantly reusable equivalents, optimising sterilisation, using low carbon waste streams, and repairing instruments. Financial cost savings were associated with these strategies.

Contents

List of tables

List of figures

List of supplementary tables

List of supplementary figures

Abbreviations

All abbreviations are specified in full at first mention in this thesis and also within the legends of relevant tables and figures, aside from international system of units (specified in full below only). This table does not include abbreviations featuring only in supplementary tables/ supplementary figures, which are specified in the relevant legend.

1,4-DCB	Dichlorobenzene
BEIS	Department for Business, Energy and Industrial Strategy
Bq Co-60 eq	Becquerel Cobalt-60
CFC11	Trichlorofluoromethane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalents
COP21	21st United Nations Climate Change Conference
COP26	26^{th} United Nations Climate Change Conference
COVID-19	Coronavirus Disease 2019
Cu	Copper
DALY	Disability Adjusted Life Year
DEFRA	Department of Environment Food and Rural Affairs
EEIO	Environmentally Extended Input Output
EfW	Energy from Waste
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDPE	High Density Polyethylene
HGV	Heavy Goods Vehicle
HVAC	Heating, Ventilation and Air Conditioning
ICE	Inventory of Carbon and Energy
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LDPE	Low Density Polyethylene
m^2a	Square Meter Years
N	Nitrogen
NHS	National Health Service
NICE	National Institute for Health and Care Excellence
NO_x	Nitrous Oxides
P	Phosphate
PAS	Publicly Available Specification
PEEK	Polyether Ether Ketone

PET	Polyethylene Terephthalate
PM	Particulate Matter
PPS	Polyphenylene Sulphide
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PVC	Polyvinyl Chloride
RCSEng	Royal College of Surgeons of England
RSCH	Royal Sussex County Hospital
SBS	Sterile Barrier System
sd	Standard Deviation
SDU	Sustainable Development Unit
SO_2	Sulphur Dioxide
UK	United Kingdom
UN	United Nations
US	United States
USA	United States of America
v.	Version
WHO	World Health Organisation
WRATE	Waste and Resources Assessment Tool for the Environment

International system of units

ºC	Degrees centigrade
g	Grams
kg	Kilograms
km	Kilometres
kW	Kilowatts
kWh	Kilowatt hour
l	Litres
m^3	Meters cubed
MJ	Megajoules
ml	Millilitres
mm	Millimetres
Mt	Million tonnes
t	Tonnes

Preface

I have published the following research papers directly drawing upon this thesis (impact factors accurate 19th October 2022):

- CHAPTER 3: Rizan C, Steinbach I, Nicholson R, Lillywhite R, Reed M, Bhutta MF. The carbon footprint of surgical operations: a systematic review. Annals of Surgery. 2020;272(6):986-995. PMID: 32516230. *Impact factor 13.79*
- CHAPTER 5: Rizan C, Bhutta MF. Environmental impact and life cycle financial cost of hybrid (reusable/ single-use) instruments versus single-use equivalents in laparoscopic cholecystectomy. Surgical Endoscopy. 2022;36(6):4067–4078. PMID: 34559257. *Impact factor 3.45*
- CHAPTER 6: Rizan C, Lillywhite R, Reed M, Bhutta MF. Minimising carbon footprint and financial costs of steam sterilisation and packaging reusable surgical instruments. British Journal of Surgery. 2022;109(2):200–210. PMID: 34849606. *Impact factor 6.94*
- CHAPTER 7: Rizan C, Bhutta MF, Reed M, Lillywhite R. The carbon footprint of waste streams in a UK hospital. Journal of Cleaner Production. 2021;286:125446. doi.org/10.1016/j.jclepro.2020.125446. *Impact factor 11.07*
- CHAPTER 8: Rizan C, Brophy T, Lillywhite R, Reed M, Bhutta MF. Life cycle assessment and life cycle cost of repairing surgical scissors. International Journal of Life Cycle Assessment. 2022;27:780–795. doi.org/10.1007/s11367-022-02064-7. *Impact factor 5.23*

CHAPTER 3 includes analysis published within the following letter to the editor:

- Rizan C, Bhutta MF. Re: The carbon footprint of single-use flexible cystoscopes compared to reusable cystoscopes. Methodological flaws led to the erroneous conclusion that single-use is “better”. Journal of Endourology. 2022;36(11):1466-1467. doi.org/10.1089/end.2022.0482. *Impact factor: 2.62*

The discussion in CHAPTER 9 draws upon the following publications:

- Rizan C, Bhutta MF. A strategy for net zero carbon surgery. British Journal of Surgery. 2021;108:737-739. doi.org/10.1093/bjs/znab130. *Invited leading article. Awarded High Altimetric Certificate. Impact factor 6.94*
- Harris H, Bhutta MF, Rizan C. A survey of UK and Irish surgeons’ attitudes, behaviours and barriers to change for environmental sustainability. Annals of the

Royal College of Surgeons of England. 2021;103:725-729. PMID: 34719956. *Impact factor 1.95*

- MacNeill A, Rizan C, Sherman J. Environmental impact of perioperative care. [Internet]. 2022. [cited 2022 Dec 28]. Available from: https://www.uptodate.com/contents/environmental-impact-of-perioperative-care

Alongside this thesis I have published the following papers in the field of sustainable healthcare of relevance to this thesis.

- Rizan C, Reed M, Bhutta MF. Environmental impact of personal protective equipment supplied to health and social care services in England in the first six months of the COVID-19 pandemic. Journal of the Royal Society of Medicine. 2021;114(5):250-263. PMID: 33726611. *Impact factor 18.00*
- Rizan C, Mortimer F, Stancliffe R, Bhutta MF. Plastics in healthcare: time for a re-evaluation. Journal of the Royal Society of Medicine. 2020;113(2):49-53. PMID: 32031491. *Impact factor 18.00*
- Rizan C, Reed M, Mortimer F, Jones A, Stancliffe R, Bhutta MF. Using surgical sustainability principles to improve planetary health and optimise surgical services following COVID-19. The Bulletin. 2020;102(5):177-181. Doi: 10.1308/rcsbull.2020.1
- Dunne H, Rizan C, Jones A, Bhutta F, Taylor T, Barna S, Taylor CJ, Okorie M. Effectiveness of an online module: climate-change and sustainability in clinical practice. BMC Med Ed. 2022;22(1):682. PMID: 36115977. *Impact factor 3.26*
- Drew J, Christie SD, Rainham D, Rizan C. HealthcareLCA: an open-access living database of health-care environmental impact assessments. Lancet Planetary Health. 2022;6(12):E1000-E1012. doi: 10.1016/S2542-5196(22)00257-1. *Impact factor 28.75*

I have contributed to the following books in the field of sustainable healthcare of relevance to this thesis.

- Rizan C, Ramasubbu D, Wilmott S, Duane B. A guide to how to reduce the impact of PPE in your dental practice. In: Duane B, editor. Sustainable dentistry – making a difference. Switzerland: Springer; 2022.
- Gray M, Bevan G, Cripps M, Jani A, Ricciardi W, Rizan C, editors. How to get better value healthcare. Fourth Edition. Oxford Press. Awaiting publication.

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This PhD was primarily funded by Health Education England Kent Surrey and Sussex, and I am especially grateful to Professor Graeme Dewhurst and Dr Timothy Chevassut for facilitating this. I was awarded a competitive Surgical Research Fellowship from the Royal College of Surgeons of England, who I would like to thank for supporting this relatively novel research area. I was appointed as Sustainable Surgery Fellow at the Centre for Sustainable Healthcare in 2018, and thank Ms Rachel Stancliffe, Dr Frances Mortimer and Ms Inge Steinbach in particular for introducing me to the world of sustainable healthcare.

I would like to acknowledge the following individuals and groups for their help in relation to specific chapters:

- CHAPTER 3: I thank Ms Inge Steinbach for conducting independent (second) data extraction from relevant papers for the systematic review, alongside Dr Rosamond Nicholson who performed an independent second search of the literature.
- CHAPTER 4: I would like to thank all patients who allowed me to observe their operations, and to surgical staff at University Hospitals Sussex NHS Foundation Trust for their co-operation with this study. Particular thanks go to consultant departmental leads in relation to this study; Mr Goldie Khera, Mr Phillip Stott, and Professor Mahmood Bhutta. I am grateful also for procurement data obtained

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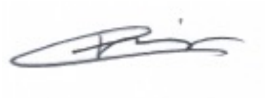
- CHAPTER 5: The research on hybrid surgical instruments was funded by Surgical Innovations Ltd who manufacture hybrid laparoscopic instruments (the company played no part in scientific conduct, analysis, or writing of this thesis or associated publication), and I would like to thank Mr Adam Power and Ms Melanie Goodall for providing me with relevant data. I thank Miss Victoria Pegna for her specialty-specific input and for championing sustainable surgery. I would also like to thank other industry partners who provided data but wish to remain anonymous.
- CHAPTER 6: I thank staff at the University Hospitals Sussex NHS Foundation Trust Sterile Services Departments for their cooperation with this study, in particular Mr Nicholas Vanderveldt, Mr Paul Hide, Mr Matthew Upton and Mr Christopher Kirby.
- CHAPTER 7: I would like to thank Mr Paul Tullet (waste manager at University Hospitals Sussex NHS Trust), Dr Ryan Woodard (BSMS), Mr Stuart Brittle and Mr Ryan Muir (Medisort), and Mr Mark Sweeting and Ms Charlotte Kyle (Veolia) for their input on waste processes.
- CHAPTER 8: I thank Mr Roger Manning (Ream Surgical Ltd) for supplying data on reusable surgical scissors manufacture and offsite instrument repairs, and Mr Tom Brophy for data on onsite repair at Barts Health NHS Trust.

Finally, I thank all those who peer-reviewed my publications relating to this thesis, and whilst the publication process was often long, this taught me perseverance and I feel this resulted in significant improvement to the academic robustness of this thesis. I am grateful to all those who supported me during my PhD either directly or indirectly, with particular thanks to my fiancé Drew who was there for me throughout my PhD journey, alongside my family and friends.

Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Signed:



Dated:

19th January 2023

CHAPTER 1 Introduction

Climate change is the greatest threat to human health of the 21st century,(1) and it is paradoxical that the provision of healthcare itself contributes to this problem, with the healthcare sector estimated to contribute 4.4% of global greenhouse gases (GHG).(2) In this thesis, a 'carbon footprint' is defined as the estimation of GHGs directly or indirectly associated with a product or process, converting GHGs to carbon dioxide equivalents (CO_2e) based on their global warming potential and allowing summation. The surgical operating theatre is a resource intensive area of the hospital using large volumes of products, many of which are single-use. Given that around two-thirds of the carbon footprint of the National Health System (NHS) in England relates to the supply chain,(3) identifying a strategy for mitigating the carbon footprint of products such as those used in the operating theatre will play an important role in the Greener NHS ambition to meet net zero carbon by 2045.(4) The approach of reduce, reuse, repair, reprocess, and recycle may be used to guide the transition to improve surgical sustainability, but in order to maximise impact, these approaches should be strategically applied to products with greatest carbon footprint.

1.1. Aims

The primary aim of this research was to evaluate strategies to mitigate the carbon footprint of products used in common operations. The focal study within this thesis (CHAPTER 4) evaluated the carbon footprint of products used in the five most common operations, aiming to identify products and underpinning processes which make the largest contributions. These findings informed studies in subsequent chapters (CHAPTER 5 - CHAPTER 8) which aimed to tackle these carbon hotspots, through switching high carbon single-use products to predominantly reusable alternatives, optimising sterilisation, identifying low- carbon waste streams, and use of repair. The ambition was that this will provide evidence to support those seeking to transition to net zero carbon surgical systems (including academic researchers, clinicians, policy makers, regulators, and healthcare industry), whilst encouraging the targeting of efforts towards areas which will make the biggest difference to GHGs. The aims of individual studies are specified at the start of the relevant chapter.

1.2. Objectives

The objectives and sub-objectives of this thesis were as follows:

- CHAPTER 3: Systematically review existing literature examining the carbon footprint of surgical operations, including products used by surgeons within the operating theatre
    - Identify carbon hotspots which can be targeted to reduce GHG emissions associated with surgery
- CHAPTER 4: Estimate the carbon footprint of products used within five high volume operations
    - Evaluate the contribution of different product categories for each operation
    - Identify individual products collectively responsible for the majority (80%) of the carbon footprint of each operation
    - Evaluate the contribution of underpinning processes for each operation, including production and disposal of single-use and reusable products and their packaging, alongside sterilisation and laundering (as applicable)
- CHAPTER 5: Evaluate and compare environmental impact of single-use laparoscopic products (laparoscopic scissors, clip appliers and ports) with hybrid equivalents using life cycle assessment
    - Evaluate financial life cycle cost associated with the alternative models
    - Evaluate the impact of altering assumptions; number of reuses of products, alternative preparation of products for sterilisation, sterilisation using fossil-fuel rich energy sources, changing carbon intensity of instrument transportation, and altering port configuration
- CHAPTER 6: Estimate carbon footprint of decontaminating reusable surgical instruments via washing and steam sterilisation, alongside packaging in alternative sterile barrier systems
    - Evaluate financial life cycle cost associated with decontamination
    - Evaluate opportunities to mitigate carbon footprint of decontamination; impact of preparing reusable instruments as sets versus individually wrapped items, altering machine loading, use of alternative energy sources for sterilisation, and alternative waste streams
    - Evaluate carbon and financial cost impact of opening instruments during an operation, and of streamlining instrument sets
- CHAPTER 7: Estimate the carbon footprint of healthcare waste streams
    - Evaluate the carbon footprint of healthcare waste undergoing high temperature incineration, low temperature incineration with energy from

waste (plus sterilisation via waste autoclave where necessary), and recycling

- CHAPTER 8: Evaluate environmental impact of repairing surgical scissors using life cycle assessment, comparing no repair versus onsite or offsite repair
  - Evaluate financial life cycle cost associated with alternative models
  - Evaluate impact of altering assumptions; number of uses of scissors, number of repairs, distance to offsite repair centre, alternative electricity sources, and alternative waste streams
  - Evaluate the scope for repair of instruments beyond surgical scissors

1.3. Overview of thesis

This section provides an overview of the thesis, with a summary of novel contributions made to the literature, and of how the chapters link together.

The remainder of this introductory chapter (CHAPTER 1) beyond this section contextualises the thesis within broader issues, starting with climate change and its impact on human health, and the generation of GHGs associated with the healthcare sector. The contribution from surgical operations and areas with greatest environmental impact are then considered, followed by strategies for mitigating the carbon footprint of products used in surgical operations.

CHAPTER 2 describes the methods used to evaluate environmental impact within this thesis, and considers the benefits and drawbacks of different methodological approaches, namely life cycle assessment, and analysis limited to carbon footprint. Whilst this thesis has multiple sub-studies, CHAPTER 2 summarises methodological commonalities which span across multiple chapters, but where elements of methods are specific to individual chapters, these are specified within respective chapters.

CHAPTER 3 provides a systematic review of existing literature examining the carbon footprint of operating theatres and of products used by surgeons. This found that the major contributors were single-use products, energy consumption, and anaesthesia. This research formed the foundation of my publication in *Annals of Surgery*, and represented the first systematic review published in this field.(5)

CHAPTER 4 estimates the carbon footprint of products used within five high volume operations, identifying the biggest carbon contributors (hotspots) at the level of individual product types and underpinning processes. This research was the first to strategically identify products used in common surgical operations with greatest carbon footprint. These findings can be used by surgeons, policy makers, and industry partners, to prioritise surgical products which have greatest carbon footprint which need to be targeted, for example through identification and adoption of low carbon alternatives where they already exist, or alternatively to highlight where innovation is required. This study analysed the contribution of underpinning processes, finding greatest GHG emissions were associated with production of single-use products (54%), followed by reusable instrument sterilisation (20%), and waste disposal of single-use products (8%). This analysis was used to inform the focus of studies in subsequent chapters which evaluate ways to optimise each of those processes.

Within CHAPTER 4, a small proportion of products (23% mean average across operations) were found to account for the majority (80%) of the carbon footprint of products used for a given operation, and these products should be targeted. CHAPTER 4 also found that over half of the carbon footprint of products used for the five common operations related to the production of single-use products. Single-use laparoscopic clip appliers, scissors, and ports were responsible for mean average of 19% of the carbon footprint of products used for laparoscopic cholecystectomy. Hybrid equivalents existed for these products which were predominantly reusable, with small single-use components, but the environmental impact had not previously been evaluated. CHAPTER 5 provides a life cycle assessment of these three products, finding switching from single-use to hybrid equivalents across the three product types was associated with 60% (mean average) reductions in 17 out of 18 midpoint environmental impact categories. This was published in the journal *Surgical Endoscopy*,(6) representing the first study to evaluate the environmental impact of hybrid products in a healthcare context.

Sterilisation of reusable items was identified within CHAPTER 4 as the next largest contributor to the carbon footprint of products used across common operations (around one-fifth total contribution). CHAPTER 6 evaluates the carbon footprint of reusable instrument sterilisation and strategies for mitigating this, finding this could be optimised by 31-42% through processing instruments in sets rather than individually wrapped, maximal loading of sterilisation machines, and recycling sterile barrier systems, with additional reductions associated with use of low-carbon energy sources. This study was published in the *British Journal of Surgery*,(7) and was the first to systematically evaluate the carbon footprint of instrument sterilisation. The results were also used to account for sterilisation within the evaluations of whole operations (CHAPTER 4), laparoscopic products (CHAPTER 5), and reusable scissors (CHAPTER 8) illustrating that this thesis is not entirely linear and that chapters interlink.

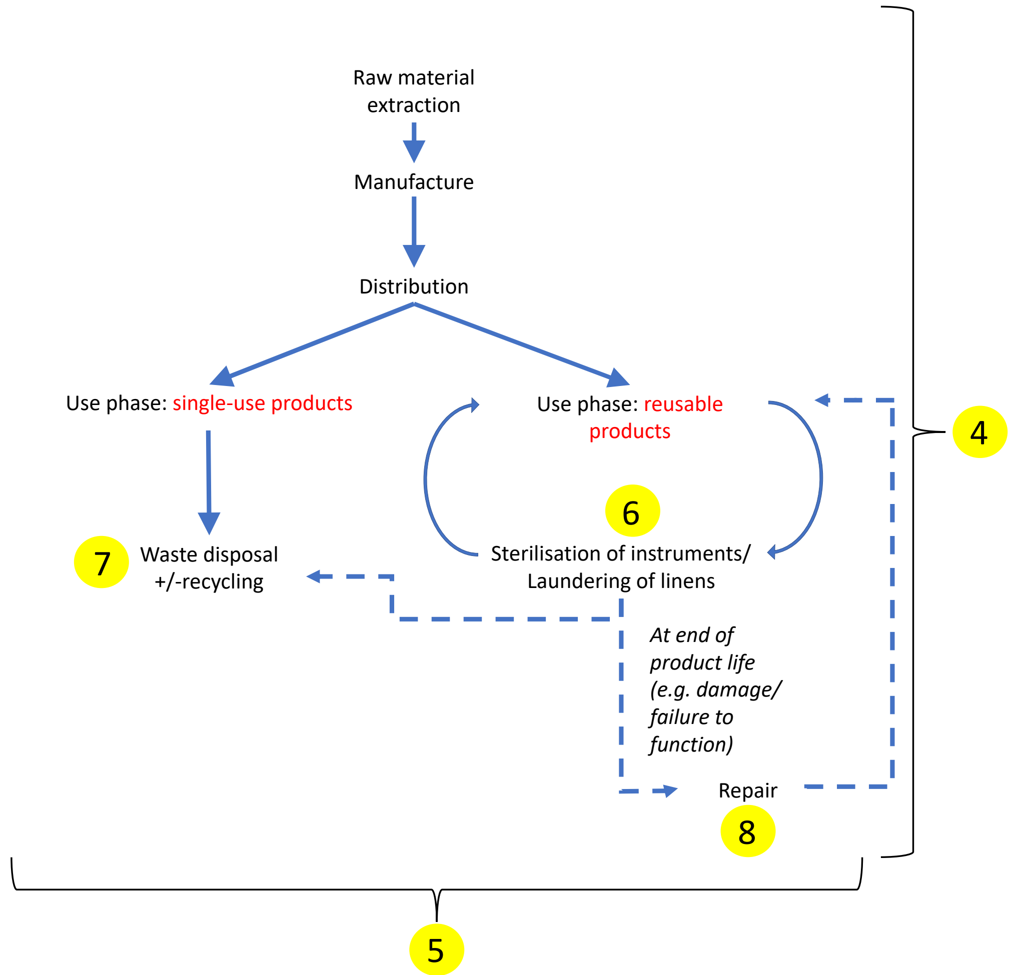
Waste was identified as the next largest contributor (8%) to the carbon footprint of products used in common operations within CHAPTER 4, and many of the operations observed used inappropriate waste streams. CHAPTER 7 evaluates the carbon footprint of healthcare waste streams, finding a 50-fold difference between recycling (21-65 kg carbon dioxide equivalents [CO_2e] per t of waste), compared with high temperature incineration (no energy recovered from waste) (1,074 kg CO_2e per t). This study was published in the *Journal of Cleaner Production*,(8) and results were used to account for waste in the evaluation of common operations (CHAPTER 4) and sterilisation (CHAPTER 6), as there was little evidence on the carbon footprint of waste specific to healthcare prior to this study, again illustrating interplay between chapters.

The chapters outlined above indicate that the carbon footprint of products used in common operations may be reduced through adopting low carbon alternative products (such as reusables or hybrids, targeted towards products with high GHG intensity), and optimising sterilisation and waste. In line with circular economy principles, there is further potential to maximise resource use through repair. CHAPTER 8 was the first study to evaluate the impact of repair in a healthcare context, and has been published in the *International Journal of Life Cycle Assessment*.(9) Here, a life cycle assessment was used to evaluate the role of repair in mitigating the carbon footprint associated with surgical scissors, finding this could be reduced by 20% through use of repair.

Finally, CHAPTER 9 discusses the key findings of this thesis, highlighting the novel contribution made to the literature. This is brought together with existing literature to outline an evidence-based strategy for mitigating the carbon footprint of products used in surgical operations. The thesis concludes by considering barriers and enablers to translating this research into practice and policy, followed by considering future areas of research, with a final conclusion.

Figure 1 demonstrates the typical life cycle stages of surgical products, and how research chapters (CHAPTER 4 - CHAPTER 8) relate to each stage. CHAPTER 4 and CHAPTER 5 include all relevant stages of products' life cycle, with the former evaluating the carbon footprint of all products used across whole operations and the latter focusing on three products. Remaining chapters focus on specific life cycle stages; sterilisation (CHAPTER 6), waste (CHAPTER 7), and repair (CHAPTER 8).

Figure 1: Stages of surgical product life cycle examined within chapters



Title

4 Carbon footprint of products used for five common surgical operations

5 Minimising carbon footprint and financial cost through use of hybrid (reusable/ single use) products in laparoscopic cholecystectomy

6 Minimising carbon footprint and financial costs of steam sterilisation and packaging of reusable surgical instruments

7 Minimising carbon footprint and financial costs of healthcare waste

8 Minimising carbon footprint and financial costs of reusable surgical scissors through repair

1.4. Background

Climate change

The Holocene epoch began approximately 11,700 years ago after the most recent major ice age, describing a geological period of time associated with relatively stable environmental conditions compatible with supporting human life.(10) The Anthropocene began following the Industrial Revolution of the late eighteenth century, signalling a new geological epoch in which human activities became the primary driver of changes to the environment.(11) There are nine planetary boundaries defined, describing environmental thresholds within which humanity can safely survive and thrive.(10) Four of these planetary boundaries have been crossed; climate change, land-system change, loss of biosphere integrity, and altered biogeochemical cycles (the former two lie within the zone of increasing risk of destabilisation and uncertainty, and the latter two at high risk).(10)

Climate change can be defined as long-term changes in mean average weather conditions, or their increased variability.(12) Climate change is considered a 'core' planetary boundary (alongside biosphere integrity) due to the importance of this to stability of other environmental systems, and the crossing of this boundary could lead to a fundamentally new state on Earth.(10) The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) concluded that human activity is the unequivocal cause of rapid global warming of the atmosphere, land, and oceans.(13) This is driven largely by anthropogenic (man-made) emissions of GHGs which absorb infrared radiation, such as carbon dioxide (CO_2), methane, nitrous oxide, halogenated gases, volatile organic compounds, and carbon monoxide.(13) The rate of climate change is unprecedented and accelerating, with atmospheric CO_2 (410 parts per million) at highest concentrations for two million years, and global surface temperature approximately 1 ºC warmer than in the year 1850-1900, with the rate of increase unprecedented in over two thousand years.(13)

The landmark Paris Agreement set a legally binding international treaty to limit global warming to 2 ºC, preferably 1.5 ºC (compared with pre-industrial levels), signed by 196 parties at the 21st United Nations (UN) Climate Change Conference (COP21) in Paris, 2015.(14) The sixth IPCC report found that in order to limit global warming to 1.5 ºC and to avoid catastrophic climate impacts, GHG emissions must reduce dramatically and sustainably.(13) The Paris Agreement rulebook was completed alongside the Glasgow Climate Pact at the 2021 26th UN Climate Change Conference (COP26) held in the United Kingdom (UK), with many countries revisiting and strengthening GHG emissions targets known as nationally determined contributions.(15) The majority of countries (representing 90% of world gross domestic product) have now committed to reach net zero emissions around the middle of this century.(15) Net zero emissions are defined by the IPCC as the state in which anthropogenic GHG emissions are balanced by anthropogenic removals over a given period of time.(12) The UK Climate Change Act (2008, amended in 2019), set a legally binding goal of reducing net GHG emissions by 100% relative to a 1990 baseline level by the year 2050.(16) However, an UN report found that global GHG emissions must halve by 2030 in order to limit global warming to 1.5 ºC, and that latest global national commitments fall short of what is required, setting a trajectory of reaching 2.7 ºC warming by the end of the 21st century.(17)

Carbon dioxide (CO_2) is responsible for around three-quarters of anthropogenic GHG emissions,(18) and CO_2 is therefore used as a reference gas. Other GHGs specified in the Kyoto protocol include methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, and nitrogen trifluoride.(19) Non-CO_2 GHGs can be assigned a global warming potential (GWP), based on the amount of radiative forcing (heating effect) associated with one t of a given gas relative to one t of CO_2, over a set time-period,(12) typically 100 years. This enables GHG emissions associated with a given product, process or system to be converted into carbon dioxide equivalents (CO_2e), but there is a lack of consensus in terminology used amongst the scientific community to describe this process. For example, terms used in guidelines include ‘product life cycle accounting’,(20) ‘life cycle GHG emissions’,(21) and ‘carbon footprint’,(22) with the latter commonly used in studies identified in the systematic review (CHAPTER 3). Whilst a ‘life cycle approach’ may be used to evaluate GHGs associated with all stages of a product’s life cycle, a ‘life cycle assessment’ (LCA) is a term used to describe the evaluation of a range of environmental impacts associated with a given product.(23) A recent review of healthcare LCAs found that almost all studies (99%) included an evaluation of GHGs as a subset of analysis, with other common environmental impact categories including ozone depletion, photochemical oxidant creation potential, acidification potential, particulate matter formation, freshwater ecotoxicity potential, and eutrophication potential.(24)

There is also lack of consensus on which GHGs to include within a carbon footprint. For example, two studies included in the systematic review (CHAPTER 3) evaluating gastro-oesophageal reflux disease,(25) and plastic surgery(26) accounted for carbon dioxide only, whilst others included other GHGs and reported results in carbon dioxide equivalents, such as an evaluation of cataract surgery,(27) and operating suites.(28) The latter study cited the Greenhouse Gas Protocol Product Life Cycle Accounting and Reporting Standard (referred to hereon in as the GHG Protocol),(20) which recommend inclusion of all GHGs included in the Kyoto Protocol,(19) with optional separate reporting of additional GHGs specified by the IPCC.(29) Meanwhile Publicly Available Specification (PAS) 2050 guidelines(21) (as cited by a study evaluating endometrial staging cancer)(30) recommend use of latest IPCC GWP conversions, which include GHGs beyond the groups specified in the Kyoto Protocol, including fluorinated ethers, perfluoropolyethers, and additional ozone depleting gases such as methyl bromide.

There is also a discrepancy in the GHGs accounted for within emission factor databases used to convert activity data into GHGs. For example, the UK Government GHG conversion factors(31) were based upon Kyoto Protocol GHGs, whilst the Inventory of Carbon and Energy database(32) collated emission factors from a broad range of secondary sources which in turn used different approaches for including GHGs (these two databases were the primary sources of emission factors for estimations of carbon footprint in CHAPTER 4, CHAPTER 6, and CHAPTER 7). Meanwhile, the ReCiPe method(33) used for life cycle assessment studies in CHAPTER 5 and CHAPTER 8 included all GHGs included in the IPCC report.

In this thesis, a ‘carbon footprint’ is defined as the estimation and summation of direct and indirect GHG emissions associated with a given product or process, including non-carbon GHGs which are converted to carbon dioxide equivalents based on their global warming potential. The term ‘carbon’ is sometimes used as shorthand to encompass other GHGs; for example, ‘net zero carbon’, ‘carbon cost’, or ‘reduce carbon’ may relate specifically to CO_2, but often implies inclusion of other GHGs (as in this thesis). In this thesis, a life cycle assessment is defined as the evaluation of environmental impact of a product or process across a range of environmental impact categories, including the carbon footprint as a subset. The different methodological approaches to environmental accounting and those used within this thesis are discussed in detail in CHAPTER 2.

Impact of climate change on human health

Planetary health is intricately linked with human health, and climate change has been proposed as the greatest threat to human health of the 21st century.(1) Climate change threatens public health directly, for example through extreme weather events such as heatwaves, flooding, drought and storms.(34) Modelling indicates that global warming of 4.1 ºC could lead to 83 million cumulative excess global deaths between the year 2020 and 2100, whilst limiting warming to 2.4 ºC could avert the majority (74 million) of those deaths.(35) There are wider impacts of global warming including those associated with poor air quality, food and water insecurity, and transmission of climate-sensitive infectious disease.(36) Air pollution is the largest environmental cause of morbidity and premature death, with 3.3 million deaths attributable to anthropogenic air pollution in 2019, with one-third of this resulting from burning of fossil-fuels.(34)

Vulnerable individuals are at greatest risk of climate-related health impacts including those with existing health conditions, the elderly, and children.(34) Health impacts of climate change also risk widening inequalities (and the associated health gap) and follows a social gradient, with those at lower levels of socioeconomic deprivation most likely to suffer from food and water insecurity, whilst also being least able to adapt their homes, to move, and to suffer disproportionately from uninsured loses.(36) For example, coastal communities (commonly experiencing higher levels of socioeconomic deprivation and greater burdens of disease compared with those inland)(37) are at greatest risk of forced migration relating to rising sea levels associated with global warming.(38) Individuals of lower socioeconomic status are disproportionately affected, whilst the poorest half of the world's population contribute a fraction of global GHGs (estimated at 7%), representing climate injustice.(39)

Climate change has been re-framed as the greatest public health opportunity, given that we can actively reduce our environmental impact, and that this in turn can directly benefit health.(40) The latest UN Climate Change Conference (COP26) was the first to place health at the centre of climate negotiations. The World Health Organisation (WHO) hosted a health pavilion at COP26, and released a special report on climate change and health in advance, emphasising the need to place health and equity at the centre of climate action.(36) This called upon government and policy makers to rapidly bring about transformative change, in order to protect both planetary and human health. The WHO special report was delivered to COP26 delegates at a Climate Action for Health event during the Science and Innovation day, alongside an open letter entitled 'Healthy Climate Prescription' signed by 600 organisations representing 46 million nurses, doctors and healthcare professionals globally.(41) Signatories included the WHO Director, the

Lancet, and World Medical Association, and the letter called upon world leaders to "avert the impending health catastrophe by limiting global warming to 1.5°C, and to make human health and equity central to all climate change mitigation and adaptation actions".(41)

Environmental impact of healthcare

Whilst climate change threatens human health,(1) it is paradoxical that the provision of healthcare itself contributes to the problem. Health Care without Harm estimated that the healthcare sector is responsible for 4.4% of global net emissions, and that if the healthcare sector were a country it would be the fifth largest emitter.(2) China, the European Union and the United States of America (USA) were found to be the biggest contributors, cumulatively responsible for over half of global healthcare sector GHGs.(2) The contribution of the healthcare sector to national GHG emissions have been evaluated in a variety of settings, including the US (655 Mt CO_2e, 10% of national total),(42) China (315 Mt CO_2e, 3%),(43) and Australia (36 Mt CO_2e, 7%).(44) Out of the 43 nations evaluated within the Health Care Without Harm report, India had the lowest healthcare GHG emissions per capita (57 times lower than the US), constituting 1.5% of India's national carbon footprint.(2)

An analysis of the carbon footprint of the NHS in England found this generated an estimated 25 Mt CO_2e per year,(3) responsible for around 4% of national GHG emissions.(4) Scope one GHG emissions are those directly emitted from (and controlled by) an organisation, including emissions of anaesthetic gases (for example nitrous oxide and fluorinated inhaled anaesthetic gases such as desflurane, sevoflurane, and isoflurane),(45) and hydrofluorocarbons or chlorofluorocarbon propellants from metered dose inhalers, and together these emissions are responsible for 5% of the NHS carbon footprint.(3) Scope one emissions also include the combustion of petrol or diesel from NHS owned and leased vehicles, which, alongside other business travel (categorised as scope three emissions), were estimated to contribute 4% of the NHS carbon footprint.(3) Combustion of fossil fuels onsite (such as within gas boilers) is also classified as scope one emissions, whilst purchased energy in the form of electricity or steam constitute scope two indirect emissions (still within direct control of the organisation). These areas are collectively considered as 'building energy' within the NHS carbon footprint, cumulatively responsible for 10% of emissions.(3) Scope three GHGs incorporate all other indirect emissions, including those embedded within the supply chain (62%), patient, visitor, and staff travel (10%), water and waste disposal (5%), and commissioned services (4%).(3) GHG emissions upstream of the health provider associated with the supply chain therefore made the largest contribution to the NHS carbon footprint (almost two-thirds), of which pharmaceuticals and chemicals (20% of total) and medical equipment (10% of total) were the biggest contributors.(3) The latter (medical equipment) includes products used directly for delivery of healthcare (such as surgical instruments, syringes for administering medications, and medical gloves). There was a further 8% contribution to the NHS carbon footprint from non-medical equipment, which may include products and capital goods which support the delivery of healthcare services such as furniture and office supplies.(3)

The relative contribution of different GHGs to the carbon footprint of healthcare varies between sources and depends on what is included in each analysis, but studies consistently find that CO_2 is responsible for the majority of healthcare GHGs, estimated at 51% in a study of global healthcare GHGs,(46) and 80% in a US setting.(47) Carbon dioxide is mainly generated by fuel combustion either onsite at healthcare providers or upstream within the healthcare supply chain, alongside associated deforestation.(46) There are smaller contributions from nitrous oxide which is emitted mainly from associated agriculture, with estimated contributions varying from 22% in the study of global healthcare GHGs,(46) to 4% in the US study.(47) Methane is responsible for an estimated 16% of global healthcare GHGs(46) (estimated at 12% in the US)(47) and is generated through associated agriculture and energy transformation processes. Fluorinated gases are used and emitted mainly within industrial process (including air conditioning, refrigeration, and foam blowing, and are also used as solvents and propellants), and were estimated to be responsible for 11% of global healthcare GHGs.(46) The study of the US healthcare sector included chlorofluorocarbons, estimating this was responsible for 4% of US healthcare GHGs.(47)

The environmental impact of healthcare delivery extends beyond global warming, for example nitrous oxide, and halogenated anaesthetic gases such as isoflurane also deplete the ozone layer and reduce the shielding effect from ultraviolet radiation.(45) The healthcare sector also contributes to air pollution, and at a global level healthcare has been associated with 2.8% emissions of particulate matter (PM_{10}, subscript referring to the maximum diameter of inhaled particles in micrometres), and 3.4% - 3.6% of the air pollutants nitrogen oxides and sulphur dioxide respectively.(46) The Sustainable

Development Unit in England (SDU) previously estimated that the 9.5 billion road miles associated with the NHS in 2017 generated 330 t of $PM_{2.5}$ and 7,285 t of nitrogen oxide, equating to around 3.5% of all road travel in England.(48) The provision of healthcare also has a considerable water footprint (estimated at 2.23 billion m^3 in England),(48) contributing to water scarcity.(46)

Ecotoxicity refers to the adverse effects of anthropogenic chemical, physical or biological agents on ecosystems. Use and disposal of pharmaceuticals is associated with increased concentrations of bioactive pharmaceutical compounds in water systems and soil, including antibiotics, analgesics and anti-inflammatory drugs.(49) Pharmaceutical residues may be absorbed by other species such as fish, reptiles, and birds, at a rate faster than elimination, leading to bioaccumulation.(49) Healthcare is increasingly reliant upon single-use plastics within healthcare, with the global medical plastics market responsible for 2% of total plastics production by value, and growing by 6.1% per year.(50) The manufacture of all plastic accounts for 8% of global oil production, with oil used both as a feedstock and a fuel in the manufacturing process.(51) Alongside the subsequent contribution to global warming due to burning of fossil fuels, inappropriate disposal means that plastic fragments now comprise 50% - 80% of shoreline debris,(52) although how much of this is medical waste is not known.

Sustainability and healthcare

The UN 2030 Agenda for Sustainable Development was adopted by all UN Member States in 2015 and aimed to provide a 'shared blueprint for peace and prosperity for people and the planet, now and into the future'.(53) This agenda was accompanied by the setting of 17 UN Sustainable Development Goals which illustrate the complex interdependence between improving health and wellbeing, reducing inequality, environmental sustainability, and economic prosperity.(53) 'Doughnut economics' is a conceptual framework used to guide sustainable use of resources,(54) which encourages humanity to operate in the safe and just space between meeting basic social needs (in line with the UN Sustainable Development Goals),(53) whilst not exceeding the maximum ecological ceiling (which can be defined by planetary boundaries previously discussed).(10) Another core concept within sustainability is that of the 'triple bottom line', which encompasses the environmental, social, and financial costs of a system.(55) The triple bottom line can alternatively be framed as three Ps; people, planet, profit, where a system is considered to be sustainable only where the three intersect.(55)

In line with these concepts, ‘sustainable healthcare’ is defined in this thesis as the provision of healthcare in a manner which meets health and wellbeing needs in a way which does not directly or indirectly negatively impact on health (or potential to provide healthcare) of other populations, separated by socioeconomic status, geography, or time. This introduction has highlighted the risk posed by climate change to human health and the disproportionate impact this has on the most vulnerable alongside future generations,(34) and summarised the contribution of healthcare to this problem. There are additional risks of unintended, and often hidden, social costs linked with the provision of healthcare, with labour rights abuses associated with the supply of some healthcare products manufactured in countries such as Pakistan, Malaysia and Mexico.(56) The healthcare system must also function within financial budgetary constraints, seeking equitable access and distributive justice of resources. The UK Centre for Sustainable Healthcare developed the ‘sustainable value’ framework, which encourages those optimising patient and population outcomes through changing processes for health delivery to consider the triple bottom line (environmental, social, and financial sustainability).(57) This thesis focuses on the environmental element of sustainable healthcare, and whilst it is supported by consideration of financial implications where relevant, social sustainability is beyond the scope of this thesis. The term ‘sustainability’ and ‘sustainable’ are used hereon in to refer to environmental sustainability.

In light of increased awareness of both the impact of planetary health on human health and the significant environmental impact of the healthcare sector itself, there is a growing movement towards mitigating the environmental impact of healthcare provision. The UK has been a leading figure for sustainable healthcare, with formation of the Sustainable Development Unit in 2008 following the UK Climate Change Act (2008). The 2019 NHS Long Term Plan strengthened commitments to deliver on the Climate Change Act targets, including ambition to halve the carbon footprint of the NHS by 2025, and also committing to reduce single-use plastics within the healthcare supply chain.(58) In 2020 NHS England launched the Greener NHS, which superseded the Sustainable Development Unit, and released a report on delivering a ‘net zero’ national health service.(4) Through this, the NHS in England became the first national healthcare system to commit to meeting net zero carbon emissions, setting targets of meeting net zero carbon emissions for those within the direct control of the NHS by 2040, and to extend this to those upstream in the supply chain by 2045.(4)

At COP26 all other UK nations joined NHS England in making Net Zero Commitments alongside 13 other countries, whilst 46 countries committed to developing low carbon, sustainable health systems.(59) Alongside mitigating climate change, healthcare systems will need to adapt to climate change, both to accommodate direct and indirect health impacts of climate change, and also to ensure that healthcare facilities can withstand extreme weather events such as flooding and heatwaves, alongside rising sea levels where relevant. At COP26 50 countries committed to developing climate resilient health systems.(59) The remainder of this sub-section focuses on the UK context, as this is the country in which research underpinning this thesis was conducted.

Two-thirds of the NHS carbon footprint relates to the supply chain, including procurement of products such as medical equipment and pharmaceuticals,(3) and this poses a major challenge for developing sustainable healthcare systems. The Greener NHS in England outlined a pathway to net zero carbon in its 2020 report, with around half of the trajectory to net zero dependent upon three factors; the alignment of suppliers to NHS net zero ambitions, the development of low-carbon alternatives and product innovation, and finally research and offsetting.(4) The development and adoption of low carbon healthcare products can be encouraged through fiscal and regulatory mechanisms, some of which are in development in the UK. The NHS outlined a roadmap for supplier alignment approved by the NHS England Public Board in 2021, which stipulates that by 2027 all suppliers must publish carbon reduction plans, and from 2030 suppliers will only qualify for NHS contracts if progress can be demonstrated against such plans.(60) From April 2022, the NHS adopted the UK Government Social Value Model for commissioning and purchase of NHS goods and services whereby a minimum of 10% weighting is applied to social value when evaluating tenders for NHS contracts.(61) Social value relates here to a number of factors including mitigating climate change (which must be considered for all procurement contracts), alongside wellbeing, equal opportunity, economic inequality, and COVID-19 recovery where relevant.(61) Finally the National Institute for Health and Care Excellence (NICE) provide evidence-based recommendations for healthcare in England, and pledged in 2021 to develop frameworks for evaluating environmental sustainability in order to inform future NICE guidance.(62)

Leadership within sustainable healthcare is also evolving at various levels. At a national level beyond the Greener NHS, the UK Health Alliance on Climate Change brings together 21 national healthcare organisations (including medical and nursing Royal Colleges, national associations, and leading medical journals) and advocates for action towards mitigating climate change and promoting public health.(63) The 2021 / 2022 NHS Standard Contract mandated for the first time that all NHS Trusts (regional organisational units of healthcare providers) and Integrated Care Systems (partnerships bringing together healthcare commissioners, providers and partner organisations within a geographical region) must submit a Green Plan outlining local strategy for mitigating GHGs, in alignment with the NHS net zero carbon ambition.(64) At the individual clinician level, there are growing numbers of individual healthcare professionals in support of the transition to sustainable healthcare. An NHS England survey conducted in 2017 of over 6,000 NHS staff found almost all (96%) thought that "it was important that the health and care system works in a way that supports the environment, such as improving resource efficiency, reducing carbon emissions and reducing waste".(65)

Alongside the development of policy, governance, and leadership, there is also a growing body of academic research evaluating the environmental impact of healthcare across many clinical areas and at different levels of the healthcare system, and these have been reviewed elsewhere.(66) Studies at a national level include those evaluating the carbon footprint of the US,(47) Australia,(44) and UK(3) healthcare systems. Studies evaluating environmental impact have been conducted across many clinical specialties, ranging from renal medicine (home versus in-centre maintenance of haemodialysis)(67) and dentistry (root canal procedure),(68) through to obstetrics (hysterectomy via different surgical approaches),(69) and intensive care (septic shock treatment).(70) Further research has been conducted at the level of clinical investigations (such as alternative abdominal imaging modalities),(71) through to healthcare products (reusable versus single-use laryngoscopes),(72) and pharmaceuticals (different anaesthetic agents).(73)

Environmental impact of surgical operations

A high volume of surgical operations are performed, with an estimated 313 million surgical procedures performed worldwide annually.(74) This 2012 estimate represented a one-third increase over eight years,(74) although this upward trend has been disrupted in recent years due to widespread cancellations and delays to planned elective cases relating to the COVID-19 pandemic.(75) Any estimated surgical volume should be treated with caution, and is dependent on how surgical 'procedures' are defined, for example an estimated 1.5 to 7.9 million procedures were performed annually in the UK (average 2009-2014), with lowest figures derived when using a 'restrictive' categorisation for what is considered a procedure, and highest for an 'inclusive' categorisation.(76) When applying the NHS Payment by Results tariff to these, surgical procedures were estimated to cost £5.6 billion to £10.9 billion annually in the UK (for procedures classified restrictively and inclusively respectively).(76) The total cost of surgical procedures (using the higher figure, and excluding upstream outpatient appointments and investigations, or downstream follow up and management of complications) was estimated to account for 9.4% of the total NHS budget.(76) The contribution of surgery to the carbon footprint of healthcare has not been formally evaluated, but is likely to make a considerable contribution given the proportion of the overall healthcare spend associated with surgery, and volumes of surgical procedures performed. It will therefore be important to evaluate ways to reduce the environmental impact of surgical operations as part of the ambition to meet net zero carbon healthcare, and this is the focus of this thesis.

The operating theatre is a resource-intensive area of a hospital which uses large quantities of single-use products (which generate large volumes of waste), and is associated with high energy demands.(28, 69) Operating theatres generate around one-fifth of hospital waste,(77) and are three to six times more energy intensive than the rest of the hospital.(28) A study examining operating suites in Canada, the US, and UK found that a typical operation had a carbon footprint of 146 kg CO_2e - 232 kg CO_2e,(28) comparable to emissions associated with driving approximately 400 miles - 650 miles in an average car (calculated through applying UK government conversion factors).(31) The same study found that a typical operating department in a large UK hospital generated over 5,000 t CO_2e per year.(28)

The principal components making up the carbon footprint of an operating theatre are the hospital infrastructure, capital goods, maintenance of the theatre environment (heating, ventilation, air-conditioning, lighting), energy associated with electronic equipment, water, anaesthetic gases, pharmaceuticals, alongside reusable and single-use products. The relative contributions of each of these components is disputed,(26, 27, 28) and will vary in different settings and with different operations. The systematic review (CHAPTER 3 of this thesis, and published in *Annals of Surgery*) identified that the biggest contributors to carbon footprint (carbon hotspots) within an operation were products that were used to perform surgery, anaesthetic gases, and energy usage.(5) These three areas were also highlighted in a subsequent systematic review of surgical and anaesthetic care by a different author group.(78)

The carbon footprint of operating theatre energy consumption has previously been estimated at 24 kg CO_2e - 145 kg CO_2e per case (assuming equal allocation of annual energy consumption across total number of cases).(28) This study estimated energy consumption based on enthalpy required to meet temperature set-points compared with meteorological data alongside theatre submeters,(28) whilst other studies allocated theatre energy consumption based on floor area alongside using power ratings, with estimated contribution of energy consumption for cataract surgery at around 15% of the operation, and <1 kg CO_2e.(79) The majority (90-99%) of operating theatre energy consumption relates to heating, ventilation and air conditioning (HVAC).(28) This can be mitigated at the stage of designing operating theatres, with potential for retrofit, including installation of occupancy sensors or set-back systems after-hours, reduced air flow turnover, use of renewable energy sources, and newer buildings with improved energy efficiency.(28) The contribution from anaesthetics will depend principally on modality and anaesthetic agents used. A study evaluating carbon footprint of anaesthesia used for 29 knee arthroplasties found this ranged from 9.9 kg CO_2e per case (spinal approach) - 13.2 kg CO_2e per case (general anaesthetic combined with spinal) when modelled using European energy supply.(80) The evidence-basis for mitigating the environmental impact of anaesthesia is relatively well established, including preferential use of inhalational agents with lowest global warming potential for general anaesthesia (especially avoiding desflurane), limiting use (and leakage) of nitrous oxide, and using gas scavenging systems.(81)

This thesis focuses on how to mitigate the carbon footprint of the third element; products used within the operating theatre, and this was chosen in light of a number of factors. Firstly, this thesis focuses on products used in the surgical operating theatre, which in turn are classified under the general category of medical equipment. This is an important area, as nearly two-thirds of NHS England carbon footprint was associated with the supply chain, with 10% of the total relating to medical equipment.(3) It is likely that some of the principles underpinning the findings of this thesis are transferrable to other products used within a healthcare context.

Secondly, surgical products likely have a large environmental impact, for example the procurement of surgical products has previously been associated with up to two-thirds of the carbon footprint of a cataract operation.(79) A single adenotonsillectomy operation was found to generate over 100 separate single-use plastic items (based on analysis I published in the *Journal of the Royal Society of Medicine*, beyond scope of this thesis).(82) An analysis conducted by the SDU of the 20 categories of medical products with highest associated GHGs included a number of items used in operating theatres, including single-use surgical instruments, gloves, surgical caps, drapes, tubing and drains.(83) Further, this problem appears to be increasing, with the global surgical equipment market currently growing by 9.8% per year, and anticipated to be worth US $24.5 billion (£20.2 billion; exchange rate 12th August 2022) by 2028.(84) Evaluating ways to reduce the carbon footprint of products used in operating theatres will therefore play an important role in the transition to sustainable models of surgical care.

Thirdly, surgical teams can influence products in the operating theatre, in terms of what is procured and made available within theatre stock rooms, how these are prepared ahead of surgery (for example composition of instrument sets), what products are used for a given operation, and also what happens to products after use (including choice of waste streams, alongside items being sent for repair). Surgical teams can therefore make a difference on a day-to-day level in terms of what products are used for surgery and how they are used. Meanwhile, the potential to mitigate carbon footprint of energy consumption is largely dependent on engineers, architects, and colleagues in facilities and estates (with smaller potential reduction of 1.5% - 8.4% of carbon footprint of operating theatre energy through switching off lights and plugged-in equipment),(28) and carbon relating to anaesthesia is largely within the sphere of control of anaesthetic colleagues. A survey of surgeons' attitudes in relation to environmental sustainability found that the majority (82%) of the 130 respondents were willing to make changes to mitigate the carbon footprint of their clinical practice, and 91% of surgeons surveyed would welcome greater leadership and guidance from national bodies on how to achieve this (I supervised this research and am last name author in resulting publication in *Annals of the Royal College of Surgeons*).(85)

Mitigating the carbon footprint of products used in surgical operations

Strategy towards meeting net zero carbon within surgery can be broadly defined in terms of circular economy principles, including reduction, reuse, repair, reprocessing, and recycling.(86) This sub-section summarises such strategy, highlighting knowledge gaps addressed in this thesis. The linear approach to medical device consumption whereby materials are extracted and resources used in product manufacture and distribution, and then items used as little as once before disposal, is unsustainable given finite resources. In contrast, circular economy principles promote the reuse and recycling of materials to enable maximal use of products already in circulation, and conservation of component materials, through designing durable, reusable products with modular components which are repairable and upgradable, and where 'waste' is considered a valuable resource with potential for regeneration via repair, remanufacture, or recycling.(87)

The environmental benefit of reducing or eliminating use of products in the operating theatre is self-evident. In the healthcare context, gloves are clearly appropriate where there is risk of contact with bodily fluids or hazardous chemicals, but there are many instances where hand washing alone is sufficient (such as when moving patients), and whilst hand washing is required before and after glove-use, overuse of gloves wastes resources. My previous LCA study (beyond scope of this thesis, published in the *Journal of the Royal Society of Medicine*) modelled the environmental impact of rationalising glove use during the COVID-19 pandemic (using hand washing only where appropriate), finding gloves were responsible for 45% of the carbon footprint of personal protective equipment, although this proportion may differ outside of the context of the pandemic.(88) There are often instances in healthcare settings where products are opened 'just in case', and as part of reduction strategies, it is important to avoid opening or requesting products until they are clearly required. There is also potential to eliminate unnecessary packaging of surgical supplies and double wrapping where it is not indicated. An Australian study found that single wrapping of sterilised instruments was as efficacious as double wrapping in preventing bacterial contamination.(89) It is important also to remove single-use products which are used infrequently or not at all from pre-prepared sets. For example, a previous study found that 12 out of 40 single-use products in a pre-packaged tonsillectomy kit were unnecessary.(90)

In low- and middle-income countries resource use is frugal out of necessity, eliminating unnecessary materials and reusing materials wherever possible. For example a cataract operation performed in India was estimated to generate only 5% of the GHGs of the same operation performed in the UK.(79) Previous LCA analyses support lower environmental impacts associated with switching a variety of operating theatre products from single-use to reusables, including surgical scissors,(91) laryngoscopes,(72), laryngeal mask airways,(92) peri-operative linens, (including surgical gowns and drapes),(93) and laparotomy pads.(94) However, contrasting findings were reported in a study comparing six reusable instrument sets used for spinal fusion surgery (each containing multiple instruments, weighing 45 kg in total) versus two much smaller single-use instrument sets (2 kg total) containing just a few instruments.(95) It is likely that development of a consolidated reusable set (containing similarly few instruments) would confer a lower carbon footprint. Other notable exceptions include several LCA studies conducted in Australia which found that the carbon footprint of a single-use ureteroscope was similar to reusable equivalents,(96) and the carbon footprints of single-use central venous catheter kits(97) and anaesthetic equipment(98) were lower than reusable equivalents. Australian electricity uses predominantly coal-based non-renewable energy sources, and where these studies remodelled processes using European and US energy sources, the carbon footprint of reusables was reduced,(97, 98) to the extent that in the case of anaesthetic equipment the carbon footprint of reusables became lower than single-use. (98) Whilst the carbon footprint of a number of reusable products have been compared with single-use equivalents, the environmental impact of using hybrid products (combining predominantly reusable products with single-use components) where a fully reusable alternative is not appropriate had not been explored prior to the research within this thesis.

The principal determinant of the life cycle carbon footprint of reusable surgical instruments is typically the sterilisation process, responsible for up to 85% of the carbon footprint of reusable surgical scissors,(91) and almost all GHG emissions associated with reusable laryngoscope blades and handles.(72) There is therefore further potential to reduce carbon footprint of reusables through optimising sterilisation. Prior to research within this thesis, no study had reported the carbon footprint and financial cost of different processes for sterilisation and preparation of reusable surgical instruments, nor how such processes can be optimised.

Repair is another mechanism that can be used to maximise resource use. The importance of maintenance and repair of surgical instruments has previously been emphasised in resource-poor settings, where maximising lifespan of devices is necessary due to difficulty in obtaining and funding replacements.(99, 100) Reduced environmental impact associated with repair over replacement has been demonstrated in other contexts, for example for household electric and electronic items(101) through to vehicles(102) but had not previously been evaluated for medical products.

Where single-use products cannot be avoided, it is possible to gain an additional use through reprocessing (also known as remanufacturing), involving sterilisation, testing, and repairing for a further single use. LCA studies have demonstrated environmental benefits of reprocessing single-use medical devices compared with purchasing new equivalent versions across a range of products including endoscopic trocars, deep vein thrombosis compression devices, pulse oximeters, scissors tips, arthroscopic shavers, diathermy clips, ultrasonic scalpels,(103) and cardiac electrophysiology catheters,(104) with 45%(104) - 50%(103) reductions in cost. The relative environmental impact of reprocessing specific single-use surgical instruments (compared with using new ones) is likely to be determined by the extent of reprocessing required (in turn dependent upon the complexity of the instrument, extent of damage from use, and sterilisation required), location of the reprocessing unit, and number of additional uses enabled.

Finally, it is possible to extend the use of some materials within either single-use or reusable products at the end of their functional life through recycling. A study of operating theatre waste found that 13% of infectious waste was potentially recyclable, accounting for non-contaminated paper/cardboard, plastics, aluminium, and glass only (i.e. items incorrectly placed into the infectious waste stream), and the authors also indicated that the recycling potential of infectious waste would be higher if products were sterilised before recycling.(105) Recycling stainless steel surgical instruments into surgical instrument mesh baskets has been shown to be both feasible and cost-effective.(106) However, the carbon footprint of different modes of healthcare waste disposal was previously poorly defined.

Summary

This chapter (CHAPTER 1) outlined the aims and objectives of this thesis. It also provided background context, exploring the interplay between human and planetary health, followed by the importance of mitigating the carbon footprint associated with delivering surgical operations, with a particular focus on surgical products. Strategies which may be used to mitigate the carbon footprint of surgical products were introduced, informed by the literature, alongside identification of knowledge gaps. The next chapter

(CHAPTER 2) provides an overview of the different methodological approaches relevant to this thesis.

CHAPTER 2 Methods

The primary aim of this thesis (as outlined in CHAPTER 1) was to evaluate strategies to mitigate the carbon footprint of products used in common surgical operations. This chapter introduces alternative methodological approaches which may be used for evaluating environmental impact, broadly classified as carbon footprinting and full life cycle assessment. This is followed by an overview of the stages involved in conducting a carbon footprint or LCA. Any methodology specific to an individual study is specified within the respective chapter.

2.1. Overview of methodological approaches

The method chosen to evaluate environmental impact will always depend on the research question, and should take into account the scale and complexity of the system being studied, alongside pragmatic factors such as level of expertise and resource availability (including time and access to specialist databases). Two commonly used methods are carbon footprinting (which evaluates the GHG emissions associated with a given product or process), and full LCA (which evaluates a range of environmental impacts, usually including the carbon footprint). Either approach can be used as a tool to quantify total impact of a given product or process, evaluate major contributors (hotspots), compare products, or to model ways to optimise processes. Both carbon footprinting and LCA can be conducted via process-based or environmentally extended input-output model approaches, and the relative merits of each of these methodological choices are considered in this section.

Carbon footprint versus life cycle assessment

As previously discussed within the introduction to this thesis, a carbon footprint provides an estimate of the direct and indirect GHG emissions associated with a given product or process. In its simplest form, a carbon footprint converts a quantified amount of resource use (for example weight of a specified material, or volume of natural gas used) into carbon dioxide equivalents (CO_2e), which can be converted using previously derived emission factors which best match the unit of study.(20) The GHGs included within carbon footprint evaluations typically include those specified in the Kyoto Protocol; carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, and most recently nitrogen trifluoride,(19) which are each assigned a global warming potential, allowing summation. A carbon footprint study can be performed at the scale of an individual product (such as surgical scissor),(91) and here a life cycle approach is often taken, whereby the material and energy flows throughout a product's life span are accounted for. It is also feasible to conduct a carbon footprint study at a larger scale, evaluating processes (such as steam sterilisation of reusable instruments),(7) patient procedures or pathways (such as a cataract operation),(27) all the way up to whole national healthcare systems.(3)

Carbon footprints report on a single category of environmental impact (GHG emissions), and focusing on this one parameter is reasonable given that climate change (driven largely by anthropogenic GHG emissions)(13) is considered fundamental for the stability of other environmental systems,(10) and that national targets towards mitigating climate change are focused on GHG emissions.(4) The use of a single metric can help to simplify the communication of results, especially when comparing multiple products or evaluating a range of mitigation strategies. However, this could also be considered a disadvantage in that other potentially important environmental impacts across other areas may be overlooked. Further advantages of conducting a carbon footprint analysis (compared with an LCA) include that this can be performed using publicly available emissions factors, requires little specialist software, and can be conducted with minimal time and expertise when using the simplest methods of evaluation.

By contrast, LCA is a method used to account for a range of different environmental 'midpoint' impact categories (including GHG emissions alongside others such as ozone depletion, eutrophication, and ecotoxicity), each focusing on single environmental problems, although the specific environmental impact categories included in an LCA vary. The advantage of conducting a full LCA includes that a range of environmental impacts are considered, allowing a more comprehensive evaluation. This can be especially helpful where comparing alternative products (for example single-use versus reusable laryngoscopes),(72) and enables an evaluation of environmental impact across a number of categories. A further advantage is that the results can be aggregated into 'endpoint' impact categories, such as determining the impact of a number of midpoint impact categories (including GHG emissions, ozone depletion, and particulate matter) on damage to human health.(107) Linking results of environmental impact studies to disability adjusted life years (DALYs) can be helpful when communicating with a clinical audience, reinforcing the link between human and planetary health. The disadvantage of

LCA is that this requires specialist software (usually involving expensive licenses), specialist training, and is time intensive.

This thesis focuses on mitigating the carbon footprint of products used in surgical operations, and the carbon footprinting approach was therefore used for the majority of the research. This was chosen as carbon footprinting was considered to be a feasible method to use when evaluating environmental impact at the scale of products used across whole operations (CHAPTER 4), and whole processes such as steam sterilisation (CHAPTER 6) and waste (CHAPTER 7). However, where single-use versus hybrid laparoscopic equipment were compared (CHAPTER 5), an LCA approach was taken to enable a more comprehensive evaluation. Having gained skills and acquired resources required to undertake an LCA, this approach was also used to evaluate the impact of repair of surgical scissors (CHAPTER 8) illustrating how pragmatic factors can influence choice of approach. Within LCA studies, the GHG emissions were the primary impact category evaluated. Within this thesis, the two approaches (LCA and carbon footprinting) are referred to collectively as an 'environmental impact assessment'.

Process-based versus environmentally extended input-output model

There are two principal methodological approaches used to perform either a carbon footprint or LCA environmental impact evaluation. The first is a 'top-down' environmentally extended input-output (EEIO) model, which uses the monetary cost of a unit of interest to estimate environmental impact, on the premise that more expensive items involve greater resource use, with higher associated GHG emissions. An industry specific characterisation factor can be applied to the economic cost to convert this to a carbon footprint. The EEIO approach incorporates all emission sources from upstream processes in the supply chain (either direct or indirect, and including flows between sectors), taking into account 'hidden' sectors such as marketing and research and development.(108) It is relatively inexpensive and simple to perform, but lacks specificity and detail, and should not be used for comparing the carbon footprint of products from within the same industrial sector.(109) The main value of estimating a carbon footprint via an EEIO method is the rapid identification of hotspots, highlighting where it may be useful to perform a more detailed carbon footprint. For example, this approach has been used at the level of evaluating the carbon footprint of a whole patient care pathway for treatment of gastro-oesophageal reflux disease,(25) and the carbon footprint of the US national healthcare system.(47)

The alternative 'bottom-up' process-based method involves collecting data on all the component processes underpinning the unit of interest. Characterisation factors can be applied, which provide average environmental impact (GHG emissions in the instance of a carbon footprint) for a given attributable processes (for example electricity consumption, transportation, and production of a given material). This enables detailed analysis with high specificity, allowing comparison between items from the same sector.(110) However, this method is resource intensive and requires study boundaries to be carefully defined, resulting in 'truncation error' whereby processes may be omitted or the so called 'hidden' sectors overlooked.(111) Examples of where this approach has been used include an LCA of childbirth,(112) and carbon footprint of endometrial cancer staging via different methods.(30)

There is debate over the relative accuracy and value of top-down versus bottom-up approaches.(113) Hybrid methods exist which attempt either to incorporate the granularity of the process-based approach alongside inclusivity of EEIO models, or which use top-down approaches for attributable components for which process data cannot be obtained.(109, 113) Examples where a hybrid approach has been used include evaluation of the carbon footprint of a cataract operation,(27) and LCA of performing a hysterectomy.(69) Within this thesis, a process-based approach was used wherever feasible, and all chapters using LCA were performed using a process-based approach. Chapters focusing on carbon footprint took process-based approaches wherever possible, with the EEIO method used for certain pharmaceuticals and cleaning chemicals (specified in relevant chapters) where there was a lack of data to support a process-based analysis. Table 1 summarises the methods used within this thesis.

Table 1: Summary of methods
DEFRA/BEIS= Department for Environment, Food and Rural Affairs (DEFRA) and Department for Business, Energy and Industrial Strategy; ICE= Inventory of Carbon and Energy

Chapter	Title	Methodological approach	Life cycle inventory and impact assessment sources
4	Carbon footprint of products used for five common surgical operations	Carbon footprint *Hybrid, predominantly process-based*	• 2021 DEFRA/BEIS Database(31) • Ecoinvent (version 3.6)(114) • ICE Database (version 3)(32) • Small World Consulting Carbon Factors Dataset (version 5.3)(115) • CHAPTER 6 • CHAPTER 7
5	Minimising carbon footprint and financial cost through use of hybrid (reusable/ single use) products in laparoscopic cholecystectomy	Life cycle assessment *Process-based*	• Ecoinvent (version 3.6) • Industry Data (version 2.0) • ReCiPe version 1.1 Midpoint and Endpoint Hierarchist method All embedded within SimaPro (version 9.10) (114)
6	Minimising carbon footprint and financial costs of steam sterilisation and packaging of reusable surgical instruments	Carbon footprint *Hybrid, predominantly process-based*	• 2019 DEFRA/ BEIS Database,(116) • ICE Database (version 3)(32) • Small World Consulting Carbon Factors dataset (version 1.5)(117) • CHAPTER 7
7	Minimising carbon footprint and financial costs of healthcare waste	Carbon footprint *Process-based*	• 2019 DEFRA/BEIS Database(116) • Greenhouse Gas Protocol Emissions from Waste Management Activities database (version 5) (118)
8	Minimising carbon footprint and financial costs of reusable surgical scissors through repair	Life cycle assessment *Process-based*	• Ecoinvent (version 3.6) • European Life Cycle Database (version 3.2) • ReCiPe version 1.1 Midpoint and Endpoint Hierarchist method All embedded within SimaPro (version 9.10) (114)

Guidelines

There are several guidelines available for evaluating the environmental impact of a given product or process. These include the ISO 14040 guidelines(23) which outline the principles and framework for conducting an LCA; and ISO 14044(119) which specifies requirements and guidelines for conducting an LCA (both released in 2006). The 2012 Publicly Available Specification (PAS) 2050 guidelines(21) focus specifically on GHG emissions associated with goods or services, and were developed by the British Standards Institution, alongside the UK Department of Environment Food and Rural Affairs (DEFRA) and the Carbon Trust. The 2011 GHG Protocol (developed by the World Resources Institute),(20) focuses on GHG emissions (i.e. carbon footprint), although the guideline specifically indicates that the principles can also be applied to other environmental impacts. The GHG Protocol explicitly encompasses and builds on the previously mentioned guidelines, and is used as the principal methodological guideline source in this thesis. There are additional supporting guidance which complement the GHG Protocol, including the 2013 GHG Protocol Technical Guidance for Calculating Scope 3 Emissions,(111) and the 2012 Greenhouse Gas Accounting Sector Guidance for Pharmaceutical Products and Medical Devices (referred to hereon in as the GHG Medical Devices Guideline).(120)

Whilst this research draws upon these guidelines, they were principally designed for the purposes of corporate reporting rather than academic research, and the guidelines were deviated where appropriate to specific research questions. For example the GHG protocol does not support comparison between products,(20) but within this thesis a consistent method was used to compare single-use versus hybrid laparoscopic equipment in CHAPTER 3.

2.2. Overview of stages involved in carbon footprint and life cycle assessment

The stages involved in conducting a carbon footprint and LCA are broadly comparable, and are considered in this section alongside methodological choices which apply across chapters. Different guidelines define different stages for performing an environmental impact assessment, but those that are relevant to the research within this thesis can broadly be considered as follows: the scope, life cycle inventory analysis, impact assessment, and uncertainty assessment. These stages are outlined in turn, drawing upon the GHG Protocol,(20) and ISO 14040(23) guidelines. Specific details for each stage are specified in the methods section of each chapter as relevant.

Scope

The first stage of an environmental impact assessment is to define the goal and scope of the study. This includes the functional unit, which specifies the function under examination, and must be consistent when comparing alternative products fulfilling the same specific function. The reference flows indicate the amount of products and processes required to fulfil this functional unit. For example, where the functional unit is the use of a pair of surgical scissors in an operation, this might be fulfilled by the following reference flows; one single-use scissor, or one use of a reusable pair of scissors (which may be used multiple times over the product's lifetime, and so the associated energy and material flows must be divided across the estimated number of uses).

The system boundary describes the material and energy flows that are included within the study (referred to as 'attributable processes') and identifies those considered potentially relevant but which are excluded. For products, this typically entails a 'cradle to grave' assessment, including raw material extraction ('cradle'), manufacture, transport, the 'use phase' for reusables (including sterilisation and laundering), and disposal ('grave'). Where a process (such as sterilisation, or waste), or surgical operation involving lots of products was evaluated, the cradle to grave approach was applied across the multiple relevant products. Material and energy flows were excluded where these were likely to contribute less than 1% to the total carbon footprint, defined as the significance threshold.(20) This included capital goods (such as sterilisation machines) and infrastructure (such as the operating theatre itself), aside from where emissions data was readily available within databases (such as for metal working machines and metal working factories, as included within LCA studies; CHAPTER 5 and CHAPTER 8).

Life cycle inventory

A life cycle inventory involves collating data on the attributable processes included within the system boundary. Such data can be classified as direct emissions data where GHG emissions are directly measured (e.g. through direct monitoring of emissions),(20) although this was not relevant to any component of this thesis. Data is categorised as process activity data where such data relates to inputs and outputs known to contribute GHG, but where direct measurement of GHG emissions is not possible. This is known as primary process activity data where original data is collected that is specific to a given functional unit under examination. Alternatively, secondary process activity data may be collected, using average, or typical process data (e.g. based on previously published studies or databases which are not specific to the functional unit). Finally, secondary financial activity data is used in EEIO models based upon the monetary cost of items.

Where material and energy flows are shared across multiple products, the contribution to the product under investigation (functional unit) versus co-products must be estimated via an ‘allocation’ method. This was avoided where it was possible to subdivide common processes and evaluate these separately, but where allocation was unavoidable, the physical allocation approach was undertaken based on the weight of products, or number of units, in line with guidelines.(20) The GHG Protocol(20) and PAS 2050 guidelines(21) specify that an attributional approach must be used to allocate a proportion of attributable processes associated with a given product across its life cycle, and this was used to build the life cycle inventories within this research.

The alternative consequential approach examines the real world consequences of a change and only allocates the material and energy flows that are affected by a change in demand associated with a given functional unit.(20) For example, where a reusable surgical instrument is introduced into a set containing multiple instruments, the emissions associated with the sterilisation of that set may be re-apportioned across all instruments in the expanded set (the attributional approach), or they may remain allocated to the instruments on the original set, with none apportioned to the newly introduced instrument (the consequential approach). The consequential approach can be useful to guide real world change in practice and policy, for example this was used in an LCA study to evaluate the consequential effect of increased energy required if switching from single-use to reusable anaesthetic equipment, modelling the likely energy source given increased demand, rather than using country averages.(98) The consequential approach typically requires the collation of additional data to inform a model of potential real world impact of a given change, including unintended consequences, and often involves an expansion of the system boundary. This was beyond the scope of this thesis, but was applied where specifically relevant to the research question in CHAPTER 5, where the consequence of switching from single-use to hybrid laparoscopic equipment was evaluated using both attributional and consequential approaches.

The majority of the data required to build the life cycle inventories was collected at University Hospitals Sussex NHS Foundation Trust hospitals. This is a publicly funded regional hospital providing both elective and emergency operations across a range of surgical specialties. In the year 2018 – 2019, around 62,000 procedures or interventions were performed annually across these hospitals. Where primary activity data collection involved quantifying and specifying materials within a given product, each component of the product was weighed using Fisherbrand FPRS4202 Precision balance scales (Fisher Scientific, Loughborough, UK). For each included material, manufacturer information was used to determine the material composition, or expert knowledge where such information was not available (through consultation with Professor Robert Lillywhite). For transportation, shipping distances were determined using the online Pier2Pier tool(121) and road distances using Google maps.(122)

Microsoft Excel was used to build the life cycle inventory for all carbon footprinting components of this thesis. For LCA components, the materials and energy flows were matched with closest processes within the Ecoinvent database (version 3.6) and modelled using SimaPro (version 9.10).(114) Where not available within Ecoinvent, the European Life Cycle Database (version 3.2) or Industry data (version 2.0) were used (also integrated within SimaPro).

Impact assessment

In order to convert the life cycle inventory into an environmental impact assessment, characterisation factors can be applied which best match the study functional unit, system boundary and the impact category of interest (for a carbon footprint study this is limited to ‘emission factors’, relating to GHG emissions). The emission factors used are specified in relevant chapters (summarised in Table 1), and the specific version of each dataset used for each study was based on the most up to date version at the time the study was submitted for publication. The principal sources of emission factors used for carbon footprint components of this thesis were as follows:

- The UK Government GHG Conversion Factors for Company Reporting databases, produced by the Department for Environment, Food and Rural Affairs (DEFRA) and Department for Business, Energy and Industrial Strategy (BEIS), hereon referred to as the ‘DEFRA/BEIS database’, based upon 2019(116) through to 2021 versions.(31) This was principally used for energy and travel.

- The Inventory of Carbon and Energy (ICE) database (version 3)(32) was the primary source of emission factors for materials as this uses average data for materials supplied to the UK.
- The Small World Consulting Carbon Factors Dataset version 1.5(117)- version 5.3(115) was used for emission factors based upon financial spend for EEIO models.
- The data derived within CHAPTER 6 and CHAPTER 7 were used as sources of emission factors or sources of activity data, to account for sterilisation of reusable instruments and waste in studies within other chapters.

For LCA components of this thesis (CHAPTER 5 and CHAPTER 8), the ReCiPe version 1.1 Midpoint Hierarchist method (integrated within SimaPro)(114) was used to characterise emissions, and to combine these into environmental impacts.(107) This method evaluates eighteen midpoint impact categories (each relating to a single environmental problem): global warming, stratospheric ozone depletion, ionising radiation, ozone formation (on human health, and terrestrial ecosystems), fine particulate matter formation, terrestrial acidification, eutrophication (freshwater and marine), ecotoxicity (terrestrial, freshwater, and marine), human toxicity (carcinogenic and non-carcinogenic), land use, resource scarcity (mineral and fossil), and water consumption. The ReCiPe version 1.1 Endpoint Hierarchist method was used to aggregate midpoint impact categories, enabling an evaluation of the associated damage to human health (measured in disability adjusted life years), ecosystems (loss of local species), and resource depletion (financial cost involved in future mineral and fossil resource extraction). Where impact on resource depletion was evaluated, this was reported in US $ in line with results in SimaPro (version 9.10).(114) Finally, ReCiPe version 1.1 Hierarchist normalisation factors were used to compare total midpoint and endpoint impacts to mean average contributions for each of those impacts from a global average person's daily routine activities,(33) and this can be helpful in communicating results of such studies.

Uncertainty assessment

There will be sources of uncertainty limiting the reliability and generalisability of findings of all environmental impact assessments. Parameter uncertainty refers to the extent to which the life cycle inventory and characterisation factors (for example those embedded within SimaPro or the DEFRA/BEIS database) truly reflect the environmental impact of the unit under investigation.(20) In general, the sample size of primary activity data was limited to one, so formal parameter uncertainty analysis (for example through a Monte Carlo approach, or pedigree approach) was not performed as it is not recommended in such instances.(123)

Findings may also be limited by a number of methodological choices, resulting in scenario uncertainty.(20) For example, truncation error exists where the results reported underestimate the true environmental impact due to the system boundary chosen.(111) This was minimised where possible through including all processes reaching the threshold of significance(20) which was defined a priori as those likely to contribute ≥ 1% to total carbon footprint for a given functional unit. The impact of key methodological assumptions can be assessed through formal sensitivity analysis,(23) (also referred to as scenario analysis)(20) and this was conducted for various studies within this thesis. Finally model uncertainty relates to the extent to which the model is representative of the real world, which may be partially evaluated within a sensitivity analysis.(23)

Life cycle costing

Where the financial cost was considered alongside environmental impact, this also took a life cycle approach, with purchase costs of products taken to account for the cost of their manufacture and distribution. Cost of sterilisation was based on the rate charged by the local hospital sterilisation services department (University Hospitals Sussex NHS Foundation Trust), whilst cost of waste disposal was modelled using national NHS Estates Returns Information Collation data.(124)

Ethical considerations

All components of this thesis were observational in nature, and the UK Health Research Authority tool confirmed formal research ethics approval was not required. Approval was however granted by Brighton and Sussex Medical School doctoral review board, and verbal consent was obtained from patients and healthcare staff before operations began where relevant.

CHAPTER 3 The carbon footprint of surgical operations: a systematic review

This chapter relates to the following publication:

- Rizan C, Steinbach I, Nicholson R, Lillywhite R, Reed M, Bhutta MF. The carbon footprint of surgical operations: a systematic review. Annals of Surgery. 2020;272(6):986-995. PMID: 32516230. *Impact factor 13.79*

CHAPTER 3 also includes analysis published within the following letter to the editor:

- Rizan C, Bhutta MF. Re: The carbon footprint of single-use flexible cystoscopes compared to reusable cystoscopes. Methodological flaws led to the erroneous conclusion that single-use is "better". Journal of Endourology. 2022;36(11):1466-1467. *Impact factor: 2.62*

3.1. Introduction

CHAPTER 1 contextualised this thesis within broader literature relating to human and planetary health, narrowing this down to focus on the carbon footprint of products used within the operating theatre. This was followed by an overview of methodological approaches used to evaluate environmental impact in CHAPTER 2. Building upon these chapters, CHAPTER 3 provides a systematic review of the carbon footprint of surgical operations and products used to perform these. As described in CHAPTER 2, LCA is an inclusive evaluation of environmental impact, but the endpoints are numerous and vary with the approaches and impact assessment data sources used, reducing the extent to which direct comparisons can be made between studies, and so only the carbon footprint component of LCA studies are included within this review.

This was the first published systematic review of its kind focusing on carbon footprint evaluations within the operating theatre. Analysis of individual surgical products, surgical suites and national surgical services were excluded from the publication in *Annals of Surgery* at the request of reviewers, in order to tighten the focus of the review, but are included in this chapter as these studies are relevant to this thesis. Prior to this publication, previous reviews of the environmental sustainability of operating theatres mostly focused on waste management strategies, alongside encouraging reduction, reuse, recycling, 'rethinking', and research.(125, 126) Other authors recommended adding in reprocessing of single-use devices, environmentally preferable procurement, and energy consumption management.(127) However, these reviews were predominantly based on low level evidence such as opinion reports, and included studies using a wide variety of methods to measure environmental impact (such as weight of waste, volume of water used, and cost incurred).

The aim of this systematic review was to identify and evaluate existing literature examining the carbon footprint of surgical operations and related products, in order to determine sources of GHG emissions and to inform the focus for this thesis.

The objectives were as follows:

- Systematically review existing literature examining the carbon footprint of surgical operations, including products used by surgeons within the operating theatre
    - Identify carbon hotspots which can be targeted to mitigate carbon footprint associated with delivery of surgery

3.2. Methods

This review was conducted and reported in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.(128)

Study selection

Original peer-reviewed research evaluating the carbon footprint of surgical operations or products used to perform surgical operations were included. Case reports, opinion-based reports, congress abstracts, meta-analyses and studies not written in English were excluded. Studies were also excluded if they focused exclusively on a) pre- or post-operative care b) processes or procedures outside of the operating theatre itself c) anaesthetic components of operations d) pharmaceuticals delivered intraoperatively, e) examined healthcare as a whole (with surgery as a subset), or f) evaluated products used predominantly outside of the operating theatre or for investigation rather than intervention.

The following databases were searched; Cochrane Database (-4/10/19), Embase (1947-2019 week 32), Ovid MEDLINE (1946- Week 32 2019), and PubMed (1966-4/10/19). Two search domains were used (Table 2), with terms within each domain combined by ‘OR’ and the two domains combined using ‘AND’. The search was conducted independently by myself and Dr Rosamond Nicholson. Study titles and their citations were screened, and irrelevant articles and duplicates discarded. Full texts were obtained for remaining articles, followed by applying inclusion and exclusion criteria. The references of included studies were screened for studies not identified through the original search. Ingeborg Steinbach performed a second independent data extraction.

Table 2: Search strategy

Domain	Term	Exploded mapped terms (Embase and Medline only)
Domain 1	operating theatre	
	operating theater	
	operating room	
	operation	
	surgery	
	surgical	surgical procedures, operative
	surgeon	surgeons
Domain 2	carbon footprint	
	climate change	environmental pollution
	ecological footprint	
	ecological sustainability	
	environmental sustainability	conservation of natural resources
	life cycle assessment	

Evaluation of study characteristics

For each study descriptive data was recorded on the study setting (including the country of origin) and the focus of the study (surgical specialty), and carbon footprinting approach (EEIO, process-based approach, or hybrid approach), alongside the carbon footprinting guideline used.

Evaluation of carbon footprint

The GHG Protocol(20) was used as a framework for extracting endpoints in this review. Where there was conflicting terminology between studies, the GHG Protocol(20) was used as the standard, using terms as defined in CHAPTER 2.

For each study, the scope was determined, including the functional unit and system boundary. The material and energy flows that were included were classified according to GHG Protocol(111) definitions of GHG emission types (scope one to three, as defined in CHAPTER 1). The data collected for the life cycle inventory were further categorised according to the data type (process versus financial activity data, and primary versus secondary data). Where reported, further data was also extracted on the number of observations made for a given process, the assumptions made in data collection, and allocation method. For each study, the method of impact assessment was recorded, including sources of emission factors and associated databases. Where possible, numerical values for impact assessment results of overall operations and products were extracted, but descriptive data (e.g. percentages or proportions) and graphical summaries were used where actual values were not recorded.

Evaluation of quality and applicability of studies

Three potential sources of uncertainty were considered within included studies; parameter uncertainty, scenario uncertainty, and model uncertainty. All stated uncertainties and limitations were extracted. Finally, the quality of each study was evaluated making reference to relevant guidelines(20, 21, 23) and critical appraisal tools.(129, 130) Studies were appraised independently by myself and Ingeborg Steinbach and discrepancies were discussed and resolved.

3.3. Results

Study selection and characteristics

The search strategy identified 4,604 records (Figure 2). Screening of titles excluded 4,381 of these and of the remaining 223, 83 were duplicates, leaving 140 articles for full text evaluation. Following application of the inclusion and exclusion criteria, 13 studies were found to be eligible. One further relevant study was identified through screening of included studies' references and another two from my knowledge of the field, resulting in a total of 16 included studies.(25, 26, 27, 28, 30, 69, 79, 91, 94, 96, 112, 131, 132, 133, 134, 135) It was not possible to obtain the full text of one article published in 1993(136) referenced within a review on reusable and single-use perioperative textiles(93) and so this study was excluded.

Of the 16 studies included, six were conducted exclusively in the US,(30, 69, 112, 131, 133, 134) four in the UK,(25, 27, 132, 135) two in Germany,(91, 94) one in Australia,(96) one in Chile(26), one in India(79), and one across three countries (Canada, USA, and UK)(28) (Table 3). Five studies examined topics specific to Obstetrics and Gynaecology,(30, 69, 112, 133, 134) two specific to Ophthalmology,(27, 79) one Gastrointestinal,(25), one Plastic surgery,(26) and one Urology.(96) One study used data from multiple specialties (Gastrointestinal, Urological, Obstetrics and Gynaecology)(131) and five were non-specific.(28, 91, 94, 132, 135)

Figure 2: Flow chart of study selection.
n=number of studies identified from each source

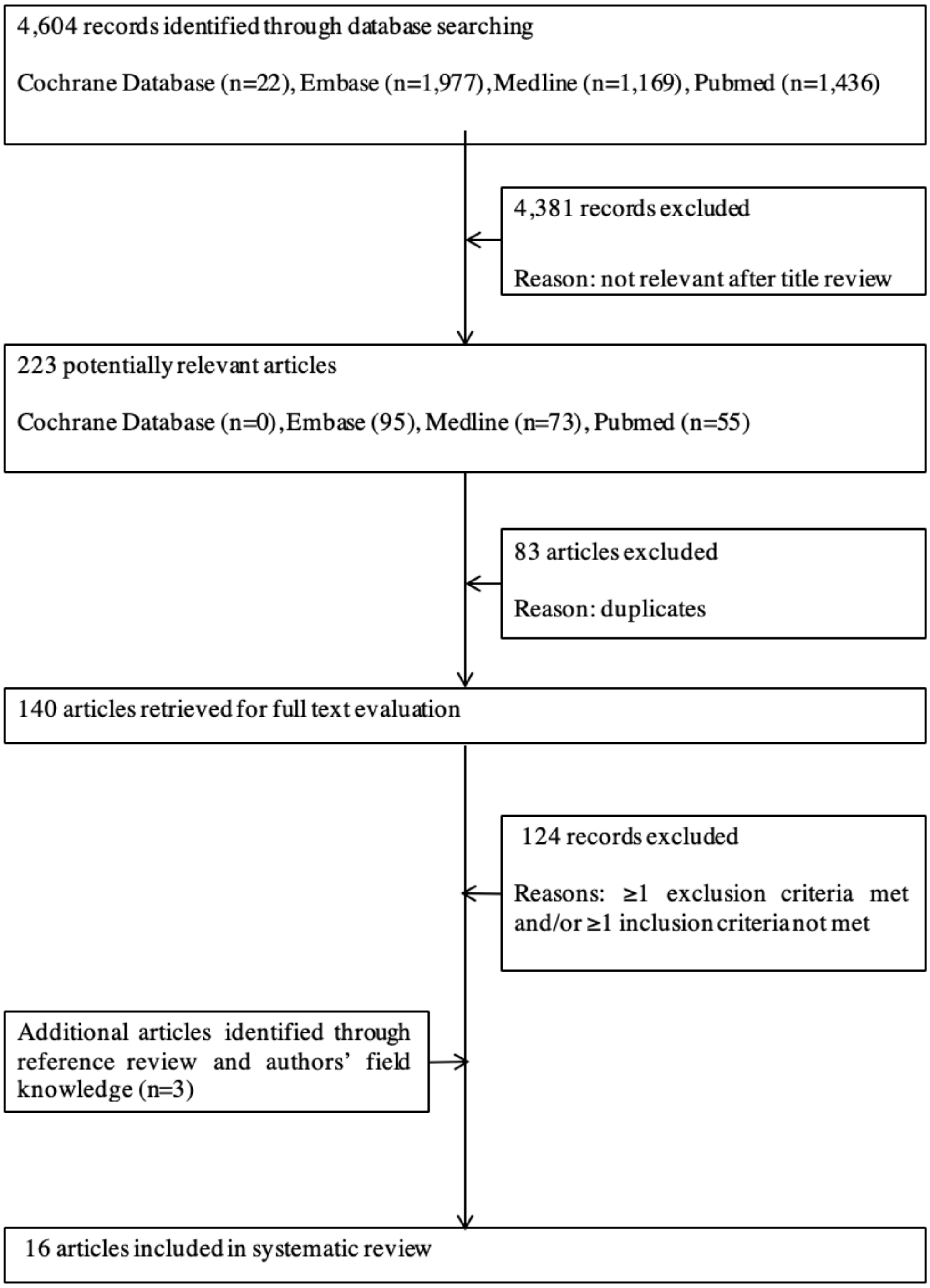


Table 3: Study characteristics and scope
*=inter-related studies, EEIO=Environmentally Extended Input-Output, GHG= greenhouse gas, HVAC= heating, ventilation & air conditioning, ISO=international organisation for standardisation, PAS= publicly available specification

Study characteristics			**Carbon footprinting approach; *guideline***	**Scope (/functional unit); *Start point - end point***
Study (year)	**Study setting; *Country***	**Focus of study; *Surgical specialty***		
Berner et al. (2017)(26)	1 air force teaching hospital; *Chile*	a) Abdominoplasty versus b) bilateral breast augmentation versus c) rhinoplasty; *Plastic surgery*	Process-based *Nil*	1 abdominoplasty/ breast augmentation/ rhinoplasty*; patient/ staff commute to theatre - recovery*
Campion et al. (2012)(112)	1 university hospital; *USA*	Childbirth: a) caesarean section versus b) natural delivery; *Obstetrics and Gynaecology*	Process-based *ISO 14040, ISO 14044*	Birth 1 baby; *a) patient enter theatre - leave b) Stage 2+3 labour*
Davis et al. (2018)(96)	1 hospital; *Australia*	a) Single-use flexible ureteroscope versus b) reusable flexible ureteroscope; *Urology*	Process-based *Not referenced*	1 use of 1 flexible ureteroscope; *Manufacture - end of life*
Gatenby (2011)(25)	21 hospitals; *UK*	Gastroesophageal reflux disease: a) surgical versus b) medical management; *Gastrointestinal*	EEIO *Nil*	1 reflux patient; *Start of secondary care for reflux - end of life*
Ibbotson et al. (2013)(91)	Customer location; *Germany*	Surgical scissors: a) disposable steel versus b) disposable plastic vs c) reusable steel; *Non-specific*	Process-based *ISO 14040*	1 pair of scissors; *Extraction raw material - end of life*
Ison et al. (2000)(135)	2 district general hospitals; *UK*	a) Single-use suction receptacle versus b) reusable suction receptacle at 2 different sites; *Non-specific*	Process-based *Nil*	Collection of 1 kg of bodily fluid; *Extraction raw material - end of life*
Kummerer et al. (1996)(94)	1 university hospital; *Germany*	Laparotomy pads: a) reusable vs b) single-use *Non-specific*	Process-based *Literature*	1 laparotomy pad; *Extraction raw material - end of life*
MacNeill et al. (2017)(28)	3 quaternary care hospitals; *Canada, USA, UK*	Whole operating suite: a) Canadian versus b) USA versus c) UK; *Non-specific*	Process-based *GHG Protocol*	1 surgical suite; *1 - year period*
Morris et al. (2013)(27)	1 university hospital; *UK*	Cataract surgery; *Ophthalmology*	Hybrid *PAS 2050*	Cataract surgery 1 eye; *Referral to 2º care - discharge*

Power et al. (2012)(131)	National database; *USA*	Minimally invasive surgery; *Gastrointestinal, Obstetrics and Gynaecology, Urology, miscellaneous*	Hybrid *GHG Protocol*	National provision minimally invasive surgery; *1 - year period*
Somner et al.(2008)(132)	2 hospitals; *UK*	Surgical scrubbing: a) turning on via elbow versus b) knee; *Non-specific*	Process-based *Nil*	1 surgical scrub; *Start - end of scrub*
Thiel et al. (2015)(69)*	1 university hospital; *USA*	Hysterectomy: a) abdominal versus b) vaginal versus c) laparoscopic versus d) robotic; *Obstetrics and Gynaecology*	Hybrid *ISO 14040, ISO 14044*	1 hysterectomy; *Patient enter theatre - leave*
Thiel et al. (2017)(79)	2 tertiary care hospitals; *India*	Cataract surgery; *Ophthalmology*	Hybrid *ISO 14040*	Cataract surgery 1 eye; *Patient enter theatre - leave*
Thiel et al. (2018)(134)*	1 university hospital; *USA*	Hysterectomy: model interventions a) anaesthesia b) surgical materials & equipment c) energy for HVAC; *Obstetrics and Gynaecology*	Hybrid *ISO 14040, ISO 14044*	1 hysterectomy; *Patient enter theatre - leave*
Unger et al. (2017)(133)*	1 university hospital; *USA*	Hysterectomy: single-use devices containing a) plastics versus b) biopolymers; *Obstetrics and Gynaecology*	Process-based *ISO 14040*	Single-use devices containing plastics suitable for biopolymer substitution; *Extraction raw material - end of life*
Woods et al. (2014)(30)	Not specified; *USA*	Endometrial cancer staging: a) laparoscopy vs b) laparotomy versus c) robotic; *Obstetrics and Gynaecology*	Process-based *PAS 2050, GHG Protocol*	1 endometrial staging procedure; *Patient enter theatre - leave*

Variation in carbon footprint approach

The carbon footprint method and terminology varied between studies (Table 3). Ten studies exclusively used ‘bottom-up’ process-based approaches, of which four simply described their method as a ‘carbon footprint’,(28, 30, 96, 132) one described it as a ‘multi-component analysis/carbon footprint’,(26) and the other five conducted full LCAs.(91, 94, 112, 133, 135) One of the LCA studies termed this a ‘life cycle inventory’.(94) A ‘top-down’ EEIO was used exclusively by one study(30) and was referred to simply as a ‘carbon footprint’. Five studies used a hybrid approach, using both EEIO and process-based approaches, of which four termed this an ‘[economic/] environment input output life cycle assessment’ (69, 79, 131, 134) and one a ‘component analysis study’.(27)

Six studies(69, 79, 91, 112, 133, 134) reported following ISO guidelines,(23) three(28, 30, 131) following the GHG Protocol Product Standard(20) and two (27, 30) using PAS 2050 guidelines.(21) Two other studies reported using guidelines but did not specify which one(s),(94, 96) and four studies did not state the use of any guideline.(25, 26, 132, 135)

Variation in scope

The functional unit for two studies was whole surgical suites or national surgical services,(28, 131) eight looked at individual surgical operations,(25, 26, 27, 30, 69, 79, 112, 134) and six examined specific surgical products or processes.(91, 94, 96, 132, 133, 135) The system boundaries are compared across studies in Table 4 and detailed in Supplementary table 1, with stated exclusions listed in Supplementary table 2.

In the ten studies examining whole surgical processes (surgical suites, national pathways, or operations),(25, 26, 27, 28, 30, 69, 79, 112, 131, 134) the majority included electricity consumption (relating to electronic equipment, heating, ventilation, air conditioning, and lighting), which constitute scope two GHGs emission. The majority also included theatre waste (with variable inclusion of specified waste streams) and linen laundering (both constituting scope three GHG emissions). There was variable inclusion of processes involved in the production of single-use and reusable products (raw material extraction, manufacturing, and transport) and linen manufacture (all scope three). Most studies omitted pre- and post-operative processes, patient and staff travel, capital goods manufacture, water use, and processing of reusable equipment (all scope three), and pharmaceuticals (including scope one anaesthetic gases and CO_2 gas insufflation where relevant). The six studies(91, 94, 96, 132, 133, 135) focusing on specific products or processes had more consistent system boundaries.

Variation in data collected, allocation method, and impact assessment method

No studies collected direct emissions data. Six studies used primary process activity data only,(26, 28, 30, 112) one used secondary process activity data only(94), one used secondary financial activity data only(25) and all others used a mixture of data types (Supplementary table 1).(27, 69, 79, 91, 96, 131, 132, 133, 134, 135) Where studies used financial activity data within an EEIO model, this incorporated all three scopes of GHG emissions where relevant. The assumptions made within data collection are listed in Supplementary table 2. Allocation methods were explicitly stated by four studies,(69, 79, 112, 134) and a range of data sources were used for impact assessments (Supplementary table 1).

Heterogeneity in functional units, methodology, and reporting of results limited comparison across studies, and meant that meta-analysis was inappropriate. The extracted study result endpoints are presented in full in Supplementary table 3.

Table 4: Study system boundaries

Cells are in grey where the process was not relevant to the study. Where broad processes were included these are in parenthesis (), and are likely to involve other related processes within the same process/ item section. X= process was included, ?= inclusion of given process ambiguous, op.= operative

Phase	Process/ item		Surgical suite/ national pathway		Specific surgical operation studies								Specific surgical device/ specific process studies					
			MacNeill et al.(28)	Power et al.(131)	Berner et al.(26)	Campion et al.(112)	Gatenby(25)	Morris et al.(27)	Thiel et al.(69)	Thiel et al.(79)	Thiel et al.(134)	Woods et al.(30)	Davis et al.(96)	Ibbotson et al.(91)	Ison et al.(135)	Kummerer et al.(94)	Unger et al.(133)	Sommer et al.(132)
Pre-op.	Investigations						X											
	Outpatient appointments						X	X										
	Outpatient building energy use						?	X										
Operation	Patient/staff travel for day of surgery				X			X										
	Capital goods manufacture						?											
	Electronic equipment energy		?		X	X	?	?	X	X	X	X						
	Heating		X			X	?	?	X		X	X						
	Ventilation, air conditioning, lighting		X			X	?	?	X	X	X	X						
	(Theatre energy use)				X			X			X							
	Water	Treatment before/after use					?	?		X								
		Heating					?	?										X
		(Water)						X										
	Anaesthetic gases	Production	X				?	?	X		X							
		Direct emissions	X				?	?	X		X							
	Intravenous anaesthetics	Production	?				?	?	X	?	X							
		Direct emissions	?				?	?	X	?	X							
	Gas insufflation	Production		X			?											
		Direct emissions		X			?		X									

	(Operation time)						X											
	Linen	Manufacture					?		X		X							
		Washing and drying	X				?	X	X	X	X							
		Transport to linen facility			X		?	X										
	Products production	Raw material extraction	X			X	?	X	X	X	?			X	X	X	X	
		Manufacturing				X	?	X	X	X	?			X	X	X	X	
		Transport in procurement				X	?	X	X	?	?			X	X	X	?	
		(Material)					?	X					X					
		Packaging					?	X							X	X	X	
	Single-use products waste disposal	Incineration	X	X		X	?	?	X	?				X	X			
		Landfill	X		?	X	?	?	X	?		X			X	X		
		Waste sterilisation	X			X	?		X	?								
		Recycling	X				?		X	X	X			X			X	
		Unspecified waste processing					?						X				X	
	Reusables processing	Sterilisation	X			X	?		X	X	X		X	X	X	X		
		Repair					?						X	X				
	Reusable products waste disposal	Incineration	?		?		?	?		?				X				
		Landfill	?		?		?	?		?					X	X		
		Recycling	?				?			?				X				
		Unspecified waste stream					?						X					
	(Unspecified type of theatre waste)	Incineration					?	X		X	X							
		Landfill			X		?	X		X	X							
		Waste sterilisation					?				X							
	Transport of (any measured) waste					X	?		X					X		X		
Peri/post-op	Recovery building energy & landfill waste				X		?											
	Postoperative inpatient care						X	X										
	Inpatient pharmaceuticals						X	X		X								
	Information technology, patient food & drink, stationary						?	X										
	Medical equipment						?	X										
	Outpatients follow up						X	X										
	Outpatient pharmaceuticals						X	X										

Annual emissions from a national pathway or entire operating suites

Data on total and component CO_2 emissions are presented graphically in Figure 3 for national pathways, and in Figure 4 for entire operating suites.

Power et al.(131) found that the national annual impact of minimally invasive surgery in the USA (over and above conventional surgery, based on CO_2 gas used for abdominal insufflation) was 355,924 t CO_2e per year (141 kg CO_2e per operation). Two studies extrapolated results of individual operations to estimate national data, concluding that hysterectomies in the USA generate 212,000 t CO_2e per year (~285 kg CO_2e - 562 kg CO_2e per operation)(69) and cataract surgery in the UK generates 63,000 t CO_2e per year (182 kg CO_2e per operation).(27)

MacNeill et al. compared the carbon footprint of a whole operating suite across one year in three large hospitals in the UK, Canada, and USA,(28) finding this ranged between 3,219 t CO_2e - 5,188 t CO_2e. Emissions at the Canadian hospital were 146 kg CO_2e per case, compared with 173 kg CO_2e per case in the UK, and 232 kg CO_2e per case in the USA, representing a 1.6 fold variation between the lowest and highest values.(28)

Analysis of single operations

The eight studies looking at single operations showed a wide range of carbon footprints of between 6 kg CO_2e - 814 kg CO_2e, which is summarised in Figure 5, Figure 6, and Figure 7.(25, 26, 27, 30, 69, 79, 112, 134) Berner et al.(26) found that an abdominoplasty had a greater carbon footprint than a rhinoplasty, which in turn was greater than a bilateral breast augmentation. Morris et al.(27) calculated the carbon footprint of a cataract operation in the UK at 182 kg CO_2e, whilst Thiel et al. calculated this to be 6 kg CO_2e in India.(79) Whilst the decision to manage a patient medically or surgically (and the surgical approach taken), is a decision made by the surgeon based upon clinical grounds and taking into account patient preference, a number of studies compared their carbon footprints. Thiel et al.(69) and Woods et al.(30) found that the most carbon intense approach to gynaecological surgery was robotic, followed by the laparoscopic approach, followed by laparotomy (followed by trans-vaginal approach within the former study). Two studies calculated the carbon footprint of an operation and compared it to non-surgical options. Campion et al.(112) found that the carbon footprint of a caesarean section was twice that of a vaginal delivery. However, none of these studies considered any processes beyond the theatre boundary, so did not take into account the impact that different surgical approaches have on length of hospital stay, infection (or other complication) rate, or need for further intervention (all with associated GHG emissions). Gatenby(25) found that the carbon footprint of surgical approaches to gastro-oesophageal reflux disease treatment was higher than medical treatment up to nine years after the operation, but becomes more carbon efficient thereafter.

Table 5: Legend for Figure 3, Figure 4, Figure 5, Figure 6 and Figure 7.
CO_2= carbon dioxide, HVAC=heating, ventilation and air conditioning

Bar colour	Category	Sub-category	
	Electricity	E1= Building energy (theatre)	E2= Building energy (recovery)
		E3= Electricity use	E4= HVAC
		E5= Lighting	E6= Medical equipment energy
		E7= Operation time	E8= Plug load
	Water	W=Water	
	General products (single-use versus reusables unspecified)	G1= 'Procurement'	G2= Waste
	Reusable products	R1= 'Reusable instruments'	R2= Reusable product production
		R3= Reusable product production & sterilisation	R4= Reusable product sterilisation
		R5= Reusable linen laundry	
	Single-use products	S1= Single-use products production	S2= Single-use instruments production
		S3= Single-use non-instrument products (gowns, gloves etc)	S4= Single-use production and waste
		S5= Waste (single-use trocar & robotic instrument)	S6= paper and ink, information technology, food
	Pharmaceuticals	P1= CO_2 capture/ compression	P2= Pharmaceuticals
		P3= Pharmaceuticals (ongoing post-op)	P4= Anaesthetics
	Transport	T1= CO_2 transportation	T2= Laundry transport
		T3= Patient travel	T4= Staff travel
		T5= Travel (unspecified)	T6= Waste transport
	Other peri-operative	O1= Day case	O2= Inpatient care
		O3= Outpatient appointment	O4= Outpatient tests
	Total	Total (no breakdown available)	

Figure 3: Carbon footprint of national pathways
Figure legend in Table 5. CO_2e= carbon dioxide equivalents, MIS= minimally invasive surgery

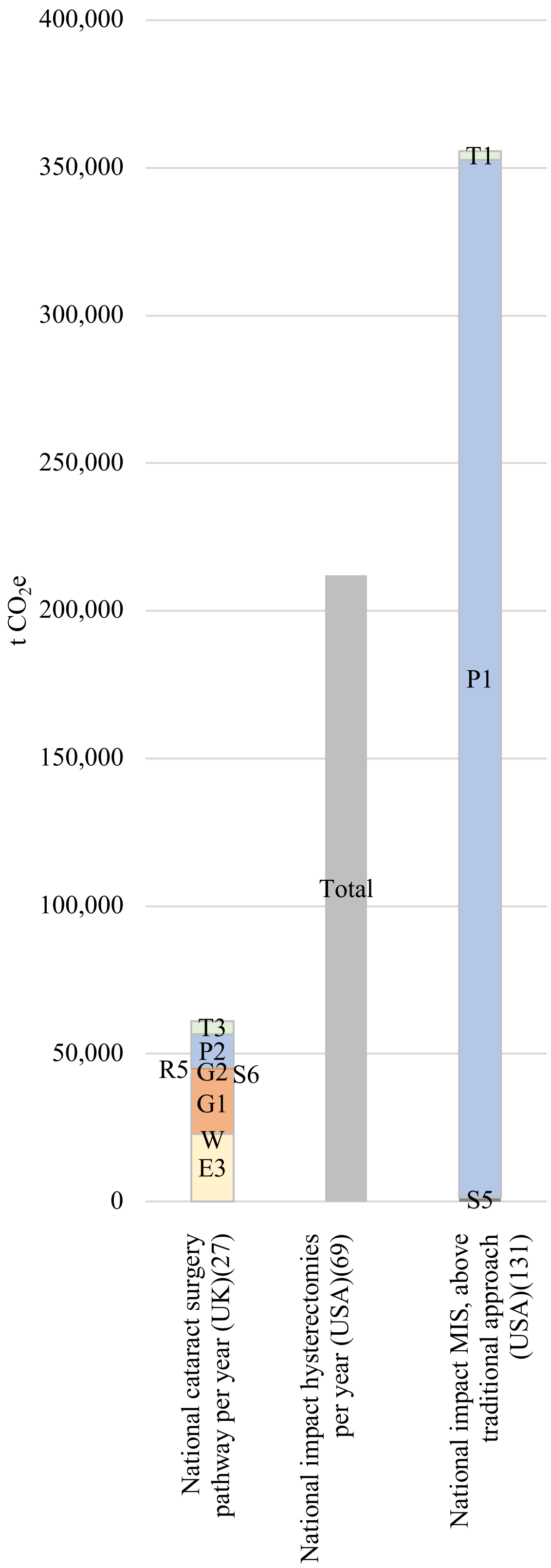


Figure 4: Carbon footprint of operating suites
Figure legend in Table 5.
CO_2e= carbon dioxide equivalents

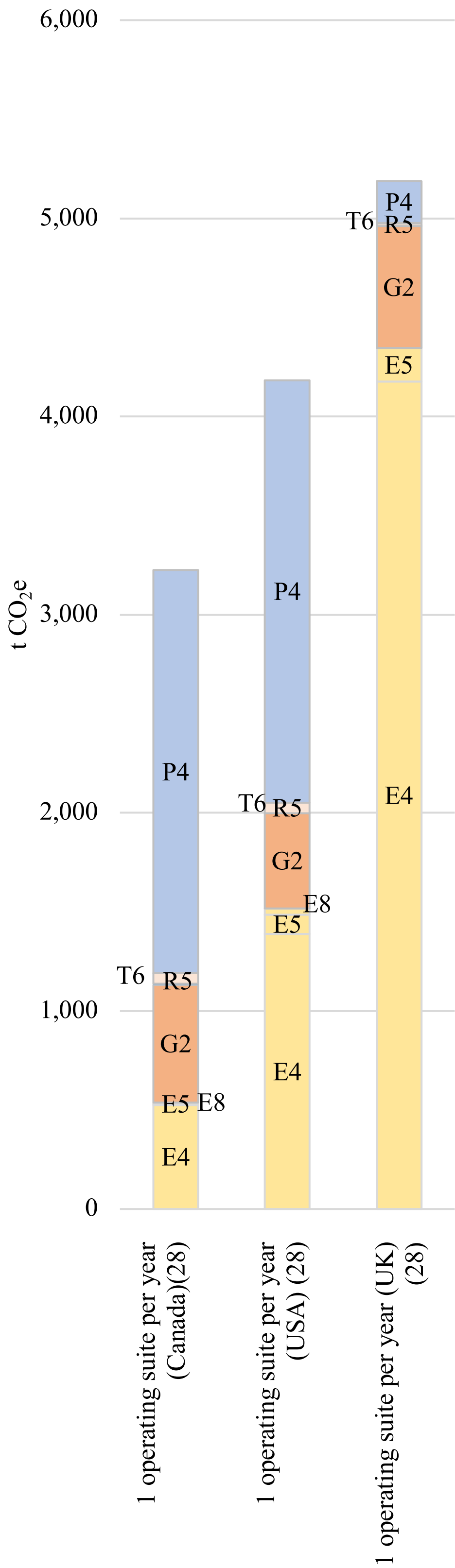


Figure 5: Carbon footprint of individual operations

Figure legend in Table 5. Some studies reported results in CO_2e (carbon dioxide equivalents), others in CO_2 (carbon dioxide). Where results were not provided in numerical form, these were estimated using descriptive or graphical data where possible (denoted by ~before study in y axis). Two studies used the same dataset, allowing extrapolation of results of Theil et al.(2015)(69) from Thiel et al. (2018)(134).

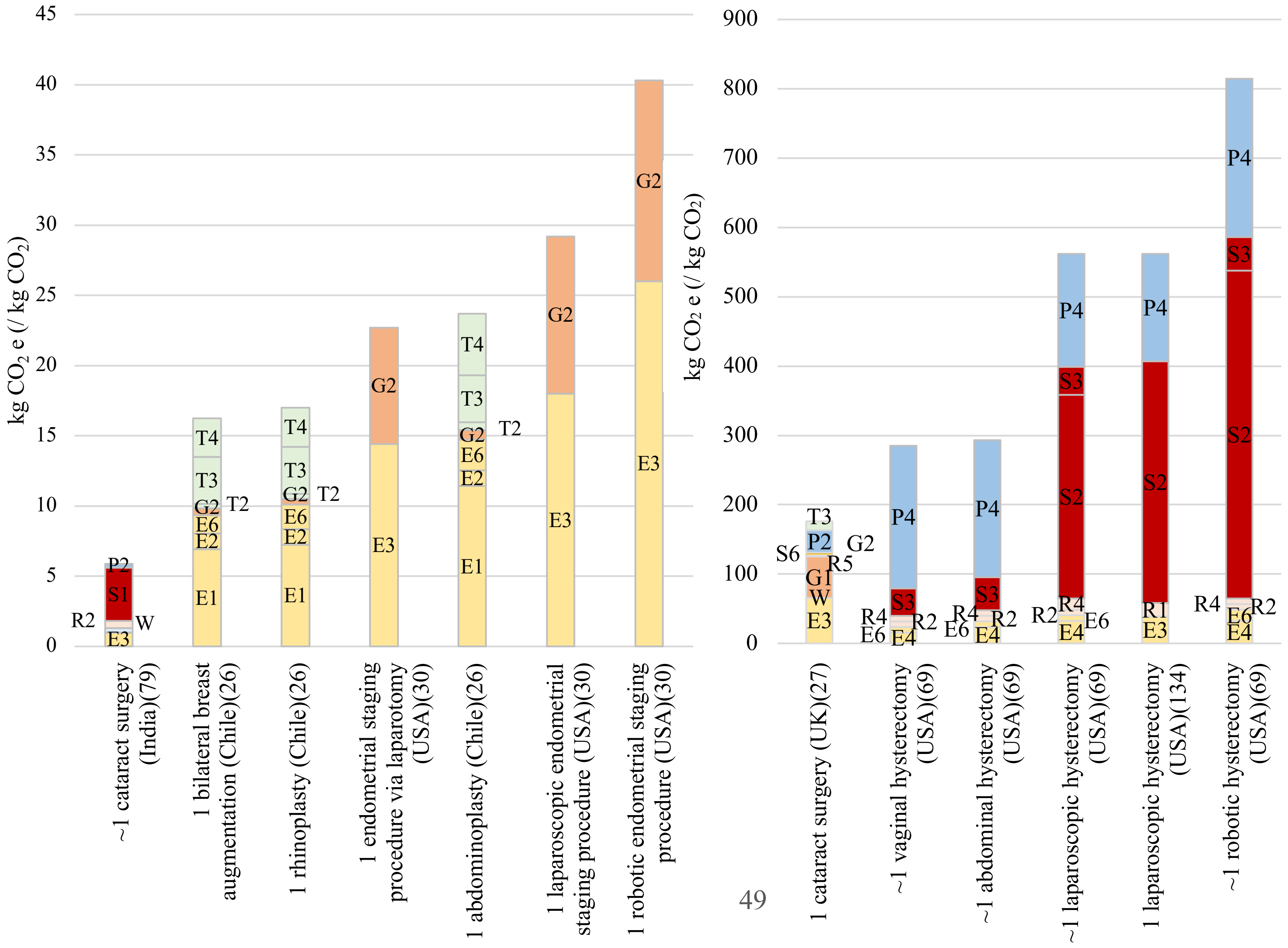


Figure 6: Carbon footprint results of one caesarean section
Figure legend in Table 5. The absolute carbon footprint was not provided in this study, but relative contributions from various processes were reported and are indicated here

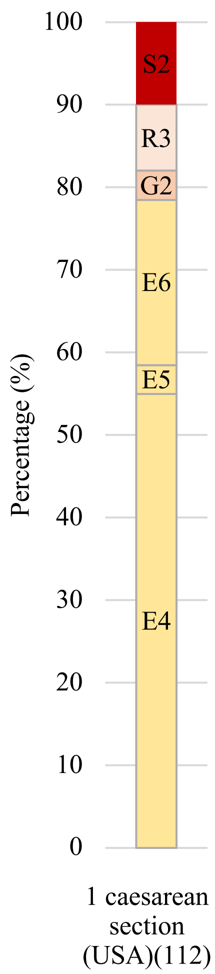
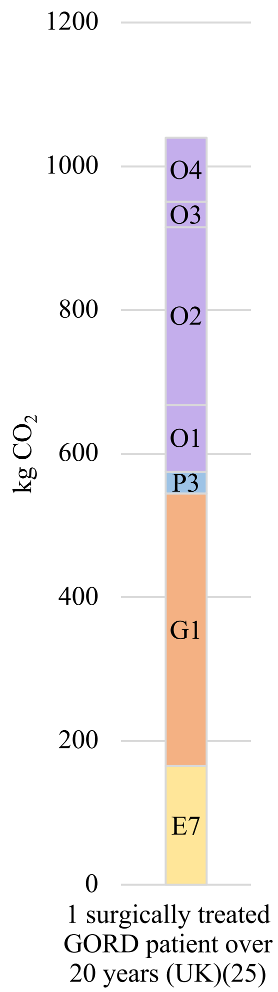


Figure 7: Carbon footprint results of surgically treated GORD patient over 20 years
Figure legend in Table 5. CO_2= carbon dioxide, GORD= gastro oesophageal reflux disease



Analysis of contributions to overall carbon footprints and carbon hotspots

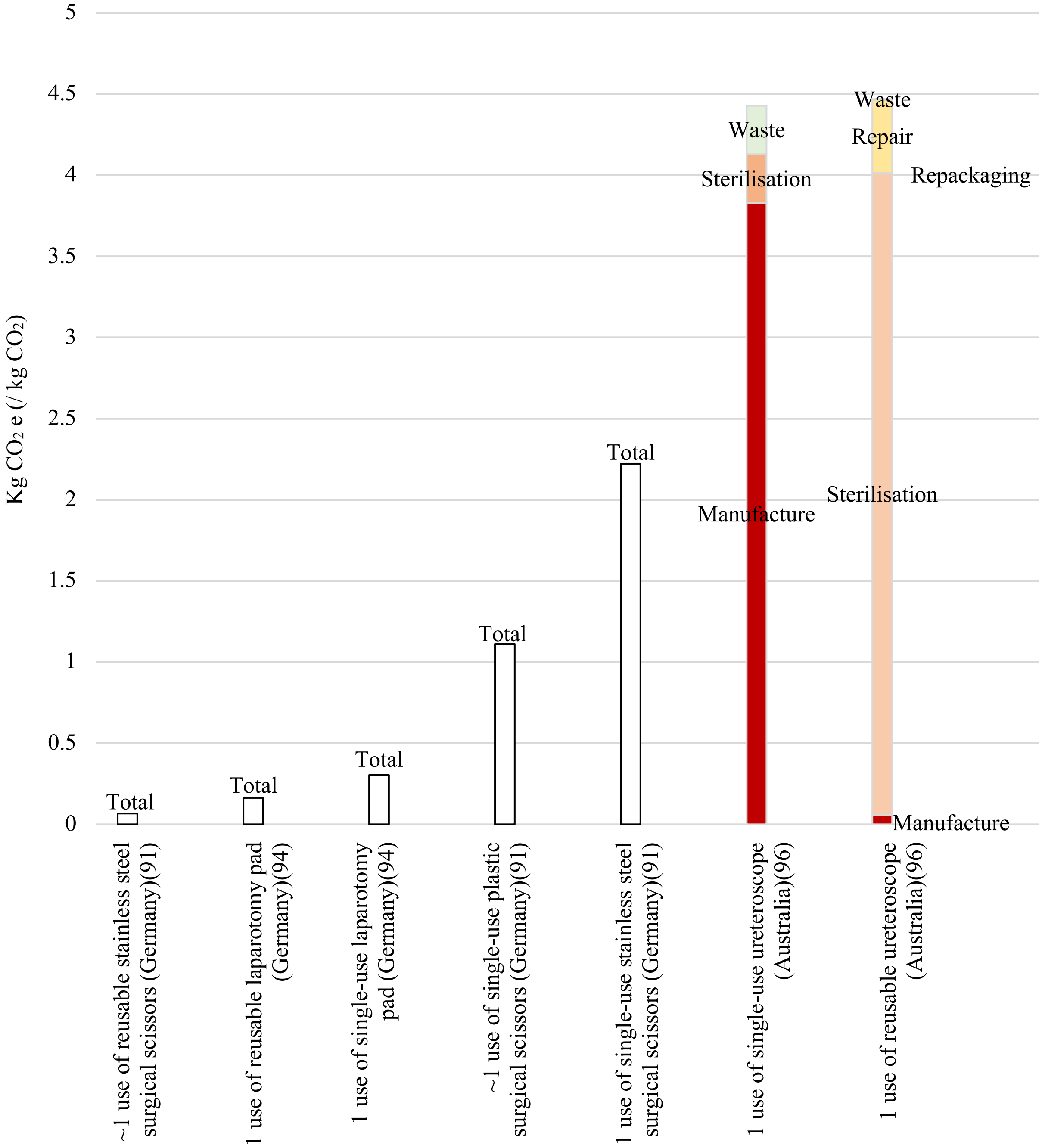
The relative contributions of individual processes to the overall carbon footprint of surgical operations are illustrated within Figure 3 - Figure 7. When measured, the choice of anaesthetic agent had a significant impact. In US and Canadian operating suites where desflurane was used, anaesthetic gases were responsible for 51% and 63% of the carbon footprint of operating suites across one year respectively,(28) but in the UK site, where desflurane was not routinely used, electricity consumption was the largest contributor, at 84% of emissions.(28) Three other studies(26, 30, 112) found electricity to be the largest source of GHG emissions, accounting for 63-78% of the carbon footprint of whole operations, but these studies did not include anaesthetics within study boundaries. The amount of electricity consumed is likely to be closely linked with the operation duration. By contrast, in cataract surgery(27, 79) and hysterectomies,(69, 134) procurement of products played a larger role (for example procurement of medical equipment accounted for up to three-quarters of the carbon footprint of a cataract operation).(79)

In three studies where electricity use was broken down, the highest consumption of electricity was for maintaining the theatre environment (heating, ventilation, and air-conditioning).(28, 69, 112) By contrast, four studies(27, 69, 79, 134) found procurement of products to be the largest hotspot, with three(69, 79, 134) specifically identifying single-use products to be largest contributors, responsible for up to two-thirds of the carbon footprint of the operation.(79) In the two studies that accounted for patient and staff travel to hospital, this was responsible for 10% - 37% of the footprint.(26, 27)

Analysis of single products or surgical processes

The carbon footprint associated with an individual surgical product ranged between ~0.07 kg CO_2 - 4.47 kg CO_2 (Figure 8). Of studies specifically evaluating the carbon footprint of reusable surgical products, for reusable stainless steel scissors this was around 3% that of single-use equivalents,(91) and for reusable laparotomy pads this was around half that of single-use equivalents.(94) Ison et al.(135) found that the global warming potential of reusable suction receptacles was less than that of single-use equivalents at the same hospital, but was significantly affected by washing machine cycle lengths at different hospital sites, and resulting water and energy consumption. By contrast Davis et al. found that reusable ureteroscopes were slightly more carbon intensive than single-use equivalents in Australia.(96) Unger et al.(133) found that switching plastics for biopolymers within single-use hysterectomy devices only marginally increased their carbon footprint. Somner et al.(132) concluded that switching from elbow to knee operated taps in theatre saved around 80 g CO_2 per surgical scrub.

Figure 8: Carbon footprint results of individual surgical devices
Where results were not provided in numerical form, these were estimated using descriptive or graphical data where possible (denoted by ~before the study). CO_2e= carbon dioxide equivalents.



Quality of studies

Table 6 evaluates the quality and risk of bias within studies using a scoring system devised using relevant guidelines(20, 21, 23) and critical appraisal tools.(129, 130). As previously outlined in Table 4, study inventory boundaries excluded potentially relevant processes across all studies aside from two.(25, 91) The other parameter relevant to study completeness was the incorporation of GHG scopes, and all three were accounted for in eight studies,(25, 27, 28, 69, 79, 94, 131, 134) two scopes by six studies (26, 30, 91, 96, 112, 135) and one scope in two studies.(132, 133)

In comparing functional units, one study failed to apply consistent methods across different units of analysis, making the assumption that laundering of linen observed at a study site in one country was representative of processes in sites in other countries.(28) Likewise, another study observed reusable suction receptacles at one study site upon actual use, whilst at another site (where reusables are no longer in use), their use was simulated.(135)

A clear hypothesis was absent from all studies, increasing risk of post-hoc analysis and selective reporting. The number of GHGs included was explicitly stated in eight studies.(25, 26, 27, 94, 96, 131, 132, 135) Transparency was limited by failure to state either assumptions or exclusions within seven studies,(26, 91, 94, 96, 132, 134, 135) and two(69, 133) did not state either. For a given process, the number of observations or data points collected was reported in three studies for all processes,(25, 30, 132) reported ambiguously or for a limited number of processes in eight studies,(26, 27, 28, 69, 79, 133, 134, 135) and not reported in five.(91, 94, 96, 112, 131) Nine studies reported the carbon footprint as numerical data for all key component processes,(25, 26, 27, 28, 30, 94, 96, 131, 134) and three (69, 79, 132) reported limited numerical data, with some important component process results presented as descriptive or graphical data. Three studies(91, 112, 133) reported only descriptive or graphical data, and one further study reported ‘GHGs’ only (with no carbon dioxide equivalents) on a logarithmic scale graph without units.(135)

Table 6: Evaluation of quality of studies

Each study is scored on a number of questions using a scoring system on a scale of 0-2 (specified in italics for each question). Cells containing scores of 0 marked in red, 1 in yellow, and 2 in green, with grey indicating the question was not relevant to the study. 1°= primary, 2°= secondary, CI= confidence interval, GHG= greenhouse gas

Category	Questions, *scoring system*	Berner et al.(26)	Campion et al.(112)	Davis et al.(96)	Gatenby(25)	Ibbotson et al.(91)	Ison et al.(135)	Kummerer et al.(94)	MacNeill et al.(28)	Morris et al.(27)	Power et al.(131)	Somner et al.(132)	Thiel et al.(69)	Thiel et al.(79)	Thiel et al.(134)	Unger et al.(133)	Woods et al.(30)
1) Completeness	a) To what extent were study inventory boundaries complete for a given functional unit? *Includes all reasonable factors: (2) Includes limited/ ambiguous factors (1) Narrow focus (0)*	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1
	b) Did the study account for all 3 scopes of GHG associated with the functional unit? *All 3 scopes measured: (2) 2 scopes measured (1) Scopes limited to 1 (0)*	1	1	1	2	1	1	2	2	2	2	0	2	2	2	0	1
2) Consistency	a) To what extent was the study consistent with a recognised carbon footprinting guideline? *Stated and referenced: (2) Stated, not referenced (1) No guideline stated (0)*	0	2	1	0	2	0		2	2	2	0	2	2	2	2	2
	b) For comparative studies, how consistently were methods applied? *Consistently applied throughout: (2) Limited consistency (1) Poor consistency (0)*	2	2	2	2	2	1	2	1			2	2		2	2	2
3) Transparency	a) Were the hypothesis(/es) and study objectives clearly stated? *Both clearly stated: (2) Either hypothesis or study objectives stated (1) Neither stated (0)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

	b) To what extent were the GHGs included clearly stated? *Number of GHGs included clearly stated: (2) Number of GHGs deducible (1) Number of GHGs not deducible (0)*	2	1	2	2	1	2	2	1	2	2	2	1	1	1	1	1
	c) To what extent were study assumptions and exclusions clearly stated? *Both assumptions and exclusions stated: (2) Limited (1) Neither stated (0)*	1	2	1	2	1	1	1	2	2	2	1	0	2	1	0	2
	d) To what extent were the number of data points collected per process clearly stated? *Clear for all processes: (2) Clear for limited processes (1) Not stated for any processes (0)*	1	0	0	2	0	1	0	1	1	0	2	1	1	0	1	2
	e) How transparent were reported GHG results? *Numerical data for all sub-processes: (2) Limited numerical data for some sub-processes (1) Descriptive or graphical data only (0)*	2	0	2	2	0	0	2	2	2	2	1	1	1	2	0	2
4) Accuracy	a) What was the specificity of the data sources to the study site? *1° data only: (2) Both 1°* and *2° data (1) 2° data only (0)*	2	2	1	0	1	1	0	2	1	1	1	1	1	1	1	2
	b) Did the study determine parameter uncertainty? *Clear statistical plan with CI reported: (2) CI reported, no clear plan (1) No CI or plan (0)*	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2
	c) Did the study determine scenario uncertainty? *Yes, demonstrating minimal uncertainty: (2) Yes, demonstrating large uncertainty (1) No (0)*	0	2	0	0	1	0	0	0	0	0	0	1	2	0	2	0
Total	Percentage (%)	54	58	50	63	50	38	50	63	64	59	50	58	64	54	46	75

The accuracy of studies was firstly addressed by establishing the specificity of data sources (primary or secondary data sources), as previously discussed (Supplementary table 1). Parameter uncertainty (uncertainty relating to data collected or emissions factors) was evaluated within three studies,(30, 69, 132) but one failed to report confidence intervals.(69) Four studies evaluated scenario uncertainty (uncertainty due to methodological assumptions), three(79, 112, 133) found modelling affected results minimally, whilst another(91) found this varied results by 0.3% - 19%.

The extent to which the results of included studies may hold external validity to other operations of the same type is limited, for example due to inventory boundaries, use of country-specific emission factors, and differences in the operative processes between patients, surgeons, and hospital settings. Further limitations and assumptions (both stated and identified by authors) are summarised in Supplementary table 2. There was a risk of publication bias across studies, although studies were published without statistically significant effect sizes.

3.4. Discussion

This review found that the carbon footprint of a single operation ranged from 6 kg CO_2e (for cataract surgery in India)(79) to 814 kg CO_2e, (for a robotic hysterectomy in the USA),(69) with the largest value being equivalent to driving up to 2,268 miles in an average petrol car.(31) MacNeill et al. compared the carbon footprint of whole operating suites across one year in three large hospitals in the UK, Canada, and US,(28) finding this ranged between 3,219 t CO_2e - 5,188 t CO_2e. Whilst this study did not look at specific individual operations, results of average operations were in keeping with included studies, with emissions of 146 kg CO_2e per average case at the Canadian hospital, 173 kg CO_2e in the UK, and 232 kg CO_2e in the USA(28) (equivalent to driving 407-646 miles in an average petrol car).(31)

The observed variation in carbon footprint of surgical operations may be due to differences in methods and boundaries, and the carbon footprint of different operations will likely depend upon the invasiveness of the procedure, patient factors, and the surgical team, which will each impact on operative time and consumables used. The carbon footprint estimates do however need some caution, particularly in comparing results between studies due to significant differences in inventory boundaries, assumptions, and other methodological considerations. Certain practices may be very context dependent, for example Thiel et al. (79) examined operating rooms in two private Indian tertiary care centres, and reported routine re-use of surgical gloves across 10 cataract operations and high theatre throughput (93 cases per day): practices that differ from those in better resourced settings.

This review found that the major carbon hotspots within operating theatres were a) energy use,(26, 28, 30, 112) and b) single-use products,(69, 79, 134) both of which can be targeted for improvement. Anaesthesia was another important consideration (especially where desflurane was used),(28) but is beyond the scope of this thesis, and it is principally within the control of anaesthetic departments, whose policy development is an important component of future strategies.(28, 137)

The main source of energy consumption was maintaining the theatre environment (heating, ventilation, and air-conditioning), whilst the contribution from plug-loads and lighting was 1.5% - 8.4% of total theatre energy carbon footprint.(28) Approaches to minimising electricity use include developing and installing occupancy sensors,(112) low-energy lighting, energy-efficient air-conditioning systems and water cooling systems.(127) Improving the energy efficiency of USA hospitals by 30% has been estimated to save \$1 billion (£0.83 billion; exchange rate 12th August 2022) and a reduction in carbon emissions of 11 Mt CO_2e.(138) Electricity should also be switched to renewable rather than fossil fuel based sources. The greatest potential to influence energy use is therefore at the theatre design stage or through retrofit, and this largely falls within the remit of facilities and estates teams. Surgeons should be mindful to turn off equipment when not in use, although the potential for a given surgeon to have influence on theatre energy consumption on a day-to-day basis will typically be limited.

The choice of products used to perform a surgical operation is largely influenced by surgeons.
Three studies found single-use products to be largest contributors,(69, 79, 134) responsible for up to two-thirds of the carbon footprint.(79) This is supported by studies published since the last review date of the systematic review in this chapter (October 2019), including two ophthalmology studies evaluating the carbon footprint of cataract surgery in France (estimated at 81 kg CO_2e per operation)(139) and New Zealand (152 kg CO_2e per operation),(140), with both studies finding that single-use products were the

largest contributors of GHG emissions (73% and 77% of total respectively). Further subsequent studies evaluating the carbon footprint of cardiac surgery (estimated at 124 kg CO_2e per operation)(141) and coronary artery bypass graft (505 kg CO_2e per operation)(142) also found that the majority of emissions (89% and 80% respectively) related to the production of single-use products. Other studies evaluating the carbon footprint of surgical operations published since the review date include an evaluation of carpal tunnel decompression (83 kg CO_2e per operation)(143) with methodological concerns discussed in detail within the discussion in CHAPTER 4, and a carbon footprint of waste generated during neurosurgical procedures (25 kg CO_2e per operation, based upon waste only) which used outdated 2011 DEFRA/BEIS emission factors.(144)

Three studies included in this systematic review (evaluating surgical scissors,(91) laparotomy pads,(94) and suction receptacles)(135) suggest that the carbon footprint of products can be reduced (by 50% - 97%) through switching from single-use to reusable surgical devices. Studies evaluating the carbon footprint of products included in the systematic review in this chapter were limited in terms of granularity of data presented, aside from one study of reusable ureteroscopes which indicated that the majority (86%) of the carbon footprint of a single-use ureteroscope was associated with product manufacture, whilst for reusable equivalents this was sterilisation using an endoscope washer disinfector (88%).(96)

The finding that reusable surgical products have lower environmental impact compared with single-use equivalents is supported by findings of a subsequent systematic review by Drew et al. published in 2021.(78) This review found the carbon footprint of reusable products used within the operating theatre were lower than single-use equivalents across 28 included studies, aside from a study of spinal fusion sets(95) (as discussed in CHAPTER 1) and where Australian electricity was modelled. As discussed in CHAPTER 1, LCA studies conducted in Australia found GHG emissions generated through use of a single-use ureteroscope were similar to reusable equivalents,(96) whilst that of single-use central venous catheter kits(97) and anaesthetic equipment(98) were lower than reusables. The more recent review by Drew et al.(78) included studies evaluated within the systematic review in this chapter, alongside others which were excluded due to their focus on anaesthetic products, pharmaceuticals, and products used predominantly outside the operating theatre, alongside multiple studies evaluating surgical textiles which failed to meet the inclusion criteria (for example constituting industry reports). Two studies evaluated in the review by Drew et al.(78) which would have been included in this systematic review (if published before the last review date) include a study finding the carbon footprint of a reusable spinal fusion instruments set had a greater carbon footprint than a single-use set.(95) This study was discussed in CHAPTER 1, and there were far more instruments in the reusable set compared with the single-use 'equivalent', making the comparability of the functional units here debatable.(95) A second study which would have been included evaluated titanium femoral knee implant manufacture, finding that additive manufacturing (using electron beam melting) was associated with four-fold carbon footprint reductions compared with conventional manufacturing using milling.(145)

A study by Hogan et al.(146) published after the last review date of this systematic review (and after that of Drew et al.)(78) also contradicted the general trend (that reusable surgical products have lower carbon footprint compared with single-use equivalents), finding that the carbon footprint of single-use cystoscopes (2.4 kg CO_2 per use) was lower than that of reusables (4.2 kg CO_2 per use).(146) Hogan et al.(146) cited the ureteroscope study by Davis et al.(96) as the source of the carbon footprint of manufacture of single-use cystoscopes, but reported this at 8.51 kg CO_2 per kg of scope,(146) whilst the original study by Davis et al.(96) reported this at 12.8 kg CO_2e (with no justification for adjustment). Using this conversion, manufacturing the 158 g single-use cystoscope modelled by Hogan et al. would generate approximately 2 kg CO_2, resulting in total carbon footprint of 3.09 kg CO_2 per single-use cystoscope (assuming all other study parameters).(146) Sterilisation accounted for the majority (83%) of the reusable cystoscope carbon footprint, based upon the following assumption; 'sterilisation performed within the department using the Olympus ETD-Double™ can reprocess up to 3 cystoscopes per cycle, with a cycle consuming 10.5 kW of electricity, equating to 10.5 kg of CO_2 cycle or 3.5 kg of CO_2 (IQR 0) per case.'(146) UK government greenhouse conversion factors estimate that consumption of one kWh UK electricity generates 0.29 kg CO_2e.(31) The generation of 10.5 kg CO_2 per cycle implies use of approximately 36 kWh electricity, indicating a sterilisation cycle of 3.4 hours (at 10.5 kW). Hogan et al. do not report the Olympus ETD-Double™ cycle duration, but this is reported elsewhere at 35 minutes,(147) aligning with experience at my local sterilisation services department (45 minutes per endoscope washer-disinfector cycle). Assuming power consumption of 10.5 kW for a 35 minute cycle (equating to 6.13 kWh), the carbon footprint of electricity used for sterilisation would be approximately 1.78 kg CO_2 per cycle (0.59 kg CO_2 per cystoscope). Assuming all other parameters from the study by Hogan et al.,(146) this indicates total 1.35 kg CO_2 per reusable cystoscope use. Amending these two parameters indicates that using a single-use ureteroscope would be associated with more than double the carbon footprint compared with choosing a reusable equivalent. I have published this analysis highlighting methodological concerns via a letter to the editor in *Journal of Endourology*.(148)

A previous study similarly found that the carbon footprint of a reusable bronchoscope (2.9 kg CO_2e per use) was higher than that of a single-use bronchoscope (1.6 kg CO_2e)(149) (excluded from the systematic review in this chapter as the product was predominantly used for investigation rather than surgical intervention). This study assumed that sterilisation department personnel used two sets of personal protective equipment (and three pairs of gloves) for every sterilisation process for reusable bronchoscopes, but did not appear to account for sterilisation (or PPE) associated with manufacture of the single-use equivalents.(149) The authors found that where two or more scopes were sterilised at the same time, the carbon footprint of reusables became lower than that of single-use equivalents.(149) Whilst the principal conclusions of these two studies indicate that single-use scopes have a lower impact than reusables, further research evaluating carbon footprint of scopes and of sterilisation via an endoscope washer disinfector is required given methodological concerns relating to existing studies. However the operations included in this thesis did not use endoscopes, and so this was beyond remit of this thesis.

Conclusion

The optimum approach to reducing the GHG emissions of a given operation should include a holistic approach, including looking at electricity use, anaesthetic gases, and use of products. Thiel et al.(134) modelled that the carbon footprint of a hysterectomy operation could be reduced by up to 83%, through optimising the instrument tray via use of minimal materials and maximum reuse(49%), switching anaesthesia to intravenous anaesthesia with propofol or similar agents (28%), and using renewable energy (6%). On a broader scale, it has been estimated that streamlining and optimising resource use in operating theatres holds the potential to save £7 million per NHS trust in the UK each year.(150) It is also important to consider reducing the need for surgery through health promotion, disease prevention and correct patient selection.(57)

This chapter (CHAPTER 3) outlined a systematic review of the carbon footprint of surgical operations. All included studies were published from 2011 onwards aside from three, reflecting that this academic field is still in its infancy but needs further exploration as a priority. Future research evaluating the carbon footprint of operations should extend assessments to other surgical contexts, and focus on the major carbon hotspot areas as identified in this systematic review; energy usage, single-use products, and anaesthesia. The original research within this thesis focuses on products used within the operating theatre, on the basis that this was identified as a major source of GHG emissions within the operating theatre (as demonstrated in this systematic review) over which surgeons can play a large influence (as outlined in CHAPTER 1). The next study (CHAPTER 4) evaluates the carbon footprint of products used in five common operations and identifies carbon hotspot products and underpinning processes, whilst subsequent studies evaluate ways to mitigate those hotspots.

CHAPTER 4 Carbon footprint of products used for five common surgical operations

4.1. Introduction

The systematic review in the previous chapter (CHAPTER 3)(5) found that the three major contributors to the carbon footprint of surgical operations were energy consumption, anaesthesia, and single-use products, with findings supported by a subsequent systematic review.(78) As previously discussed, the majority of operating theatre energy consumption related to heating, ventilation, and air conditioning, which can be tackled through operating theatre design and use of renewable energy sources.(28) The impact of general anaesthesia can be reduced for example through preferential use of inhalational agents with low global warming potential, gas scavenging systems, and preferencing regional or total intravenous anaesthesia.(81) Reducing single-use products in the operating room is also an important strategy,(151) but to date has received little analysis. As described in CHAPTER 1, medical equipment accounts for 10% of the NHS carbon footprint in England,(3) and mitigating this will play an important role in meeting environmental sustainability goals, particularly for products used in resource intensive areas such as surgical operating rooms. Choice of products for an operation is largely determined by surgeons, and many seem willing to make changes to mitigate carbon footprint, but lack knowledge on how to do so.(85) Addressing this will require evidence to firstly identify and prioritise healthcare products and underpinning processes which have greatest carbon footprint (as per the study in this chapter), and secondly to determine ways to mitigate those hotspot areas (addressed in subsequent studies).

Studies have previously estimated the carbon footprint of products used in surgery relative to other components of whole operations (reviewed in CHAPTER 3), associating use of products with up to three-quarters of the carbon footprint of a cataract operation.(79) Whilst previous studies have evaluated individual surgical products (reviewed in CHAPTER 3), few previous studies have reported the carbon footprint of individual products used across whole operations,(69, 79, 112) although an LCA of a hysterectomy identified production of cotton (e.g. used for laparotomy pads and operating towels), spun bound polypropylene (gowns, drapes, and instrument tray wrap), and paper and cardboard (packaging) as large contributors across different environmental impact categories.(69)

The aim of this study (CHAPTER 4) was to systematically evaluate the carbon footprint of products used in common operations, and to identify the products and processes making biggest contributions (hotspots), which can be targeted for change in practice and policy.

The objectives were as follows:

1. Estimate the carbon footprint of products used within five high volume operations
    a. Evaluate the contribution of different product categories for each operation
    b. Identify individual products collectively responsible for the majority (80%) of the carbon footprint of each operation
    c. Evaluate contribution of underpinning processes for each operation, including production and disposal of single-use and reusable products and their packaging, alongside sterilisation and laundering (as applicable)

4.2. Methods

The method used for this study aligns with the methodological approach outlined in CHAPTER 2, and this section only includes details specific to the current chapter.

Scope

Analysis was based upon the five highest volume surgical procedures performed in the NHS in England using 2017-2018 Hospital Episode Statistics database,(152) and included only operations typically performed by surgeons from surgical specialties recognised by the Royal College of Surgeons of England,(153) excluding diagnostic procedures, or those commonly performed outside the operating theatre, and those lacking specificity within the database. Operations selected were total knee arthroplasty (80,627 performed in one year), cholecystectomy (73,069), inguinal hernia repair (64,650), carpal tunnel decompression (47,023), and tonsillectomy (46,131).(152) The functional unit was defined as one of each of these operations.

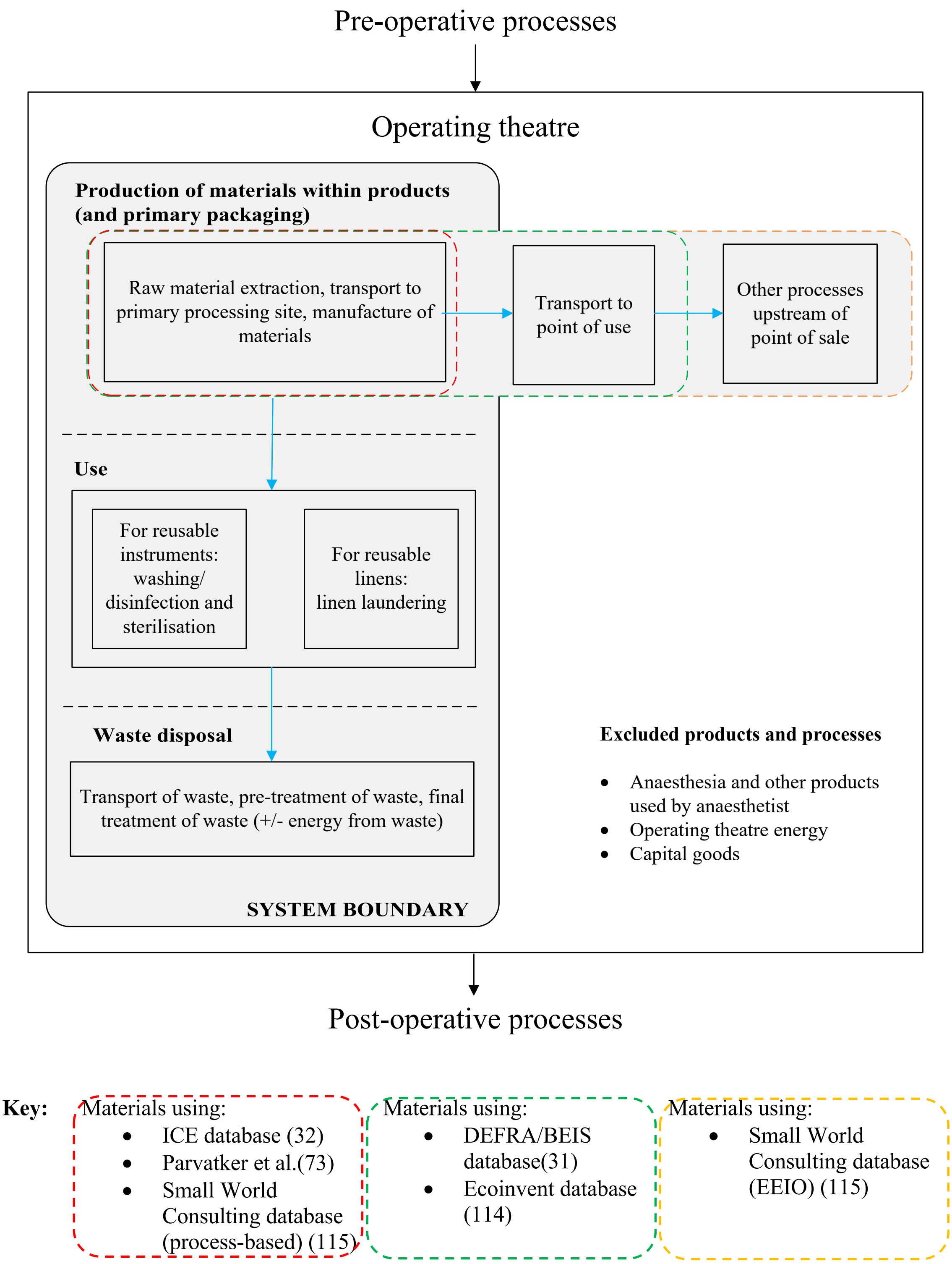
The system boundary was set to include production of materials for products used within the operating theatre, and associated primary packaging (excluding bulk packaging), and encompassed ‘cradle to factory gate’ activity, including raw material extraction, transportation to the primary processing site, primary processing, and manufacture of materials (Figure 9). Emission factors available for a small number of materials (indicated in Supplementary table 4) included transportation from the factory gate to point of use (equating to the manufacturing site of multi-component products). Where an EEIO model was used, this encompassed all activities from raw material extraction to point of sale. Due to the study scale and lack of available data, processes involved in the manufacture of multi-component products (beyond production of constituent materials) and onward distribution to site of use were excluded. Waste disposal was included, alongside steam sterilisation and laundering for reusable instruments and textiles respectively. Sterilisation of single-use products was excluded as contribution to total carbon footprint of such products has previously been estimated at <1% for a central venous catheter.(97) Operating theatre capital goods were excluded (as these were unlikely to reach the significance threshold),(20) alongside anaesthetic components (aside from those administered by the surgeon), operating theatre electricity (including HVAC), and water consumption.

Life cycle inventory

A process-based carbon footprint approach using activity data was used for the majority of products, but where unfeasible (due to lack of relevant emission factors), an EEIO model was used based on financial data. The life cycle inventory was built based upon direct observation of operating theatres across three University Hospitals Sussex NHS Foundation Trust sites (Royal Sussex County Hospital [RSCH], Princess Royal Hospital, and Lewes Victoria Hospital) between March 2019 and January 2020. Ten of each type of operation were observed, except for laparoscopic cholecystectomy and inguinal hernia repair where only six of each were observed (onset of the Covid pandemic curtailed data collection). Emergency and revision cases were excluded. Where additional products were identified during observations which had not previously been noted for a given operation type, and where such products could reasonably be assumed to have been used in earlier observed operations (as verified with theatre staff), these were added to other operation inventories as relevant.

Figure 9: System boundary for carbon footprint of products used for five common surgical operations

DEFRA/BEIS= Department of Environment Food and Rural Affairs/ Department for Business, Energy and Industrial Strategy, EEIO= environmentally extended input-output, ICE= Inventory of Carbon and Energy.



Material composition of products was determined through packaging and manufacturer information where available, or through expert assessment by Professor Robert Lillywhite. Individual material components were weighed, and where it was not possible to deconstruct multi-component products, weight was allocated based on probable ratio. For reusable products, the number of product lifetime uses was estimated through a combination of product manufacturer correspondence, a one-year retrospective audit of instrument sterilisation at RSCH (providing data on number of uses of individual instrument sets per year), and expert assessment of instrument age and likely lifespan (for example based on instrument markings, design, and manufacturer stamps). Some 'single-use' products were used across multiple operations in a given day, and typical number of uses was determined through discussion with operating theatre staff. The choice of waste streams used for disposal of single-use products was directly observed for individual operations (non-specified recycling was processed as domestic waste at the study site, and so was classified as domestic waste). For reusable products, the waste streams used for disposal at the end of products' life were determined through discussion with the on-site sterile services department and the reusable linens supplier.

Impact assessment

Carbon footprint of each product was determined through applying best available emission factors from a variety of sources (Supplementary table 4). The Inventory of Carbon and Energy (ICE) database (version 3)(32) was the primary source of emission factors for materials as this uses average data for materials supplied to the UK. Where materials were not included in the ICE database, the DEFRA/BEIS database(31) was used, and where not included there, the Ecoinvent (version 3.6) database embedded within SimaPro (version 9.10)(114) was used which includes global average processes. Process-based emission factors were unavailable for the majority of pharmaceuticals and cleaning chemicals (aside from some anaesthetic agents sourced from relevant literature),(73) and so financial spend emission factors were used from the Small World Consulting Carbon Factors Dataset (version 5.3),(115) which was also used for process based emission factors for stainless steel. Findings from CHAPTER 6 and CHAPTER 7 (conducted at the same study site) were used to provide emission factors for healthcare waste and sterilisation.(7, 8)

There were no available emission factors specific to healthcare linen laundering, and so this was evaluated using activity data from previous studies.(154, 155) The energy and water requirements of healthcare laundry were determined using data reported within an LCA study by Vozzola et al. which examined reusable isolation gowns made from woven polyester.(154) This was based on a 2016 survey by the International Association of

Healthcare Textile Managers, which surveyed nineteen healthcare laundry companies (thirteen in the USA and six in Canada), and these are likely to use similar processes to UK sites. There was a lack of evidence on emission factors relating to detergents, and this component of linen laundering was not included in the study by Vozzola et al.(154) A report published by RMIT University(155) identified that detergents were responsible for 2.5% of the carbon footprint of laundering surgical gowns (including energy and water use, and excluding transport), and an uplift factor was applied to the relevant sub-total here. The carbon footprint of transportation was also included, based on the journey from the principal study site (RSCH) to the linen laundering facility (Elis, Camberwell). The carbon footprint was determined using emission factors outlined in Supplementary table 5, and estimated to be 0.46 kg CO_2e per kg of dry linen (Table 7). This value is similar to that reported by the European Textile Services Association which estimates that the carbon footprint of hotel linen laundering was 0.43 kg CO_2e per kg.(156)

Table 7: Carbon footprint of laundering of reusable healthcare linen
CO_2e= carbon dioxide, RSCH= Royal Sussex County Hospital

Input	**Source**	**Quantity used per kg of dry linen**	**Carbon footprint (g CO_2e per kg dry linen)**	
			Component	**Total**
Natural gas	Vozzola et al.(154)	1.59 kWh	331	461
Electricity	Vozzola et al.(154)	0.28 kWh	89	
Water supply	Vozzola et al.(154)	0.011 m^3	4	
Water treatment	Vozzola et al.(154)	0.011 m^3	8	
Detergent	RMIT(155)	N/A	11	
Travel	RSCH to Elis round trip	161 km	18	

Hotspot analysis

Mean average carbon footprint of each operation type were determined. To ascertain products or processes to potentially prioritise, carbon footprint for products (single-use and reusable) in each operation type were categorised on three measures:

1. By product category; total carbon footprint associated with use of instrument sets and individually wrapped instruments, equipment, personal protective equipment, patient and/or instrument table drapes, cleaning products, and pharmaceuticals (each categorised as single-use or reusable as appropriate) were determined.
2. By product type; product types were ordered by individual carbon footprint at a more granular level (e.g. sterile surgical gloves), and those that cumulatively contributed ≥ 80% to the total were determined.
3. By process; total carbon footprint associated with production of products, production of packaging, sterilisation, linen laundering, and waste disposal were determined.

For the purposes of hotspot analysis, the carbon footprint of sterilisation was allocated across instruments within a set according to weight, and washing of instrument set containers assigned to the container itself. Where the carbon footprint of material production was determined using the EEIO method, 90% was allocated to the product and 10% to packaging. When reporting mean averages across the whole dataset, these were weighted equally for each of the five operation types.

4.3. Results

Carbon footprint of products used in operations

Across each of ten carpal tunnel decompression operations, one reusable instrument set and one single-use hand pack was used, alongside a mean average of 6.4 other reusable products, 46.9 other single-use products, and 3.7 pharmaceutical agents (these numbers refer to the count of individual products used, rather than product types). One of two reusable instrument sets were used in each of the six inguinal hernia repair operations, two of which used an additional individually wrapped reusable instrument, alongside mean average of 9.7 other reusable products, 58.2 single-use products, and 4.6 pharmaceutical products. One single-use knee pack was used for each of ten knee arthroplasty operations, alongside a mean average of 6.2 reusable instrument sets, 4.2 individually wrapped reusable instruments, 5.8 other reusable products, 113.4 other single-use products, and 9.5 pharmaceutical products. Across each of six laparoscopic cholecystectomy operations three reusable instrument sets were used, alongside mean average of 1.3 individually wrapped reusable instruments, 11.5 other reusable products, 63.8 other single-use products, and 6.7 pharmaceutical products. One of two reusable instrument sets were used for the ten tonsillectomy operations, alongside a mean average of 9.2 other reusable products, 30.4 other single-use products, and 3.2 pharmaceutical products.

Supplementary table 6 - Supplementary table 15 show the carbon footprint of reusable and single-use products used across each operation type, Supplementary table 16 - Supplementary table 20 show the number of each product type used for each operation, and Supplementary table 21- Supplementary table 25 combine these data to calculate overall carbon footprint of each product for each operation. The mean average carbon footprint of products used for carpal tunnel decompression was 12.0 kg CO_2e (range 11.3 kg CO_2e - 12.9 kg CO_2e); for inguinal hernia repair 11.7 kg CO_2e (range 10.1 - 15.0); for knee arthroplasty 85.5 kg CO_2e (range 72.3 - 94.9); for laparoscopic cholecystectomy 20.3 kg CO_2e (range 18.8 - 22.0); and 7.5 kg CO_2e for tonsillectomy (range 6.3 - 8.2).

Hotspot analysis of product categories

Table 8 shows the mean average contribution of product categories to total carbon footprint of products used in five operation types (individual operation results in Table 9). Across the dataset, around two-thirds (68%) of carbon footprint related to single-use products, and one-third (32%) to reusable products. Greatest contributions were from single-use equipment and medical devices (mean average 24%), and by reusable instrument sets and individually wrapped reusable instruments (24%). This was followed by single-use patient or instrument table drapes (14%), pharmaceuticals (13%), single-use personal protective equipment (11%), single-use products associated with cleaning and waste (6%), reusable personal protective equipment (4%), reusable patient and instrument table drapes (3%), and non-set reusable equipment (0.1%).

Table 8: Mean carbon footprint of products used in all five operations by product category
'Instrument set and individually wrapped instruments' carbon footprint includes single-use sterile barrier system and single-use products within the set where relevant. CO_2e= carbon dioxide equivalents, sd= standard deviation

Operation		**Carbon footprint (g CO_2e)**											
		Reusable products					**Single-use products**						
		Instrument sets and individually wrapped instruments	Personal protective equipment	Patient and/or instrument table drapes	Non-set equipment	**Total reusable**	Personal protective equipment	Patient and/or instrument table drapes	Equipment and medical devices	Pharma-ceuticals	Cleaning products, waste	**Total single-use**	**Total for oper-ation**
Carpal tunnel decompression	Mean ± sd	1,922 ± 0	265 ± 49	N/A	56 ± 38	**2,242 ± 39**	2,722 ± 400	3,881 ± 0	1,699 ± 301	795 ± 242	671 ± 36	**9,768 ± 399**	**12,011 ± 412**
	% of total	16 %	2 %		0.46 %	**19 %**	23%	32 %	14 %	7 %	6 %	**81 %**	**100%**
	Range	1,922-1,922	232 -371		0-79	**2,154-2,294**	1,890-3,330	3,881-3,881	1,388-2,245	422-1,123	629 -756	**9,060-10,583**	**11,294 - 12,863**
Inguinal hernia repair	Mean ± sd	2,669 ± 360	560 ± 213	1,042 ± 235	10 ± 0.2	**4,281 ± 323**	1,850 ± 652	666 ± 620	2,596 ± 919	1,426 ± 1,463	861 ± 96	**7,398 ± 1,631**	**11,679 ± 1,840**
	% of total	23 %	5 %	9 %	0.08 %	**37**	16%	6 %	22 %	12 %	7 %	**63 %**	**100 %**
	Range	2,396-3,214	290-796	745-1,222	9-10	**3,860-4,620**	1,356-2,705	0-1,667	1,744-3,927	145-4,070	707-926	**5,705-10,343**	**10,128 - 14,963**
Knee arthroplasty	Mean ± sd	14,808 ± 2,162	433 ± 65	N/A	0.09 ± 0.2	**15,242 ± 2,133**	5,904 ± 1,217	12,801 ± 270	22,781 ± 2,034	26,807 ± 5,912	1,919 ± 213	**70,212 ± 7,190**	**85,454 ± 7,097**
	% of total	17 %	1 %		0.0001 %	**18 %**	7%	15 %	27 %	31 %	2 %	**82 %**	**100 %**

	Range	12,031-18,965	387-542		0-0.44	**12,418-19,351**	3,915 7,410	12,421-13,171	20,774-25,340	15,407-33,607	1,671-2,320	**55,145-80,120**	**72,247-94,875**
Laparoscopic cholecystectomy	Mean ± sd	6,674 ± 109	977 ± 226	1,165 ± 53	9 ± 0	**8,825 ± 326**	1,121 ± 560	740 ± 38	7,253 ± 1,292	1,419 ± 487	932 ± 91	**11,465 ± 1,141**	**20,290 ± 1,408**
	% of total	33 %	5 %	6 %	0.05 %	**43 %**	6%	4 %	36 %	7 %	5 %	**57 %**	**100 %**
	Range	6,604 -6,820	659-1,263	1,098-1,222	9-9	**8,371-9,283**	551-2,095	705-775	5,646-8,655	939-2,254	801-1,014	**10,190-12,772**	**18,751 - 22,024**
Tonsillectomy	Mean ± sd	2,296 ± 36	712 ± 56	94 ± 197	N/A	**3,102 ± 211**	387 ± 59	1,060 ± 150	1,754 ± 494	460 ± 227	711 ± 50	**4,372 ± 758**	**7,474 ± 734**
	% of total	31 %	10 %	1 %		**42 %**	5%	14 %	23 %	6 %	10 %	**58 %**	**100 %**
	Range	2,279-2,364	660-808	0-475		**2,945-3,499**	323-489	755-1,131	1,159-2,268	115-658	663-795	**3,392-5,129**	**6,337-8,170**
Mean average % contribution of product category to total carbon footprint across all five operations		24 %	4 %	3 %	0.1 %	**32 %**	11 %	14 %	24 %	13 %	6 %	**68 %**	**100 %**

Table 9: Carbon footprint of products used in individual operations by product category
'Instrument set and individually wrapped instruments' carbon footprint includes single-use sterile barrier system and single-use products within the set where relevant. C1=carpal tunnel decompression operation one etc, CO_2e= carbon dioxide equivalents

Operation		**Carbon footprint (g CO_2e)**											
		Reusable products					**Single-use products**						
		Instrument sets and individually wrapped instruments	Personal protective equipment	Patient and/or instrument table drapes	Non-set equipment	**Total reusable**	Personal protective equipment	Patient and/or instrument table drapes	Equipment and medical devices	Pharma-ceuticals	Cleaning products, waste	**Total single -use**	**Total for operat-ion**
Carpal tunnel decompression	C1	1,922	232	N/A	79	**2,234**	2,720	3,881	1,789	735	699	**9,825**	**12,058**
	C2	1,922	232	N/A	79	**2,234**	2,720	3,881	1,902	735	685	**9,924**	**12,158**
	C3	1,922	232	N/A	79	**2,234**	2,720	3,881	2,054	735	657	**10,047**	**12,281**
	C4	1,922	279	N/A	79	**2,280**	2,677	3,881	2,245	1,123	657	**10,583**	**12,863**
	C5	1,922	325	N/A	N/A	**2,247**	2,609	3,881	1,778	885	643	**9,796**	**12,043**
	C6	1,922	232	N/A	N/A	**2,154**	2,583	3,881	1,476	885	657	**9,482**	**11,636**
	C7	1,922	371	N/A	N/A	**2,294**	2,665	3,881	1,431	885	629	**9,491**	**11,784**
	C8	1,922	232	N/A	79	**2,234**	3,307	3,881	1,388	422	756	**9,754**	**11,988**
	C9	1,922	232	N/A	79	**2,234**	1,890	3,881	1,509	1,123	657	**9,060**	**11,294**
	C10	1,922	279	N/A	79	**2,280**	3,330	3,881	1,418	422	671	**9,722**	**12,003**
	Mean C1-C10	1,922	265	N/A	56	**2,242**	2,722	3,881	1,699	795	671	**9,768**	**12,011**
	% of total	16%	2%	N/A	0.46%	**19%**	23%	32%	14%	7%	6%	**81%**	**100%**
Inguinal hernia repair	H1	3,214	591	745	10	**4,559**	1,512	N/A	3,927	1,668	773	**7,880**	**12,440**
	H2	3,017	533	745	10	**4,304**	1,458	N/A	3,539	1,668	707	**7,372**	**11,676**
	H3	2,396	356	1,098	10	**3,860**	2,672	775	2,215	145	926	**6,734**	**10,593**
	H4	2,593	796	1,222	10	**4,620**	1,356	1,667	2,345	4,070	906	**10,343**	**14,963**
	H5	2,396	290	1,222	10	**3,918**	2,705	775	1,803	145	926	**6,356**	**10,273**
	H6	2,396	796	1,222	9	**4,423**	1,396	775	1,744	863	926	**5,705**	**10,128**
	Mean H1-H6	2,669	560	1,042	10	**4,281**	1,850	666	2,596	1,426	861	**7,398**	**11,679**
	% of total	23%	5%	9%	0.08%	**37**	16%	6%	22%	12%	7%	**63%**	**100%**

Knee arthroplasty	K1	14,291	464	N/A	N/A	**14,756**	7,073	12,421	24,869	33,607	2,150	**80,120**	**94,875**
	K2	12,056	542	N/A	N/A	**12,598**	5,204	12,861	20,783	28,815	2,016	**69,679**	**82,278**
	K3	14,495	542	N/A	N/A	**15,036**	5,447	12,861	21,383	28,699	2,087	**70,477**	**85,513**
	K4	14,283	387	N/A	N/A	**14,670**	6,307	12,861	25,049	16,551	1,671	**62,439**	**77,109**
	K5	13,895	464	N/A	0.44	**14,359**	6,683	12,861	25,184	29,682	2,320	**76,730**	**91,089**
	K6	16,715	387	N/A	N/A	**17,102**	3,915	12,471	21,596	15,407	1,756	**55,145**	**72,247**
	K7	16,882	387	N/A	0.44	**17,269**	4,118	12,471	20,774	28,610	1,798	**67,770**	**85,039**
	K8	18,965	387	N/A	N/A	**19,351**	5,936	13,171	25,340	28,510	1,727	**74,684**	**94,036**
	K9	14,470	387	N/A	N/A	**14,857**	7,410	13,171	21,795	28,510	1,798	**72,683**	**87,540**
	K10	12,031	387	N/A	N/A	**12,418**	6,945	12,861	21,037	29,682	1,868	**72,395**	**84,813**
	Mean K1-K6	14,808	433	N/A	0.09	**15,242**	5,904	12,801	22,781	26,807	1,919	**70,212**	**85,454**
	% of total	17%	1%	N/A	0.0001%	**18%**	7%	15%	27%	31%	2%	**82%**	**100%**
Laparoscopic cholecystectomy	L1	6,604	659	1,098	9	**8,371**	2,095	775	5,646	1,220	1,006	**10,743**	**19,113**
	L2	6,604	1,064	1,222	9	**8,900**	907	775	6,732	1,117	986	**10,517**	**19,417**
	L3	6,808	1,106	1,098	9	**9,022**	667	775	8,655	1,730	945	**12,772**	**21,795**
	L4	6,820	1,263	1,190	9	**9,283**	551	705	8,430	2,254	801	**12,741**	**22,024**
	L5	6,604	757	1,190	9	**8,561**	1,202	705	6,016	1,252	1,014	**10,190**	**18,751**
	L6	6,604	1,010	1,190	9	**8,814**	1,305	705	8,037	939	840	**11,827**	**20,640**
	Mean L1-L6	6,674	977	1,165	9	**8,825**	1,121	740	7,253	1,419	932	**11,465**	**20,290**
	% of total	33%	5%	6%	0.05%	**43%**	6%	4%	36%	7%	5%	**57%**	**100%**
Tonsillectomy	T1	2,279	669	N/A	N/A	**2,948**	467	1,131	1,410	360	693	**4,062**	**7,010**
	T2	2,364	660	475	N/A	**3,499**	489	775	1,414	361	795	**3,834**	**7,333**
	T3	2,364	660	460	N/A	**3,484**	449	775	1,264	361	795	**3,644**	**7,128**
	T4	2,279	666	N/A	N/A	**2,945**	323	1,131	1,211	115	663	**3,443**	**6,388**
	T5	2,279	666	N/A	N/A	**2,945**	323	1,131	1,159	115	663	**3,392**	**6,337**
	T6	2,279	761	N/A	N/A	**3,041**	364	1,131	2,268	658	708	**5,129**	**8,170**
	T7	2,279	712	N/A	N/A	**2,992**	364	1,131	2,228	658	678	**5,059**	**8,051**
	T8	2,279	808	N/A	N/A	**3,087**	367	1,131	2,228	658	678	**5,062**	**8,150**
	T9	2,279	758	N/A	N/A	**3,038**	375	1,131	2,177	658	739	**5,080**	**8,118**
	T10	2,279	761	N/A	N/A	**3,041**	352	1,131	2,177	658	693	**5,011**	**8,052**
	Mean T1-T10	2,296	712	94	N/A	**3,102**	387	1,060	1,754	460	711	**4,372**	**7,474**
	% of total	31%	10%	1%	N/A	**42%**	5%	14%	23%	6%	10%	**58%**	**100%**

Hotspot analysis of individual products

The mean average carbon footprint of individual products used across operations is ranked in Supplementary table 26 - Supplementary table 30. Across the dataset, a small proportion of product types were responsible for ≥ 80% of the carbon footprint of any given operation (Figure 10): 21/77 product types (27%) for carpal tunnel decompression; 35/148 (24%) for inguinal hernia repair; 47/463 (10%) for knee arthroplasty; 40/141 (28%) for laparoscopic cholecystectomy; and 28/104 (27%) for tonsillectomy. A mean average across operations of 23% of product types were responsible for ≥ 80% carbon footprint.

Table 10 lists products responsible cumulatively for ≥ 80% of mean average carbon footprint of each operation (Supplementary table 26- Supplementary table 30 provide detailed breakdown). The five highest contributing products for carpal tunnel decompression were the single-use fenestrated hand drape (mean average 23%), single-use surgical gowns (17%), single-use instrument table drape (9%), crepe bandage (3%), and orange waste bag (3%). For inguinal hernia repair this was the single-use surgical gowns (10%), reusable high fluid drape (6%), single-use monopolar diathermy with smoke evacuation 6%), topical skin adhesive (6%), and single-use instrument table drape (6%). For knee arthroplasty, greatest carbon footprints were associated with the bone cement mix either with tobramycin or gentamicin (22% and 6% respectively, the latter used for fewer operations), the single-use pulsed lavage system (4%), posterior stabilised femoral implant (4%), and single-use instrument table drape (4%). For laparoscopic cholecystectomy highest impacts were associated with the single-use endoscopic clip applier (8%), reusable high fluid drape (5%), single-use 12 mm port (5%), levobupivacaine (4%), and single-use suction irrigation (4%). Finally for tonsillectomy this was the single-use instrument table drape (11%), single-use suction tubing (7%), reusable tonsillectomy set container (7%), reusable surgical gown (6%), and single-use coblation™ wand (6%).

Figure 10: Proportion of product types responsible for cumulative carbon footprint for each operation
Cumulative carbon footprint contribution and proportion of product types based on mean averages for each operation type. Each data point relates to a single product type (e.g. suction receptacle). Arrows mark point at which 80% of carbon footprint reached.

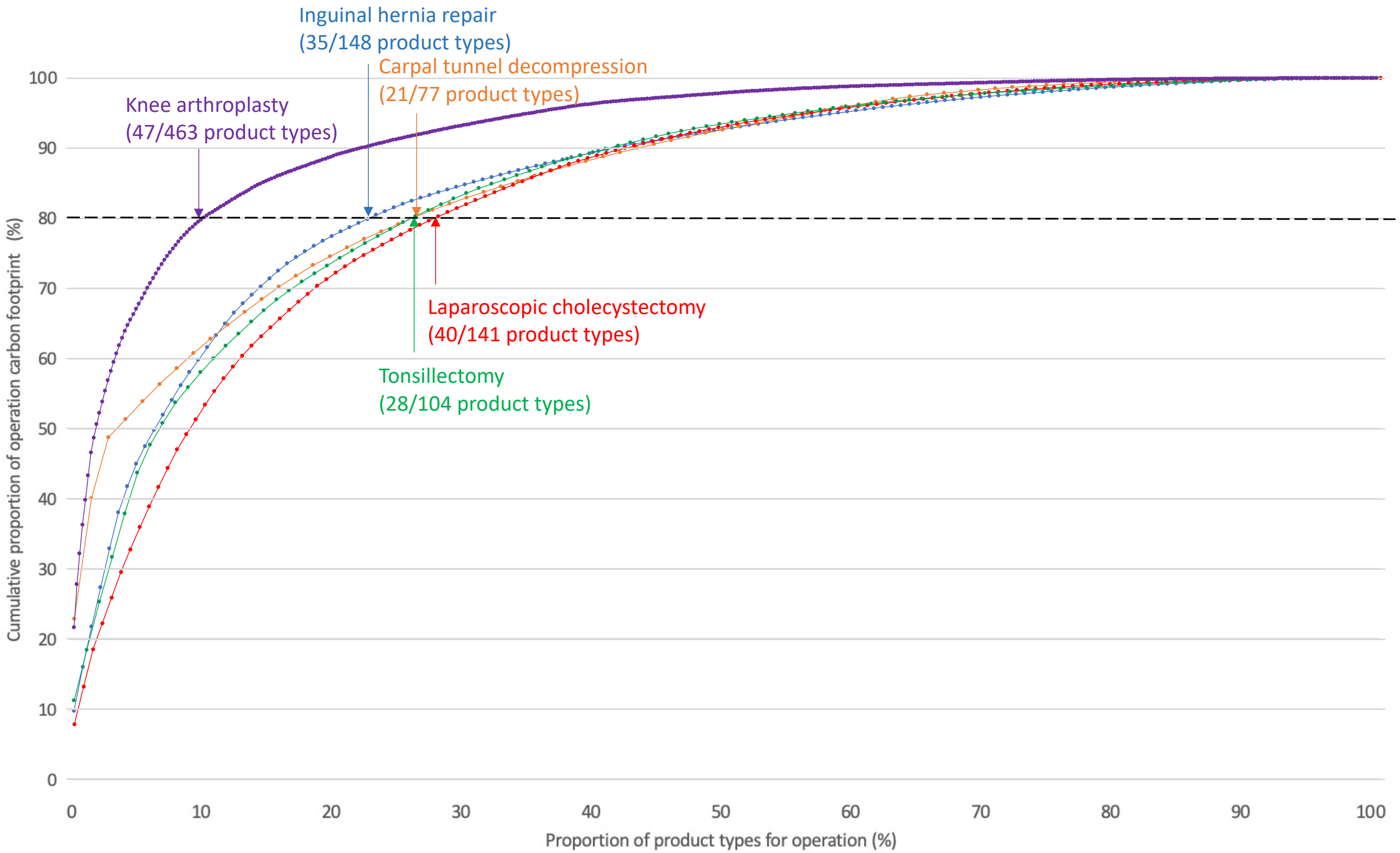


Table 10: Product types responsible for majority (≥ 80%) of carbon footprint of each operation

Mean average contribution of each product type across operations is specified in parenthesis (carbon footprint; percentage contribution), and depends upon the carbon footprint of the product, number of products used, and number of operations in which product was used. Individual product types contributing >10% carbon footprint indicated in dark red, 5-10% in red, 3-5% orange, <1% green. Products are clustered in yellow or blue (alternating) where products used across multiple operation types, ordered by magnitude of carbon footprint within clusters.

Item name (mean average carbon footprint g CO_2e for operation type; mean average % contribution to total for operation type)

		Carpal tunnel decompression (21/77 product types)	Inguinal hernia repair (35/148 product types)	Knee arthroplasty (47/463 product types)	Laparoscopic cholecystectomy (40/141 product types)	Tonsillectomy (28/104 product types)
Reusable instruments	Instrument sets and individually wrapped instruments		General basic set B container (429; 4%)	Basic major ortho set container (644; 1%) Femoral and tibial preparation set size 3-6 container (644; 1%) Miscellaneous knee system set container (644; 1%) Orthopedic surgical drill container (644; 1%) Cruciate retaining femoral and tibial trialing set (size 3-6) container (579; 1%) Patella preparation and trialing set container (451; 1%)	General basic set container (643; 3%) Laparoscopic set container base (399; 2%) Laparoscopic set wire cage (322; 2%) Laparoscopic set container lid (247; 1%)	Tonsillectomy set A container (514; 7%) Tonsillectomy set B container (129; 2%)
		Bipolar lead (268; 2%) Sponge holder forceps (222;2%) Weitlaner retractor (181; 2%)	Kidney dish (131; 1%) Rampley sponge holder forceps (85; 1%) Schnidt artery forceps (78; 1%) Towel clips (70; 1%) Spencer Wells curved artery forceps (69; 1%)	Heath mallet (283; 0.3%)	Laparoscope light lead (533; 3%) Hopkins laparoscope (239; 1%) Kelly crocodile grasping forceps (229; 1%) Kidney dish (196; 1%) Langenbeck retractor small (172; 1%) Raptor toothed grasping forceps (152; 1%) Diathermy lead (143; 1%) Quiver (137; 1%) Rampley sponge holder forceps (127; 1%)	Long Draffin bipod stand (161; 2%) Short Draffin bipod stand (139; 2%) Bipolar diathermy lead (78; 1%) Boyle Davis gag (73; 1%) St Clair Thompson Adenoid curette (69; 1%)
	Personal protective equipment	Scrubs (265; 2%)	Scrubs (290; 2%)	Scrubs (433; 1%)	Scrubs (368; 2%)	Scrubs (232; 3%)
			Surgical gown (269; 2%)		Surgical gown 1/pack (337; 2%) Surgical gown 2/pack (270; 1%)	Surgical gown (474; 6%)
	Patient and/or instrument table drapes		High fluid drape (732; 6%) Low fluid drape (248; 2%)		High fluid drape (1,088; 5%)	ENT split head drape (94; 1%)
Single-use items	Single-use components reusable instrument sets	Outer tray wrap (244; 2%) Inner tray wrap (123; 1%)	Outer tray wrap (209; 2%) Inner tray wrap (205; 2%)		Inner tray wrap (444; 2%) Outer tray wrap (228; 2%)	
	Personal protective equipment	Surgical gown (2,063; 17%)	Surgical gown (1,138; 10%)	Surgical gown (1,826; 2%) Surgical gown from knee pack (1,089; 1%)	Surgical gown (270; 2%)	
		Sterile gloves (298; 2%)	Sterile gloves 1 pair/pack (215; 2%) Sterile gloves 2 pairs/pack (179; 2%) Non-sterile gloves (135; 1%) Latex free sterile gloves (76; 1%)	Sterile gloves 1 pair/ pack (670; 1%) Sterile gloves 2 pairs/ pack (501; 1%)	Sterile gloves 2 pairs/ pack (289; 1%) Sterile gloves 1 pair/ pack (190; 1%) Non-sterile gloves (124; 1%)	Sterile gloves (298; 4%)
				Orthopedic hood (1,345; 2%)		
	Patient and/or instrument table drapes	Instrument table drape (1,050; 9%)	Instrument table drape (646; 6%)	Instrument table drape 160x240 cm (3,009; 4%) Instrument table drape 140x90 cm (1,406; 2%) Instrument table drape 140x190 cm (1,038; 2%)	Instrument table drape (740; 4%)	Instrument table drape (840; 11%)

Single -use items		Fenestrated hand drape (2,740; 23%)		Patient extremity drape (1,636; 2%) Patient drape fluid collection (1,287; 2%) Patient drape 240x150 cm (1,163; 2%) Mayo patient drape (842; 1%) Impervious split patient drape (644; 1%) Stockinette impervious patient drape (584; 1%)		Fenestrated ENT drape (220; 3%)
	Equipment and medical devices	Gauze (224; 2%) Gauze from hand pack (188; 2%)	Gauze 10x7.5cm (380; 3%) Gauze 10x10cm (142; 1%) Gauze 30x30cm (119; 1%)		Gauze (256; 1%)	Tonsil swab pack (96; 1%)
		Needle counter (237; 2%)	Needle counter (254; 2%)		Needle counter (254; 1%)	
				Pulsed lavage system (3,727; 4%) Suction tubing (437; 1%)	Suction irrigation (743; 4%)	Suction tubing (539; 7%) Suction receptacle (433; 6%) Yankauer sucker (90; 1%)
		Crepe bandage (309; 3%)		Crepe bandage (550; 1%)		
			20ml syringe (104; 1%)	50ml syringe (301; 0.4%)		
		Kidney dish (147; 1%) Bowl (127; 1%)	Monopolar diathermy with smoke evacuation (675; 6%) Mesh (246; 2%) Incontinence pad (154; 1%) Diathermy pad (97; 1%) Surgical suspensory bandage (67; 1%)	Posterior stabilized femoral implant (3,528; 4%) Primary tibial baseplate implant (2,997; 4%) Cruciate retaining femoral implant (2,759; 3%) Tibial bearing insert cruciate retaining implant (710; 1%) Tibial bearing insert posterior stabilised implant (444; 1%) Symmetric patella implant (359; 0.4%) Cement mixing & delivering system (1,315; 2%) Tourniquet pressure cuff (980; 1%) Small tray (589; 1%) Swab tray (322; 0.4%) Incontinence pad (261; 0.3%)	Endoscopic clip applier (1,590; 8%) 12mm port (1,077; 5%) 5mm port (655; 3%) Laparoscopic scissors (551; 3%) Insufflation tubing (600; 3%) Anti-fog endoscopic demister (565; 3%) Laparoscope cover (139; 1%)	Coblator (466; 6%)
	Pharmaceuticals	Lidocaine with adrenaline (211; 2%) Lidocaine (151; 1%) Bupivacaine hydrochloride (125; 1%)	Levobupivacaine (602; 5%)	Ropivacaine (623; 1%)	Levobupivacaine (756; 4%)	Chirocaine (126; 2%) Bupivacaine with adrenaline (74; 1%)
				Sodium chloride for irrigation (918; 1%)	Sodium chloride for irrigation (148; 1%)	Sodium chloride infusion bag (146; 2%) Sodium chloride (114; 2%)
			Topical skin adhesive (654; 6%) Chlorhexidine (72; 1%)	Topical skin adhesive (392; 0.5%) Chlorhexidine gluconate in denatured ethanol with red stain solution (393; 0.5%)		
				Bone cement with tobramycin (18,499; 22%) Bone cement with gentamycin (5,281; 6%)	Carbon dioxide (423; 2%)	
	Cleaning products, waste	Orange waste bag (307; 3%)	Orange waste bag, large (205; 2%) Orange waste bag, small (91; 1%)	Orange waste bag (615; 1%)	Orange waste bag (154; 1%)	Yellow waste bag (123; 2%) Black waste bag (84; 1%) Clear waste bag- swab count (81;1%) Clear waste bag- recycling (79; 1%)
		Mop head (152; 1%)	Mop head (194; 2%) Disinfectant wipe (140; 1%)	Mop head (253; 0.3%) Disinfectant wipe (486; 1%)	Mop head (186; 1%) Disinfectant wipe (149; 1%)	Mop head (160; 2%) Disinfectant wipe (75; 1%)

Hotspot analysis of processes

Figure 11 and Table 11 shows mean average contribution of processes to carbon footprint of the five operation types (individual operation results Table 12). Across the five operations, mean average contributions were greatest from the production of single-use products (54%), followed by sterilisation (20%), waste disposal of single-use products (8%), production of packaging for single-use products (6%), and linen laundering (6%). There were small contributions from the production of single-use packaging for reusables (3%), production of reusables (2%), and waste disposal of reusables (1%).

Figure 11: Carbon footprint of operations, broken down by underpinning processes
Mean average carbon footprint across all operations for each operation type. CO_2e= carbon dioxide equivalents.

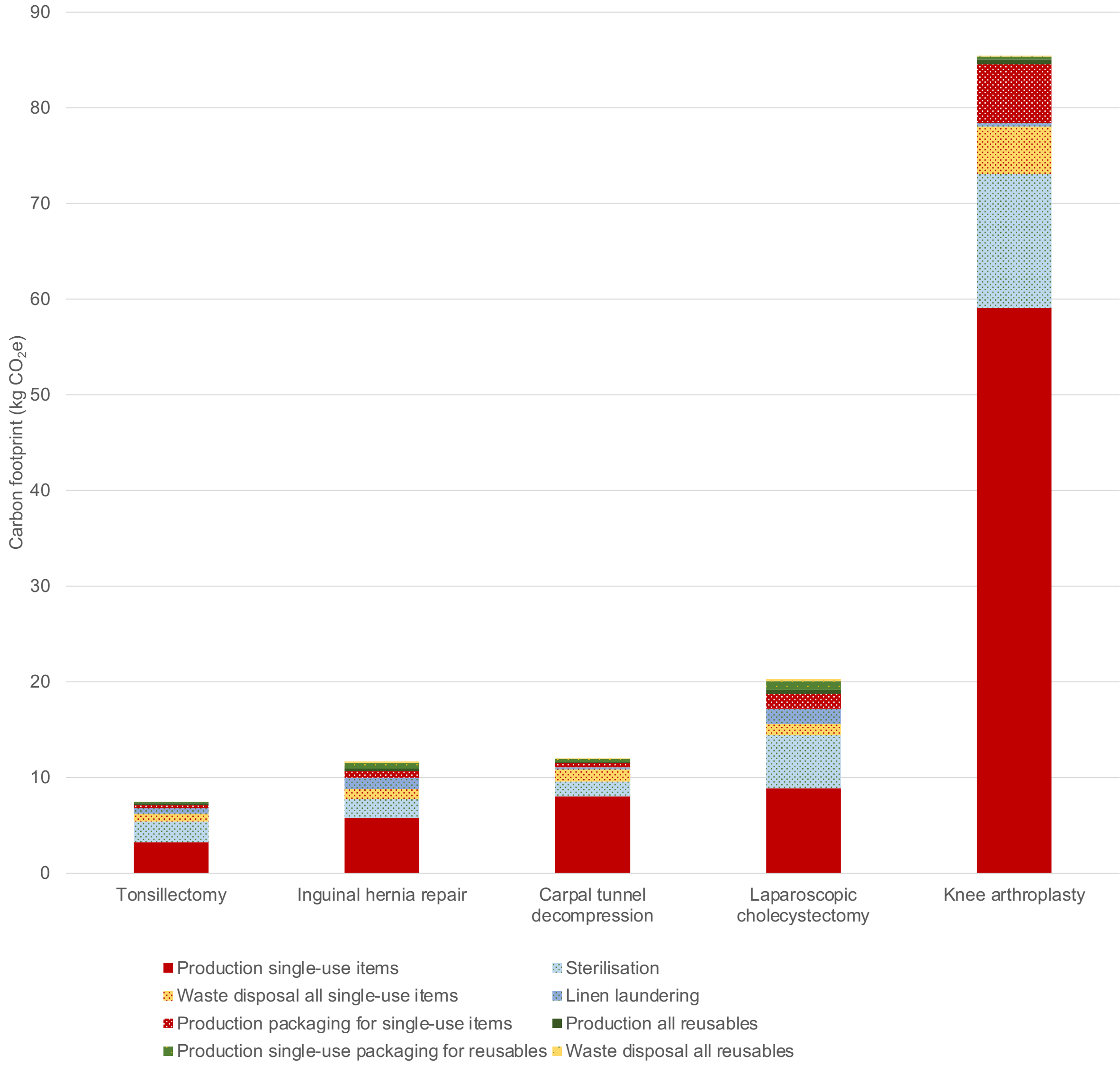


Table 11: Mean carbon footprint of processes across life cycle of products used in all five operations
CO_2e= carbon dioxide equivalents, sd=standard deviation

Operation		Carbon footprint (g CO_2e)								
		Reusable products process					Single-use products process			Total for operation
		Production of all reusables	Production of single-use packaging for reusables	Sterilisation	Linen laundering	Waste disposal all reusables	Production single-use products	Production packaging for single-use products	Waste disposal all single-use products	
Carpal tunnel decompression	Mean ± sd	99 ± 25	309 ± 2	1,531 ± 0	221 ± 41	82 ± 7	8,041 ± 341	462 ± 40	1,266 ± 61	**12,011 ± 412**
	Percentage of total	1%	3%	13%	2%	1%	67%	4%	11%	**100%**
	Range	51-119	305-310	1,531-1,531	194-310	73-87	7,567-8,805	385-515	1,108-1,324	**11,294-12,863**
Inguinal hernia repair	Mean ± sd	272 ± 81	572 ± 562	1,995 ± 311	1,174 ± 247	156 ± 118	5,756 ± 1,521	698 ± 73	1,056 ± 279	**11,679 ± 1,840**
	Percentage of total	2%	5%	17%	10%	1%	49%	6%	9%	**100%**
	Range	171-357	120-1,293	1,531-2,299	881-1,457	58-312	4,492-8,709	569-767	728-1,442	**10,128-14,963**
Knee arthroplasty	Mean ± sd	539 ± 92	285 ± 50	13,965 ± 2,029	362 ± 55	90 ± 15	59,115 ± 6,490	6,134 ± 695	4,963 ± 168	**85,454 ± 7,097**
	Percentage of total	1%	0.33%	16%	0.42%	0.11%	69%	7%	6%	**100%**
	Range	425-687	191-348	11,351-17,959	323-453	65-112	45,874-68,193	4,608-6,875	4,663-5,202	**72,247-94,875**
Laparoscopic cholecystectomy	Mean ± sd	458 ± 38	895 ± 78	5,579 ± 75	1,586 ± 150	224 ± 19	8,859 ± 1,032	1,539 ± 120	1,152 ± 326	**20,290 ± 1,408**
	Percentage of total	2%	4%	27%	8%	1%	44%	8%	6%	**100%**
	Range	398-506	792-1,007	5,530-5,676	1,351-1,777	199-246	7,777-10,259	1,338-1,664	764-1,597	**18,751-22,024**

Tonsillectomy	Mean ± sd	217 ± 19	125 ± 31	2,154 ± 0	561 ± 127	26 ± 10	3,245 ± 460	324 ± 143	823 ± 192	**7,474** **± 734**
	Percentage of total	3%	2%	29%	8%	0.35%	43%	4%	11%	**100**
	Range	199- 249	110- 184	2,154- 2,154	455- 790	21- 51	2,508- 3,686	154- 463	482- 986	**6,337-** **8,170**
Mean average % contribution of process category to total carbon footprint across all five operations		2%	3%	20%	6%	1%	54%	6%	8%	**100%**

Table 12: Carbon footprint of processes across life cycle of products used in individual operations

C1=carpal tunnel decompression operation one etc. CO_2e= carbon dioxide equivalents

Operation		Carbon footprint (g CO_2e)								
		Reusable products					Single-use products			
		Production all reusables	Production single-use packaging for reusables	Sterilisation	Linen laundering	Waste disposal all reusables	Production single-use products	Production packaging for single-use products	Waste disposal all single-use products	Total for operation
Carpal tunnel decompression	C1	112	310	1,531	194	87	8,071	475	1,278	**12,058**
	C2	112	310	1,531	194	87	8,166	479	1,279	**12,158**
	C3	112	310	1,531	194	87	8,278	482	1,287	**12,281**
	C4	119	310	1,531	233	87	8,805	483	1,295	**12,863**
	C5	67	305	1,531	272	73	7,994	515	1,287	**12,043**
	C6	51	305	1,531	194	73	7,755	482	1,245	**11,636**
	C7	74	305	1,531	310	73	7,767	478	1,246	**11,784**
	C8	112	310	1,531	194	87	8,007	423	1,324	**11,988**
	C9	112	310	1,531	194	87	7,567	385	1,108	**11,294**
	C10	119	310	1,531	233	87	7,995	414	1,313	**12,003**
	Mean C1-C10	99	309	1,531	221	82	8,041	462	1,266	**12,011**
	Percentage of total	1%	3%	13%	2%	1%	67%	4%	11%	**100%**
Inguinal hernia repair	H1	181	1,293	1,677	929	312	5,859	747	1,442	**12,440**
	H2	171	1,293	1,531	881	301	5,445	704	1,351	**11,676**
	H3	283	120	2,154	1,161	58	5,168	737	912	**10,593**
	H4	357	282	2,299	1,457	101	8,709	767	991	**14,963**
	H5	283	163	2,154	1,162	72	4,862	665	912	**10,273**
	H6	356	282	2,154	1,457	90	4,492	569	728	**10,128**
	Mean H1-H6	272	572	1,995	1,174	156	5,756	698	1,056	**11,679**
	Percentage of total	2%	5%	17%	10%	1%	49%	6%	9%	**100%**

Knee arthroplasty	K1	519	260	13,505	388	83	68,193	6,875	5,051	**94,875**
	K2	458	256	11,351	453	80	58,858	6,064	4,758	**82,278**
	K3	520	315	13,651	453	98	59,290	6,366	4,821	**85,513**
	K4	483	272	13,505	323	87	52,205	5,234	5,000	**77,109**
	K5	501	191	13,215	388	65	65,302	6,304	5,124	**91,089**
	K6	687	331	15,659	323	102	45,874	4,608	4,663	**72,247**
	K7	682	348	15,805	323	112	56,009	6,759	5,002	**85,039**
	K8	624	337	17,959	323	108	63,401	6,334	4,949	**94,036**
	K9	488	301	13,651	323	94	61,035	6,446	5,202	**87,540**
	K10	425	242	11,351	323	76	60,982	6,353	5,059	**84,813**
	Mean K1-K6	539	285	13,965	362	90	59,115	6,134	4,963	**85,454**
	Percentage of total	1%	0.33%	16%	0.42%	0.11%	69%	7%	6%	**100%**
Laparoscopic cholecystectomy	L1	398	792	5,530	1,351	216	7,947	1,493	1,387	**19,113**
	L2	476	893	5,530	1,676	240	7,777	1,514	1,311	**19,417**
	L3	469	951	5,676	1,597	246	9,680	1,579	1,597	**21,795**
	L4	506	1,007	5,676	1,777	233	10,259	1,645	922	**22,024**
	L5	431	834	5,530	1,483	199	8,172	1,338	764	**18,751**
	L6	468	893	5,530	1,630	209	9,319	1,664	928	**20,640**
	Mean L1-L6	458	895	5,579	1,586	224	8,859	1,539	1,152	**20,290**
	Percentage of total	2%	4%	27%	8%	1%	44%	8%	6%	**100%**
Tonsillectomy	T1	199	110	2,154	457	21	3,024	222	823	**7,010**
	T2	249	184	2,154	790	51	3,152	211	542	**7,333**
	T3	249	184	2,154	790	36	3,032	202	482	**7,128**
	T4	199	110	2,154	455	21	2,548	159	743	**6,388**
	T5	199	110	2,154	455	21	2,508	154	736	**6,337**
	T6	214	110	2,154	535	22	3,686	463	986	**8,170**
	T7	206	110	2,154	493	21	3,628	459	979	**8,051**
	T8	222	110	2,154	573	22	3,630	459	979	**8,150**
	T9	214	110	2,154	532	22	3,647	454	985	**8,118**
	T10	214	110	2,154	535	22	3,591	454	973	**8,052**
	Mean T1-T10	217	125	2,154	561	26	3,245	324	823	**7,474**
	Percentage of total	3%	2%	29%	8%	0.35%	43%	4%	11%	**100%**

4.4. Discussion

This study evaluated the carbon footprint of products used in common surgical operations, finding the mean average carbon footprint of products used for tonsillectomy was 7.5 kg CO_2e, 11.7 kg CO_2e for inguinal hernia repair, 12.0 kg CO_2e for carpal tunnel decompression, 20.3 kg CO_2e for laparoscopic cholecystectomy, and 85.5 kg CO_2e for knee arthroplasty. At the time of writing there was only one published study of an operation included in this analysis,(143) which estimated the carbon footprint of carpal tunnel decompression at 83 kg CO_2e.(143) However, that estimate was limited to theatre energy consumption, sterilisation of reusable products, and waste (and excluded production of products). The majority of the carbon footprint related to sterilisation, with one sterilisation cycle estimated to use 864 kW for 1.2 hours (1,037 kWh);(143) without clear reason for the large discrepancy with either my published data of 12.03 kWh per cycle for a washer/ disinfector, and 50.55 kWh per cycle for a steam steriliser (CHAPTER 6),(7) or another study by McGain et al. which found steam steriliser electricity consumption was 1.9 kWh per kg reusable products.(157)

Across the five operations assessed, relatively few products (mean average 23%) were associated with ≥ 80% of the carbon footprint of products used (which aligns with the Pareto Principle, whereby 80% of an effect is associated with 20% inputs).(158) Strategies to mitigate carbon footprint of common operations should include eliminating or finding low carbon alternatives for products, in particular those with biggest contribution such as those highlighted in this study (Table 10). Greatest contributions (by process) were associated with production of single-use products (54%), followed by reusable instrument sterilisation (20%), and waste disposal of single-use products (8%). The following three chapters within this thesis evaluate ways to target each of these hotspot areas in turn.

The largest contributing hotspot process identified in this study was production of single-use products (54%), with production and disposal of single-use products including associated packaging responsible for over two-thirds of the carbon footprint of products used across operations (Table 11, mean summed average 69%). The next study (CHAPTER 5) focuses on three single-use products (single-use laparoscopic clip appliers, scissors, and ports) which were collectively found in the current chapter to be responsible for mean average of 19% of the carbon footprint of products used for laparoscopic cholecystectomy, and evaluates the environmental and financial impact of switching to hybrid alternatives (predominantly reusable products).

Sterilisation of reusable instruments was responsible for one-fifth (mean average) of the carbon footprint of products across operations examined in the current study. CHAPTER 6 estimates the carbon footprint of sterilisation (and was used as a source of emission factors for the current study), and seeks to evaluate opportunities for mitigating this. The third hotspot process was waste (constituting 9% of the carbon footprint for disposal of both single-use and reusable products), and in operations observed within this study, infectious waste and clinical waste streams were predominantly used for disposal of operating theatre waste, even though non-infectious offensive waste streams would have been appropriate for disposal in many instances.(159) CHAPTER 7 estimates the carbon footprint of healthcare waste (used as a source of emission factors in the current study), and evaluates the potential to mitigate the carbon footprint of healthcare waste through choice of waste stream.

The impact of surgical variation on carbon footprint is an important area of future research beyond the scope of this thesis. Examples of such variation may relate to surgeon preference in approach and equipment choices, patient factors, and differences in resources and infrastructure between theatre sites. Within this study dataset, the carbon impact of preference within the surgical team was noted such as use of a navigation set for knee arthroplasty (K8; additional 2.25 kg CO_2e); and use of an additional single-use table drape for inguinal hernia repair as the scrub nurse (unlike others) felt the table drape already open was not thick enough (H4; additional 775.39 g CO_2e). Surgical complications influenced carbon footprint, for example gallbladder perforation during two laparoscopic cholecystectomies (L3, L4) required washout using suction irrigation, suction receptacle, and 1 L normal saline bag (cumulatively 2.06-2.26 kg CO_2e). There were also instances where items fell on the floor requiring replacement such as a monopolar diathermy with smoke removal device (H4; additional 641 g CO_2e); and a tibial implant was also dropped in one instance (K7), requiring the opening of another implant (1,110 g CO_2e), cement mixing bowl (2,036 g CO_2e), and bone cement (13,203 g CO_2e).

There were also opportunities to switch many products in single-use pre-prepared packs for reusables equivalents. For example, the single- use hand set (used for carpal tunnel decompression) contained a single-use kidney dish, bowl, light cover, patient drape, and table drape, all of which could potentially be reusable, and the set also contained a sponge which was not used by any of the surgeons locally. A recent study evaluating single-use products opened for hand surgery found that an average of 11.5 products were thrown away without being used per case (including bipolar forceps, drapes, and sponges), most of which were products included in a pre-prepared set (of which an average of 23% was wasted).(160) Another study found 12 out of 40 disposable products in a pre-packaged kit for tonsil surgery were unnecessary.(90)

Limitations

The study in this chapter is limited by the validity of emission factors in databases reporting national or global average emissions of materials and inputs, and differences in system boundaries between these sources. Use of such databases was a pragmatic decision as it was not feasible to obtain primary data upstream of the hospital study site. There may have been observer bias, whereby use of products within the observed operations may have been influenced by my presence.

A hybrid approach was used in this study, whereby a process-based approach was used wherever possible (for most products), and the EEIO model (based upon financial spend data) was applied where there was a lack of available emission factors (for a small number of pharmaceuticals and chemicals). Combining such methods resulted in the system boundaries differing between included products (Figure 9), limiting the extent to which products derived through different approaches can be compared. The impact on results of this study is likely small for most operations evaluated, as the components modelled using an EEIO approach had a mean average contribution of 2% of total carbon footprint results for carpal tunnel decompression, 8% for inguinal hernia repair, and 4% for both laparoscopic cholecystectomy and tonsillectomy. However, for knee arthroplasty 31% of the carbon footprint of all products was determined through the EEIO method, of which bone cement was responsible for 91% of EEIO derived results, estimated at 13 kg CO_2e per packet of bone cement, of which one -two packets were used per operation (in two and eights cases respectively). Where a process-based approach was modelled instead based on the component materials with available emission factors (as detailed in Supplementary table 31), the carbon footprint of bone cement with gentamicin and tobramycin reduced to 683 g CO_2e – 947 g CO_2e per packet respectively, with differences between products principally driven by differences in the weight of packaging. Using these process-based bone cement figures and assuming all other parameters from the study, the mean average total carbon footprint for knee arthroplasty was 63.2 kg CO_2e (range 57.4 kg CO_2e – 70.0 kg CO_2e). However, process-based emission factors were not available for a number of materials within the bone cement (N,n-dimethyl-para- toluidine, hydroquinone, gentamicin sulphate, dibenzoyl peroxide, and tobramycin sulphate), which were accounted for within the EEIO model. The large discrepancy between results derived through EEIO and process-based approaches for bone cement highlight the need for development of emission factors relating to pharmaceutical products.

Further illustrating the importance of this limitation, the only operation to deviate from the trend seen in Figure 10 was knee arthroplasty (wherein 10% products predicted 80% carbon footprint). The carbon footprint of the two products with highest contributions (bone cement with either gentamicin or tobramycin, both 13 kg CO_2e per patient) were determined using an EEIO model based upon financial spend which likely overestimated carbon footprint given high associated costs (£68-£69 respectively). When bone cement was removed from this analysis, 23% of products predicted 80% of the carbon footprint of knee arthroplasty, aligning with the remaining dataset.

Findings of this study may not be generalisable to other contexts, for example to UK surgeons practising alternative approaches or techniques in surgery, and even less so to other countries such as the USA where single-use products are widely used in surgery, or to low-income countries where use of reusable products is the norm. The findings should be used with caution to compare individual products, and instead full LCAs should be conducted, including detailed primary data across the product life cycle and evaluating a range of environmental impacts. However, these findings do identify principal types of product and processes underlying carbon footprint of equipment used in common surgical operations, and will serve as a useful tool for guiding strategy and policy in this area.

Conclusion

Production of single-use products, sterilisation of reusable instruments, and waste disposal were the largest contributors to the carbon footprint of products used across five common operations. Relatively few products (23%) were responsible for ≥ 80% of carbon footprint, and so efforts should be targeted in particular towards these products, through eliminating single-use products or switching to reusables where feasible, alongside optimising associated sterilisation processes and waste segregation. The next three studies address each of these three hotspot processes in turn.

CHAPTER 5 Minimising carbon footprint and financial cost through use of hybrid (reusable/ single-use) products in laparoscopic cholecystectomy

This chapter relates to the following publication:

- Rizan C, Bhutta MF. Environmental impact and life cycle financial cost of hybrid (reusable/ single-use) instruments versus single-use equivalents in laparoscopic cholecystectomy. Surgical Endoscopy. 2022;36(6):4067–4078. PMID: 34559257. *Impact factor 3.45*

This study was funded by Surgical Innovations Ltd who manufacture hybrid laparoscopic products, but the company played no part in the scientific conduct, analysis, or writing of this chapter or associated publication.

5.1. Introduction

The previous study (CHAPTER 4) identified carbon intensive products and processes within five common operations. This highlighted carbon hotspot products which can be targeted when seeking to mitigate carbon footprint, for example evaluating opportunities for elimination or substitution with low carbon alternatives. CHAPTER 4 found that around one-fifth (19%) of the carbon footprint of the products used for a laparoscopic cholecystectomy related to three single-use products; laparoscopic clip appliers (8%), laparoscopic scissors (3%), and laparoscopic ports (8%). When seeking to mitigate carbon footprint of products used for a laparoscopic cholecystectomy these three products are therefore important targets for identifying low-carbon alternative products.

When performing laparoscopic operations, surgeons have traditionally chosen between single-use and reusable laparoscopic products. Anecdotally many surgeons prefer single-use versions due to historical concerns over sterility, or possible failure of reusable products (e.g. less reliably sharp dissecting scissors or failure of clip appliers).(161) However, the financial cost of single-use laparoscopic products is typically higher than reusables,(161) estimated at nineteen times more in laparoscopic cholecystectomy after accounting for costs of sterilisation, repair, and replacement.(162) There are likely reductions in environmental impact also of reusable alternatives.(78)

An alternative option which may bring together advantages of each approach would be the use of hybrid products, also referred to as ‘resposable’ products or ‘modular systems’, which are predominantly reusable, but which have single-use components (referred to as ‘hybrid’ products hereon in). For example, in laparoscopy they may include a reusable trocar and port with single-use seal, or a reusable product handle with single-use insert. Such devices likely reduce the environmental impact as well as financial cost of laparoscopic products, but this has not previously been evaluated. This study (CHAPTER 5) evaluates the environmental and financial impact of switching the three products (laparoscopic clip applier, ports, and scissors) from reusable to hybrid alternatives, and was the first publication to evaluate the role of hybrid equipment in mitigating carbon footprint within healthcare.

The decision to focus on these three products was informed by the results of the previous study (CHAPTER 4), and represents a good target for a detailed study due to the widespread application of these products across laparoscopic surgery. The advent of minimally invasive surgery has led to huge advances in abdominal surgery over the last three decades, with advantages over open approaches including faster recovery, shortened hospital stay, and reduced pain and scarring.(163) An estimated 14 million laparoscopic procedures were performed worldwide in 2020, at which point the global laparoscopic devices and accessories market was estimated at US $13.7 billion (£11.3 billion; exchange rate 12th August 2022) per annum.(164) Cholecystectomy is the most commonly performed laparoscopic procedure,(165) but others include appendicectomy, colectomy, and bariatric operations, as well as gynaecological and urological procedures.

The aim of this study was to evaluate the environmental and financial life-cycle impact of switching single-use products with hybrid equivalents, focusing on three products (laparoscopic scissors, clip appliers and ports) identified in CHAPTER 4 as carbon hotspots within products used for laparoscopic cholecystectomy.

The objectives were as follows:

- Evaluate and compare the environmental impact of single-use laparoscopic products (laparoscopic scissors, clip appliers and ports) with hybrid equivalents using LCA
    - Evaluate financial life cycle cost associated with the alternative models

- Evaluate impact of altering assumptions; number of reuses of products, alternative preparation of products for sterilisation, sterilisation using fossil-fuel rich energy sources, changing carbon intensity of product transportation, and altering port configuration

5.2. Methods

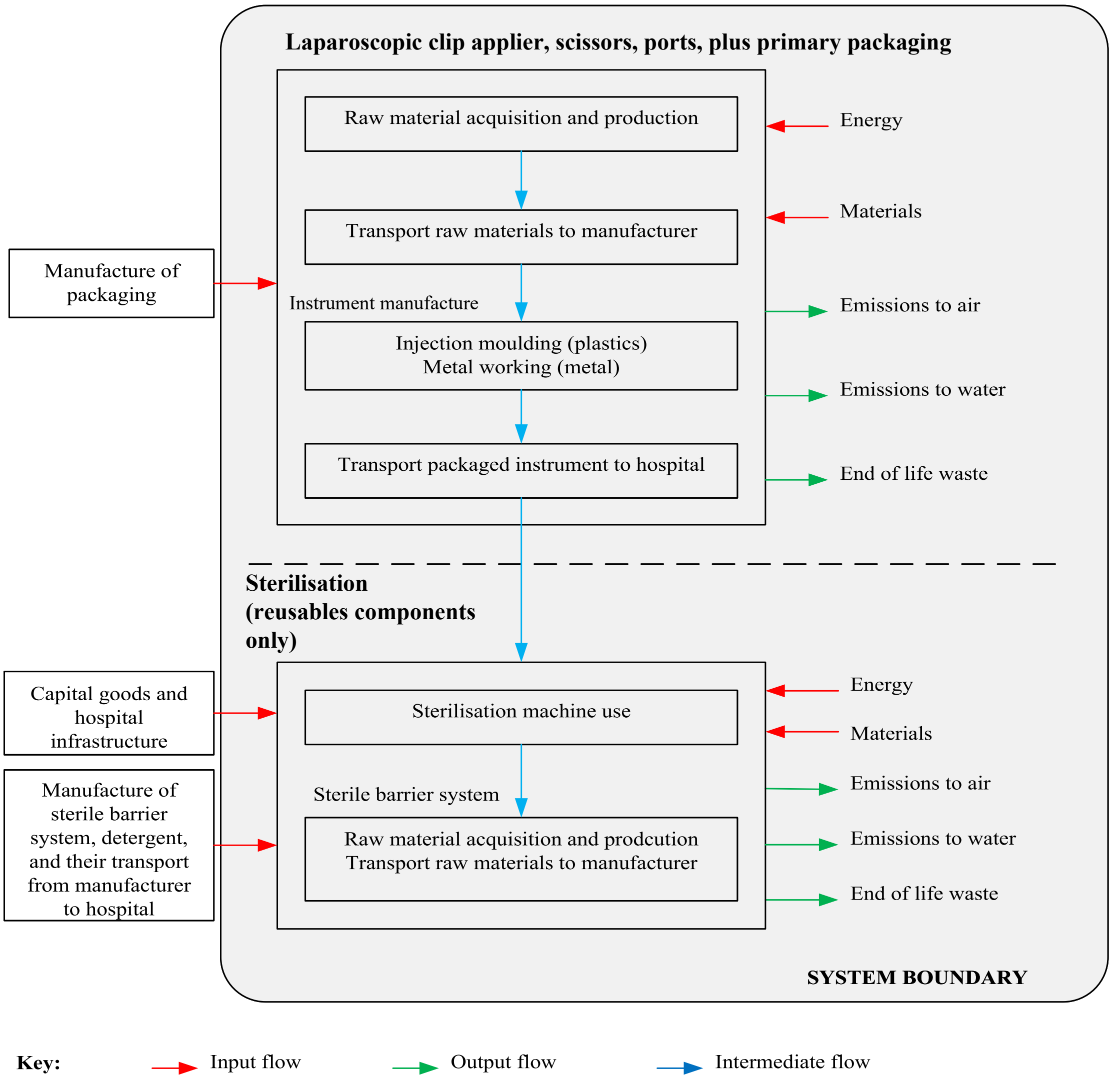
The method used for this study aligns with the approach outlined in CHAPTER 2, and this section only includes details specific to the current chapter.

Scope

Three types of products routinely used in laparoscopic cholecystectomy were analysed, comparing single-use versus hybrid alternatives of laparoscopic clip appliers, laparoscopic scissors, and ports (small diameter 5 mm ports, and large diameter 10 mm – 11 mm ports). The functional unit was defined as the number of these three types of products typically required to perform one laparoscopic cholecystectomy, namely two small diameter ports, two large diameter ports, one laparoscopic scissor, and one laparoscopic clip applier. The hybrid laparoscopic clip applier entailed a reusable clip applier handle and shaft, and single-use clip cartridge insert; the hybrid laparoscopic scissors had a reusable handle, and single-use scissors shaft with blades; the hybrid 5 mm ports involved a reusable cannula, reusable trocar, and single-use valve; and the hybrid 10 mm ports used a reusable cannula, reusable trocar, and a single-use universal seal. The term ‘use’ in this study refers to the use of these products for a single laparoscopic cholecystectomy operation.

This was a process-based cradle to grave LCA, with the system boundary outlined in Figure 12.

Figure 12: System boundary for life cycle assessment of single-use versus hybrid products in laparoscopic cholecystectomy



Processes included were energy and materials required for raw material acquisition, production, and transport of products, alongside injection moulding (for plastic components) and metal working (for metal components). The manufacture of associated packaging was excluded. Processes included in sterilisation (for the reusable components of hybrid products only), were energy and materials required by the sterilisation machines, and for the sterile barrier system (including associated raw material acquisition and production, and transport of raw materials to the manufacturer). Capital goods and the hospital infrastructure were excluded, alongside manufacture and transport of the sterile barrier system and detergent from the manufacturer to the hospital. Emissions to air and water were included for processes where integrated within SimaPro life cycle inventory databases.(114) Disposal of waste at the end of product life was included for all materials.

Life cycle inventory

Hybrid products were supplied by Surgical Innovations Ltd (Leeds, UK) and Microline Surgical Inc (Beverly, USA). Equivalent single-use products were identified from the catalogue of the UK National Health Service (NHS) Supply Chain. The material composition of each product and associated primary packaging were determined using information provided by manufacturers through personal correspondence, or expert knowledge where manufacturers were unable to provide sufficient detail, and the weight of component materials determined.

Material specific global average environmental impact of raw material extraction, production, and transportation to the 'end user' (in this case the manufacturer) of products and packaging was determined through matching materials identified with the closest processes within Ecoinvent (version 3.6), or where unavailable, in Industry Data (version 2.0, both databases integrated within SimaPro).(114) All processes selected from SimaPro databases for this study are detailed in Supplementary table 32.

Environmental impact of product manufacture was approximated using global average metal working processes for all metal components of products, and injection moulding processes for plastic components of products (as modelled in Ecoinvent version 3.6).(114) The mode and distance of international transportation from site of manufacture to the UK was determined through discussion with product suppliers, and an additional 80 km of travel by road using a heavy goods vehicle was assumed both within country of origin and in the UK, with the first and last 8 km at either end of this journey by courier.

Reusable components of hybrid products were assumed to be integrated into a reusable general laparoscopic set, as is common practice. All reusable components were assumed to be sterilised and re-used 500 times, in accordance with manufacturer guidance on typical usage. Sterilisation material and energy requirements are outlined in Supplementary table 33 based on activity data presented in CHAPTER 6 (which estimates carbon footprint of sterilisation). The typical weight of products on a general laparoscopic set was assumed to be 730 g (based on information provided at the time by RSCH) and the weight of hybrid reusable components was 594 g. Thus, hybrid products within a set were assumed to comprise 45% of total weight, and 45% of environmental impact from sterilisation of the set were apportioned to the reusable components of hybrid products. At the end of their life, all items were assumed to be disposed of as clinical waste via high-temperature incineration.

Impact assessment

Following development of the LCA inventory within SimaPro, the ReCiPe Midpoint Hierarchist method (version 1.1, integrated within SimaPro) was used to characterise such emissions, and to combine these into 18 midpoint environmental impacts (as defined in CHAPTER 2).(107) The global warming impact category results were the primary outcome measure, and were used to determine processes contributing most to the carbon footprint of the three products via hotspot analysis. The ReCiPe Endpoint Hierarchist method (version 1.1) was used to aggregate midpoint impact categories to calculate endpoint factors, and midpoint and endpoint impacts were normalised (using the method defined in CHAPTER 2).(33)

Sensitivity analysis

To determine sensitivity of results to allocation methods and key assumptions, five alternative scenarios were modelled.

First, the impact of altering the number of uses of products was determined, and this was also used to identify the threshold at which the carbon footprint of reusables became lower than using single-use equivalents. Laparoscopic clip appliers are not typically used across all laparoscopic operations performed in a given surgical department (but laparoscopic scissors and ports typically are), and clip appliers would therefore not always be integrated into general laparoscopic sets. The second scenario assumed that the clip applier was sterilised separately in a flexible double wrapped polyethylene pouch (Supplementary table 34). Here the total weight of products in the laparoscopic general set was assumed to be 1.1 kg, with sterilisation of surgical scissors and ports apportioned accordingly (366 g out of 1,096 g = 33%). Third, the impact of switching the electricity source for sterilisation to that typical of Australia was modelled, to evaluate the impact of using these products in a country using a lower proportion of renewable energy. Fourth, the impact of changing overseas transport of single-use products to shipping by sea was modelled.

Finally, the carbon footprint of using three 5 mm ports and one 10 mm / 11 mm port was modelled, as this is a commonly used alternative port configuration for laparoscopic cholecystectomy. In the baseline scenario 5 mm single-use ports were modelled based upon use of a dual pack (containing two cannulas, one syringe, and one trocar), and for this alternative scenario, a single-pack was modelled based on removal of duplicate components.

Consequentialist approach to LCA

The baseline analysis used standard practice of an attributional approach to LCA,(20) where products were allocated a proportion of the total life cycle material and energies required for processes shared with other products. Alternative analysis was applied to the base scenario using the consequential approach to LCA, which examines consequences of a change.(20) Specifically, when switching from single-use to hybrid laparoscopic products, hybrid components are typically integrated into surgical sets already destined for sterilisation, meaning under the consequentialist model there is no additional impact from sterilisation.

Life cycle costing

The cost of products reported in the NHS Supply Chain database(166) was equated to the cost of manufacture and distribution. Disposal at the end of product life was costed at £617.22 per t, based on the price of clinical waste incineration reported by the NHS Digital Estates Returns Information Collection dataset.(124) Cost of sterilising reusable components of hybrid products was based on the charge made by the RSCH sterilisation services per product set, apportioned according to the weight of hybrid reusable components (45%).

5.3. Results

Table 13 details the determined material composition and life-span assumptions used for the laparoscopic products, and travel parameters are outlined in Table 14.

Table 13: Material composition of laparoscopic clip applier, scissors, and ports
*= not disclosed at request of manufacturer, HDPE= high density polyethylene, LDPE= low density polyethylene; PEEK= polyether ether ketone, PET= Polyethylene terephthalate, PPS (polyphenylene sulphide), PVC= polyvinylchloride

Product	Sub-component	Supplier (model)	Number of products per laparoscopic cholecystectomy	Product		Packaging	
				Material	Weight (g)	Material	Weight (g)
Hybrid clip applier	Reusable clip applier	Microline Surgical (1002 Reusable multi-fire clip applier 10 mm)	1	Stainless steel PEEK Liquid crystal polymer	146.71 71.2 9.7	Cardboard (corrugated) Polyurethane foam Paper	163.49 62.7 39.43
	Single-use clip cartridge	Microline Surgical (1122 Disp. 10 clips M/L Titanium K2 cartridge)	1	Stainless steel Polycarbonate Titanium	13.8 0.4 0.08	HDPE Paper LDPE	4.6 1.1 0.34
Single-use Clip applier	Single-use clip applier and cartridge	Not disclosed*	1	Stainless steel Polypropylene Polycarbonate PVC Nylon Titanium	64.13 24.91 19.83 6.71 0.40 0.08	Cardboard (boxboard) PET Paper HDPE	135.70 97.18 42.94 9.39
Hybrid laparoscopic scissors	Reusable handle	Surgical Innovations (101-43000 Logic™ Vertical Handle without ratchet)	1	PPS Stainless steel Copper Zinc Nickel	51.9 19.97 0.3 0.3 0.3	Paper Cardboard (boxboard)	22.30 49.97
	Single-use scissors shaft with blades	Surgical Innovations (120-7000 LogiCut™ Metzenbaum Scissors disp.)	1	Stainless steel Aluminium PPS Silicone	14.84 8.7 0.8 0.8	HDPE	8.42
Single-use laparoscopic scissors	Single-use laparoscopic scissor	Not disclosed*	1	Stainless steel Polycarbonate Silicone Polyester Copper Zinc Nickel	27.23 26.68 5.53 0.54 0.3 0.3 0.3	Nylon HDPE Paper Polypropylene	14.01 14.01 8.28 4.4

Hybrid 5 mm port	Reusable 5 mm cannula	Surgical Innovations (YC0509511 YelloPort+PLUS™ 5.5 mm x 95 mm Cannula Threaded +Luer)	2	PEEK Polyoxymethylene PVC Brass Nickel Chromium	10.1 6.4 0.9 0.37 0.37 0.37	Paper HDPE	22 13.6
	Reusable 5 mm trocar	Surgical Innovations (YT0509503 YelloPort+PLUS™ 5.5 mm x 95 mm Pencil Point Trocar)	2	Stainless steel Polyoxymethylene Brass PVC	23.4 10 1.1 0.8	Paper HDPE	22 7.5
	Single-use 5 mm duckbill valve	Surgical Innovations (YA05VSS02 YelloPort+PLUS™ 5 mm Valve S-Use (Tube 2/50 seals))	2	Silicone	1.77	Nylon HDPE Aluminium PET	0.625 0.875 0.25 0.25
Single-use 5 mm port	Single-use 5 mm port (dual pack)	Not disclosed*	1	Polycarbonate Polypropylene Silicone Polyolefin	59.83 7.38 4.36 1.42	Nylon HDPE	5.29 8.54
	Single-use 5 mm port (single pack- scenario modelling)	Not disclosed*	1	Polycarbonate Polypropylene Silicone Polyolefin	37.68 5.66 2.18 0.71	Nylon HDPE	5.29 8.54
Hybrid 10 mm port	Reusable 10 mm cannula	Surgical Innovations (EC1010520 YelloPort Elite™ 10 mm x 105 mm Cannula)	2	PEEK PVC	8.3 2.2	Paper HDPE	22.06 7.5
	Reusable 10 mm trocar	Surgical Innovations (ET1010503 YelloPort Elite™ 10 mm x 105 mm Pencil Point Trocar)	2	Stainless steel Polyoxymethylene PVC	62 17.3 3.2	Paper HDPE	21.7 7.5
	Single-use 5-12 mm universal seal	Surgical Innovations (EA512US YelloPort Elite™ 5-12 mm Universal Seal)	2	Polycarbonate Silicone HDPE Polyester	17.9 3.8 0.7 0.4	Nylon HDPE Aluminium PET	0.53 1.29 0.76 0.76
Single-use 11 mm port	Single-use 11 mm port	Not disclosed*	2	Polycarbonate Polypropylene Silicone	58.84 6.29 3.86	Nylon HDPE LDPE	5.09 8.29 0.46

				Stainless steel Polyolefin	1.29 1.6		

Table 14: Transport assumptions for laparoscopic product manufacture and distribution

Alternative scenarios assuming shipping direct to London Gateway port. * Air freight from California/ Massachusetts (USA) to Amersfoort (Netherlands), to UK via road.

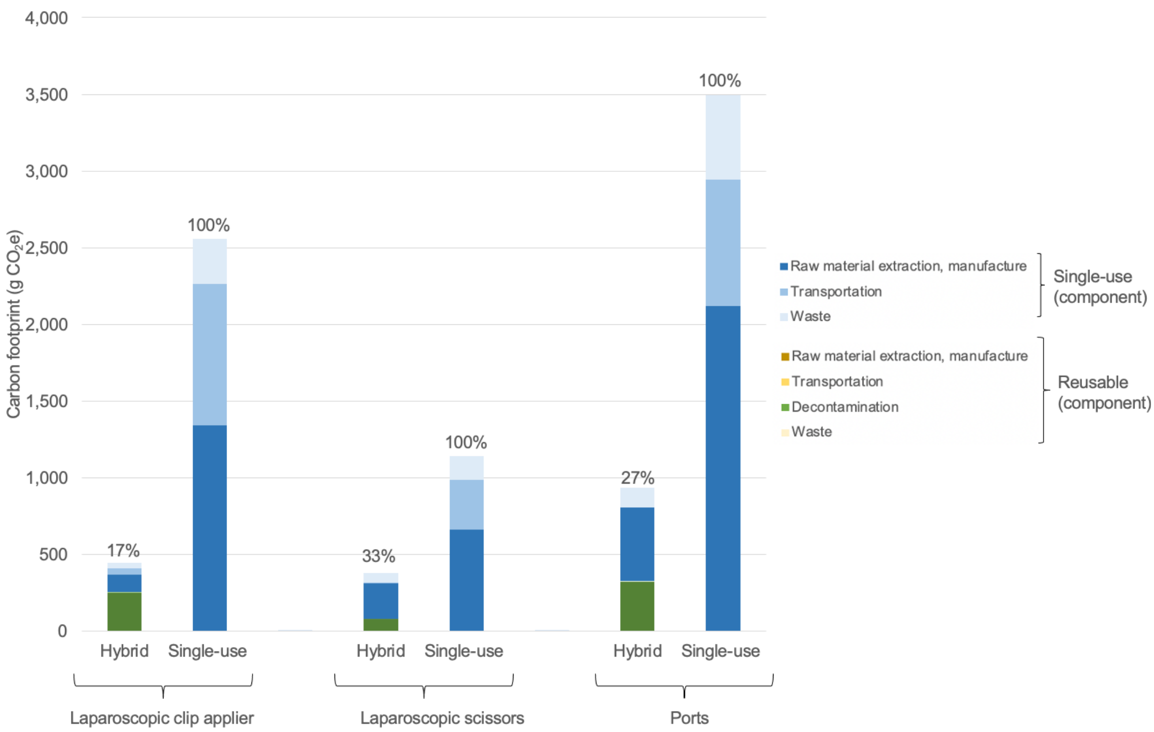
Product	Site of manufacture	Overseas travel mode *(alternative scenario)*	Overseas distance (km) *(alternative scenario)*	UK travel mode	UK travel distance (km)
Hybrid laparoscopic clip applier	Massachusetts (USA)	Heavy goods vehicle Courier Air freight*	492 16 5,633	Heavy goods vehicle Courier	64 16
Single-use laparoscopic clip applier	Ohio (USA)	Heavy goods vehicle Courier Air freight	64 16 6,437	Heavy goods vehicle Courier	64 16
		Heavy goods vehicle *Courier* *Shipping (from Philadelphia)*	*781* *16* *5,650*		
Hybrid laparoscopic scissors	Leeds (UK)	N/A	N/A	Heavy goods vehicle Courier	64 16
Single-use laparoscopic scissors	California (USA)	Heavy goods vehicle Courier Air freight*	492 16 8,851	Heavy goods vehicle Courier	64 16
		Heavy goods vehicle *Courier* *Shipping*	*64* *16* *15,039*		
Hybrid ports	Leeds (UK)	N/A	N/A	Heavy goods vehicle Courier	64 16
Single-use ports	California (USA)	Heavy goods vehicle Courier Air freight*	492 16 8,851	Heavy goods vehicle Courier	64 16
		Heavy goods vehicle *Courier* *Shipping*	*64* *16* *15,039*		

Environmental life cycle assessment

The carbon footprint of laparoscopic hybrid products compared to single-use equivalents per operation were 17% for a laparoscopic clip applier (445 g CO_2e versus 2,559 g CO_2e); 33% for laparoscopic scissors (378 g CO_2e versus 1,139 g CO_2e); and 27% for four ports (933 g CO_2e versus 3,495 g CO_2e per operation) (Figure 13). When combined, the carbon footprint of using hybrid versions of all three product types for an operation was 24% of that for single-use equivalents (1,756 g CO_2e versus 7,194 g CO_2e), saving a total of 5.4 kg CO_2e per operation. This equates to the normal activities of a global average person over 6 hours (normalised results).

Figure 13: Carbon footprint of hybrid versus single-use laparoscopic clip applier, scissors, and ports, and relative contributions of sub-processes

Modelled per use of one laparoscopic clip applier, one laparoscopic scissors, two 5 mm ports, and two 10 mm – 11 mm ports, comparing hybrid with single-use equivalents. Percentage figures above bars indicate proportion (%) relative to single-use equivalents. 'Raw material extraction, manufacture' includes global averages for transportation from site of extraction to the manufacturer.



Hotspot analysis indicated that the majority of the carbon footprint of hybrid products was due to single-use components (mean 62%, range 43% - 79%), followed by sterilisation of reusable components (mean 37%, range 21% - 56%) (Table 15). For single-use products, raw material extraction and manufacture (including transportation between these two processes) was a major contributor (mean 57%, range 52% - 61%), followed by onward transportation (mean 29%, range 24% - 36%), and waste (mean 14%, range 12% - 16%). Supplementary figure 1 - Supplementary figure 6 provide network diagrams visualising these process drivers of the carbon footprint for each product.

The environmental impact of using a combination of hybrid laparoscopic clip appliers, scissors, and ports for an operation was lower than using single-use equivalents across all 18 midpoint environmental impact categories except for marine eutrophication (Figure 14), with mean average reductions in environmental impact of 60% (range minus 32% to plus 84%). Disaggregated data for each product showed midpoint environmental impact categories to be lower for each hybrid product, with a small number of exceptions (Table 16). Contribution analysis indicated that the 3% higher freshwater ecotoxicity impacts (Supplementary figure 7) and 7% higher marine ecotoxicity impacts (Supplementary figure 8) for hybrid compared to single-use laparoscopic scissors were principally due to aluminium within the single-use component of the hybrid scissors (38% for freshwater ecotoxicity, and 37% for marine ecotoxicity), alongside copper assumed to be used within the metal working process (contributing 50% to both categories). Higher marine eutrophication impacts for the hybrid laparoscopic clip applier (38% higher) and ports (76% higher) were largely attributable (89% and 85% respectively) to the handling of wastewater from decontamination (Supplementary figure 9 and Supplementary figure 10). The ionising radiation impact of hybrid laparoscopic scissors and ports (Supplementary figure 11 and Supplementary figure 12) was higher than single-use equivalents (14% and 32% respectively) due to the electricity used in the sterilisation process (accounting for 55% and 78% of the impact respectively).

Table 15: Contributions of processes to carbon footprint of hybrid versus single-use laparoscopic clip applier, scissors, and ports
Contributions of processes to carbon footprint of one use of one laparoscopic clip applier, one laparoscopic scissors, two 5 mm ports, and two 10 mm – 11 mm ports (number required to perform a single laparoscopic cholecystectomy)

Component	**Process**	**Carbon footprint (g CO_2) (% contribution to total for product category)**							
		Laparoscopic clip applier		**Laparoscopic scissors**		**Ports**		**Total**	
		Hybrid	**Single-use**	**Hybrid**	**Single-use**	**Hybrid**	**Single-use**	**Hybrid**	**Single-use**
Reusable component	Raw material extraction and manufacture	4.37 (1%)	N/A	1.27 (0.3%)	N/A	4.58 (0.5%)	N/A	10 (1%)	N/A
	Transportation	2.05 (0.5%)		0.01 (0.003%)		0.04 (0.004%)		2 (0.1%)	
	Sterilisation	247 (56%)		79 (21%)		319 (34%)		646 (37%)	
	Waste	1.15 (0.3%)		0.37 (0.1%)		1.49 (0.004%)		3 (0.2%)	
Single-use component	Raw material extraction and manufacture	112 (25%)	1,342 (52%)	232 (61%)	660 (58%)	481 (52%)	2,122 (61%)	824 (47%)	4,125 (57%)
	Transportation	42 (9%)	923 (36%)	2 (0.4%)	324 (28%)	2 (0.2%)	823 (24%)	46 (3%)	2,070 (29%)
	Waste	36 (8%)	294 (12%)	64 (17%)	154 (14%)	125 (13%)	550 (16%)	225 (13%)	999 (14%)
Total		**445**	**2,559**	**378**	**1,139**	**933**	**3,495**	**1,756**	**7,193**

Figure 14: Environmental impact (midpoint categories) of hybrid versus single-use laparoscopic clip applier, scissors, and ports
Modelled on one use of one laparoscopic clip applier, one laparoscopic scissor, two 5 mm ports, and two 10 mm – 11 mm ports (number required to perform a single laparoscopic cholecystectomy), comparing hybrid with single-use equivalents. Environmental impact compared as proportion (%) of single-use equivalents. Numbers above bars relate to midpoint category absolute figures for product. 1,4-DCB =dichlorobenzene, CFC11= Trichlorofluoromethane, CO_2e= carbon dioxide equivalents, Cu= copper, eq= equivalents, Bq Co-60 eq = becquerel Cobalt-60, m^2a = square metre years, N= nitrogen, NO_x= nitrous oxides, P=phosphate, PM2.5 = particulate matter <2.5 micrometres, SO_2= sulphur dioxide

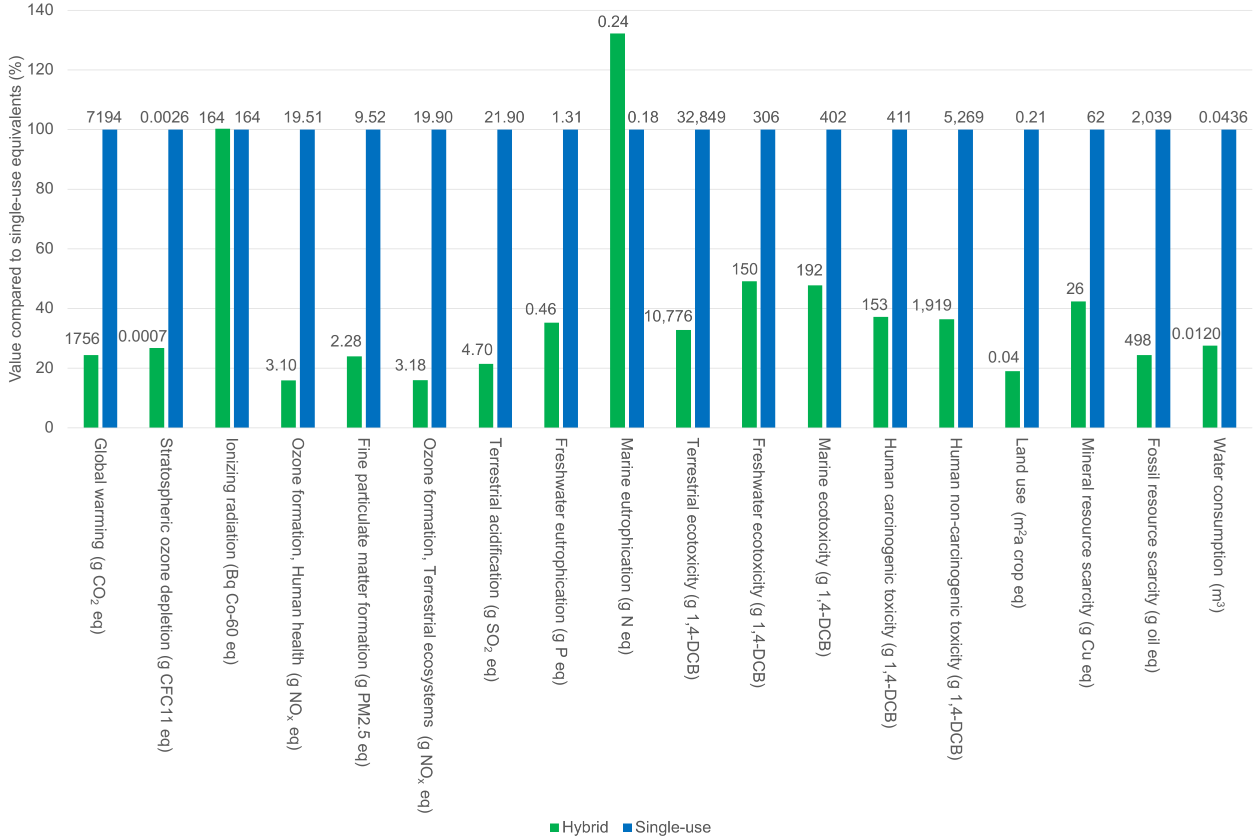


Table 16: Environmental impact (midpoint categories) per use of hybrid versus single-use laparoscopic clip applier, scissors, and ports
Modelled on one use of one clip applier, one laparoscopic scissors, two 5 mm ports, and two 10 mm – 11 mm ports, comparing hybrid with single-use equivalents. Normalised results= environmental impact relative to the global average person's contribution to the impact category over one year. 1,4-DCB =dichlorobenzene, CFC11= Trichlorofluoromethane, CO_2e= carbon dioxide equivalents, Cu= copper, eq= equivalents, Bq Co-60 eq = becquerel Cobalt-60, m^2a = square metre years, N= nitrogen, NO_x= nitrous oxides, P=phosphate, PM2.5 = particulate matter <2.5 micrometres, SO_2= sulphur dioxide

Impact category	Unit	Laparoscopic clip applier		Laparoscopic scissors		Ports		Total (Normalised results)	
		Hybrid	Single-use	Hybrid	Single-use	Hybrid	Single-use	Hybrid	Single-use
Global warming	g CO_2e	445	2,559	378	1,139	933	3,495	1,756 ($2.20e^{-4}$)	7,194 ($9.01e^{-4}$)
Stratospheric ozone depletion	g CFC11 eq	0.0002	0.0008	0.0001	0.0005	0.0004	0.0013	0.0007 ($1.16e^{-5}$)	0.0026 ($4.34e^{-5}$)
Ionizing radiation	Bq Co-60 eq	57	80	28	25	79	59	164 ($3.42e^{-4}$)	164 ($3.41e^{-4}$)
Ozone formation, Human health	g NO_x eq	0.89	8.12	0.79	3.17	1.42	8.21	3.10 ($1.51e^{-4}$)	19.51 ($9.48e^{-4}$)
Fine particulate matter formation	g PM2.5 eq	0.62	4.08	0.78	1.91	0.89	3.53	2.28 ($8.93e^{-5}$)	9.52 ($3.72e^{-4}$)
Ozone formation, Terrestrial ecosystems	g NOx eq	0.91	8.27	0.81	3.24	1.46	8.39	3.18 ($1.79e^{-4}$)	19.90 ($1.12e^{-3}$)
Terrestrial acidification	g SO_2 eq	1.18	8.53	1.44	4.46	2.08	8.91	4.70 ($1.15e^{-4}$)	21.90 ($5.34e^{-4}$)
Freshwater eutrophication	g P eq	0.12	0.62	0.17	0.26	0.17	0.43	0.46 ($7.09e^{-4}$)	1.31 ($2.01e^{-3}$)
Marine eutrophication	g N eq	0.09	0.06	0.04	0.05	0.12	0.07	0.24 ($5.25e^{-5}$)	0.18 ($3.97e^{-5}$)
Terrestrial ecotoxicity	g 1,4-DCB	3,976	19,767	5,628	8,939	1,171	4,142	10,776 ($1.04e^{-2}$)	32,849 ($3.17e^{-2}$)
Freshwater ecotoxicity	g 1,4-DCB	36	176	97	91	17	39	150 ($1.23e^{-1}$)	306 ($2.5e^{-1}$)
Marine ecotoxicity	g 1,4-DCB	47	230	122	118	23	54	192 ($1.86e^{-1}$)	402 ($3.89e^{-1}$)

Human carcinogenic toxicity	g 1,4-DCB	45	203	65	91	43	117	153 ($5.52e^{-2}$)	411 ($1.48e^{-1}$)
Human non-carcinogenic toxicity	g 1,4-DCB	576	2,871	952	1,386	390	1,013	1,919 ($1.29e^{-2}$)	5,269 ($3.54e^{-2}$)
Land use	m^2a crop eq	0.01	0.16	0.01	0.02	0.02	0.03	0.04 ($8.04e^{-6}$)	0.21 ($3.37e^{-5}$)
Mineral resource scarcity	g Cu eq	9	39	14	19	3	4	26 ($2.18e^{-7}$)	62 ($5.13e^{-7}$)
Fossil resource scarcity	g oil eq	137	784	100	315	261	940	498 ($5.08e^{-4}$)	2,039 ($2.08e^{-3}$)
Water consumption	m^3	0.0030	0.0146	0.0028	0.0083	0.0081	0.0208	0.0139 ($5.22e^{-5}$)	0.0437 ($1.64e^{-4}$)

For endpoint categories, using a combination of hybrid laparoscopic clip appliers, scissors, and ports for a single laparoscopic cholecystectomy saved an estimated $1.13e^{-5}$ DALYs (disability associated life years), $2.37e^{-8}$ species.year (loss of local species per year), and US \$0.6 impact on resource depletion, representing reductions of 74%, 76%, and 78% respectively compared to single-use equivalents (Table 17, Figure 15).

Table 17: Environmental impact (endpoint categories) of hybrid versus single-use laparoscopic clip applier, scissors, and ports
Modelled on one use of one laparoscopic clip applier, one laparoscopic scissors, two 5 mm ports, and two 10 mm – 11 mm ports (number required to perform a single laparoscopic cholecystectomy), comparing hybrid with single-use equivalents. Normalised results= environmental impact relative to the global average person's contribution to the impact category over one year. DALYs= disability adjusted life years, species.year=loss of local species per year, US \$=extra costs involved for future mineral and fossil resource extraction

Damage category	Unit	Laparoscopic clip applier		Laparoscopic scissors		Ports		Total (Normalised results)	
		Hybrid	**Single-use**	**Hybrid**	**Single-use**	**Hybrid**	**Single-use**	**Hybrid**	**Single-use**
Human health	DALY	$1.09e^{-6}$	$6.30e^{-6}$	$1.28e^{-6}$	$2.90e^{-6}$	$1.67e^{-6}$	$6.13e^{-6}$	$4.04e^{-6}$ ($1.7e^{-4}$)	$1.53e^{-5}$ ($6.45e^{-4}$)
Ecosystems	species.yr	$1.96e^{-9}$	$1.24e^{-8}$	$1.84e^{-9}$	$5.22e^{-9}$	$3.67e^{-9}$	$1.36e^{-8}$	$7.47e^{-9}$ ($1.04e^{-5}$)	$3.12e^{-8}$ ($4.36e^{-5}$)
Resources	US \$	0.05	0.29	0.03	0.12	0.09	0.34	$1.63e^{-1}$ ($5.82e^{-6}$)	$7.56e^{-1}$ ($2.7e^{-5}$)

Sensitivity analysis

For all hybrid products, carbon footprint was lower than single-use equivalents when the reusable component was used more than twice. Impact on carbon plateaued at around 10 uses of reusable components, with little additional gain (<1%) after using laparoscopic scissors 60 times, ports 70 times, and clip appliers 100 times (Figure 16). However, continued use of products beyond these figures would save the additional carbon burden of obtaining new products.

Figure 15: Environmental impact (endpoint categories) of hybrid versus single-use laparoscopic clip applier, scissors, and ports
Modelled per use of one laparoscopic clip applier, one laparoscopic scissors, two 5 mm ports, and two 10 mm – 11 mm ports, comparing hybrid with single-use equivalents. Environmental impact compared as proportion (%) of single-use equivalents. Numbers above bars relate to endpoint category absolute figures for product, measured in disability adjusted life years (DALYs), loss of local species per year (species.year), and extra costs involved for future mineral, and fossil resource extraction (US $).

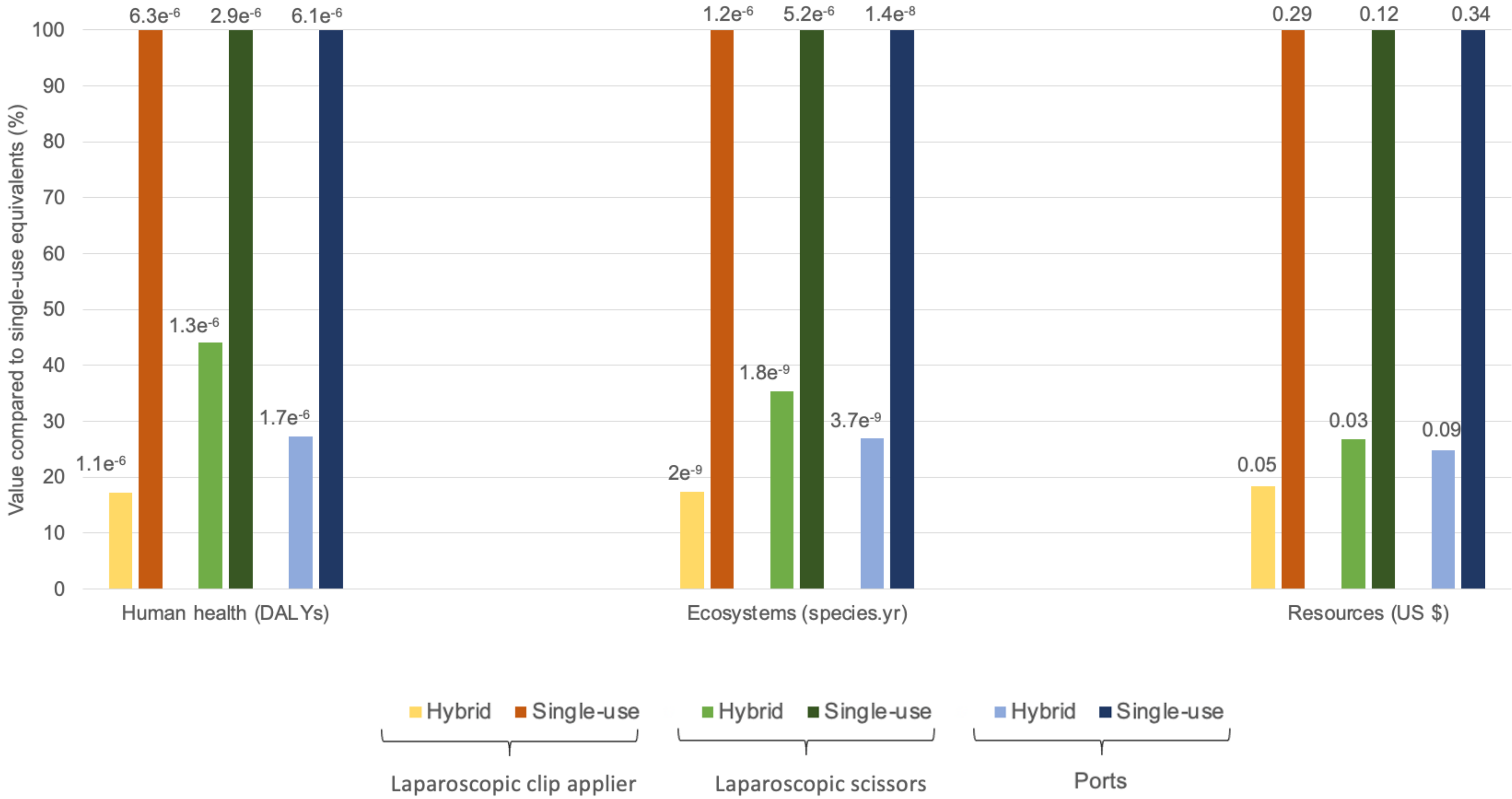
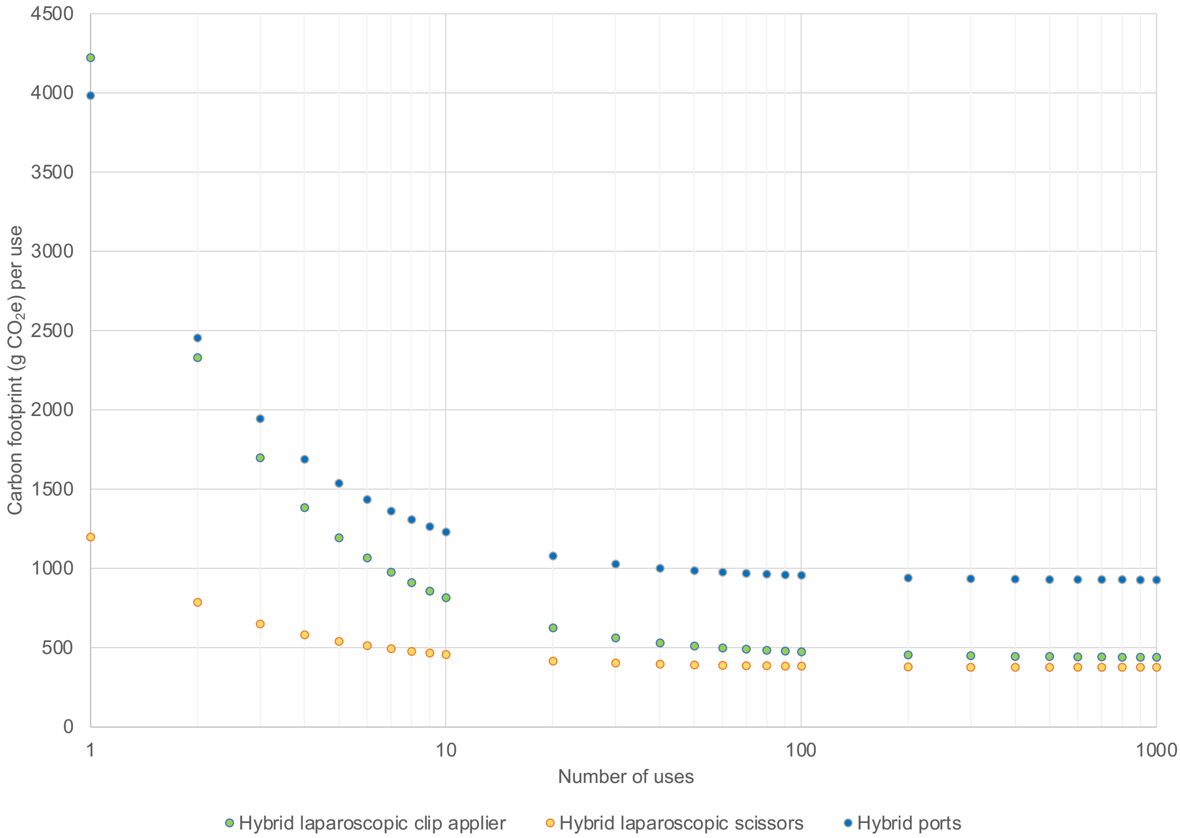


Figure 16: Impact of number of uses of reusable components of hybrid laparoscopic clip applier, scissors, and ports on carbon footprint
Modelled per use of one hybrid laparoscopic clip applier, one hybrid laparoscopic scissor, two 5 mm hybrid ports, and two 10 mm – 11 mm hybrid ports



When packaged and sterilised separately, the carbon footprint of the hybrid laparoscopic clip applier increased 3.7-fold to 1,650 g CO_2e per use (Supplementary table 35). There were small accompanying increases for laparoscopic scissors (to 394 g CO_2e per use, 4% increase) and ports (999 g CO_2e per use, 7% increase), due to a greater proportional weight in the reusable instrument set. Nevertheless, in this alternative model the carbon footprint of all hybrid products remained lower than single-use equivalents (36% less for laparoscopic clip appliers, 65% less for laparoscopic scissors, and 71% less for ports).

The carbon footprint of the sterilisation process itself was 54% higher when Australian electricity was modelled, which increased carbon footprint of the hybrid products by 11% -30% (Supplementary table 36), but this remained lower (63% - 77%) than single-use equivalents.

Shipping in place of air freight for international transport of single-use products reduced the carbon footprint by 22% - 33% relative to the baseline single-use products (Supplementary table 37), but the hybrid baseline products remained lower than the shipped single-use equivalents; by 74% for the clip applier, 55% for the scissors, and 65% for the ports.

Finally, using three hybrid 5 mm ports and one 10 mm port (635 g CO_2e per operation) resulted in a 32% reduction in carbon footprint relative to the base scenario hybrid port setup (Supplementary table 38). The use of single-use ports with this alternative port configuration was associated with a six-fold increase in carbon footprint compared with use of hybrids (3,613 g CO_2e), constituting a 3% increase relative to the base scenario single-use port setup.

Consequentialist approach to LCA

Under the consequential approach to LCA, carbon footprint of a hybrid laparoscopic clip applier was 198 g CO_2e (7% of single-use equivalent of 2,559 g CO_2e), for scissors this was 299 g CO_2e (26% of single-use equivalent of 1,139 g CO_2e), and for four hybrid ports was 614 g CO_2e (18% of single-use equivalent of 3,495 g CO_2e). When combined, under the consequentialist approach the carbon footprint of using hybrid versions of all three product types for an operation was 15% of that for single-use equivalents (1,110 g versus 7,194 g CO_2e), saving a total of 6,083 g CO_2e.

Life cycle financial cost

Per operation, the cost of hybrid compared to single-use products (Table 18) was 33% for a clip applier (£52 versus £156), 83% for scissors (£20 versus £24), and 58% for ports (£59 versus £102). Most of the costs of hybrid products (≥ 87% contribution in all cases) were from the single-use components, with smaller contributions from sterilisation (≤ 10%), reusable components (≤ 4%), or waste (≤ 0.2%). For a single laparoscopic cholecystectomy, cost of using a combination of hybrid laparoscopic clip appliers, scissors, and ports was 47% that of single-use equivalents (£131 versus £282).

Table 18: Life cycle costing of hybrid versus single-use laparoscopic clip applier, scissors, and ports
Cost per laparoscopic cholecystectomy, modelled on one use of one clip applier, one laparoscopic scissors, two 5 mm ports, and two 10 mm – 11 mm ports, comparing hybrid with single-use equivalents

Product	Cost per laparoscopic cholecystectomy (£)				
	Reusable component	Single-use component	Sterilisation	Waste	Total
Hybrid laparoscopic clip applier	0.92	46.42	4.39	0.01	51.74
Single-use laparoscopic clip applier	N/A	156.14	N/A	0.25	156.39
Hybrid laparoscopic scissors	0.56	18	1.40	0.02	19.98
Single-use laparoscopic scissors	N/A	24.12	N/A	0.06	24.18
Hybrid ports	2.08	51	5.66	0.04	58.78
Single-use ports	N/A	101.44	N/A	0.16	101.60

5.4. Discussion

This study found that the carbon footprint of using hybrid scissors, ports, and clip appliers was 76% lower than using single-use equivalents, saving 5.4 kg CO_2e per operation (equal to driving 15 miles in an average petrol car).(31) There were almost 73,000 laparoscopic cholecystectomy operations performed in the year 2019 - 2020 in England,(167) and if the three hybrid products analysed were used across all of these operations in place of single-use equivalents, this would save 396 t CO_2e, equivalent to 50 years of daily activities of a global average person (normalised results), or driving 1.1 million miles in an average petrol car.(31) Additional reductions include an estimated 0.82 DALYs (equating to 296 disability adjusted life days), 0.0017 species.year, and US $43,188 due to resource depletion. Under a consequentialist analysis, these values would be even higher. The direct financial costs across the lifespan of the hybrid products were less than half those of single-use equivalents, and would save over £11 million per year if adopted for all laparoscopic cholecystectomies in England.

Sensitivity analysis found hybrid laparoscopic products remained preferable to single-use equivalents even if there was infrequent reuse of hybrid products, if hybrid clip appliers were packaged and sterilised separately to the main product set, if using a fossil-fuel rich source for sterilisation, if switching international transport of single-use equipment to shipping in preference to air freight, or if altering port configuration. The latter scenario analysis indicated that use of three 5 mm hybrid ports and one 10 mm port (instead of two of each), reduced the carbon footprint by around one-third, principally due to the difference in the weight of the single-use component (10 mm hybrid port was associated with a 22.8 g single-use universal seal, whilst the 5 mm hybrid port was associated with a 1.77 g single-use valve). Adoption of this downsized hybrid port setup may therefore correspond with additional reductions in environmental impact, with further reductions anticipated for three-port microlaparoscopic approaches, eliminating the need for one of the ports altogether. However, adoption of the alternative port setup was associated with marginal increases in carbon footprint for single-use ports when obtained as three individually wrapped 5 mm ports (each containing its own syringe, trocar, and cannula), and one 11 mm port. This contrasts with use of a double pack containing two 5 mm ports, as modelled in the base scenario, where one syringe and one trocar was shared between two cannulas. This indicates that where single-use ports are used, use of dual packs (and development of triple packs for surgeons wishing to use this configuration), may confer carbon reductions where this eliminates duplicate single-use products.

Use of plastics within healthcare is also gaining increasing attention,(82) and when using hybrid laparoscopic clip appliers, scissors, and ports for a laparoscopic cholecystectomy, the total plastic was 15% that of using single-use equivalents (saving around 405 g plastics per laparoscopic cholecystectomy), and generating just 15% of the waste (saving the generation of 645 g of waste per operation). If extrapolated across all laparoscopic cholecystectomies in England this would save an estimated production and disposal of 30 t of plastic per year.

Since publishing findings of this study,(6) an LCA study by Boberg et al. has evaluated fully reusable laparoscopic ports, finding that two large and two small fully reusable laparoscopic ports (236 g CO_2e) held around one-fifth of the carbon footprint of single-use equivalents (1,130 g CO_2e).(168) This indicates that increasing the reusable proportion of hybrid ports would likely confer further reductions in carbon footprint. The study by Boberg et al. also found that the single-use ports were twice as expensive as reusables,(6) in line with findings comparing single-use versus hybrid ports in this study. The carbon footprint estimate for single-use ports determined by Boberg et al.(168) was around one-third of that reported in this study, and this likely relates to differences in products evaluated, system boundaries, and assumptions. For example total weight of four single-use ports (including packaging) modelled by Boberg et al.(168) was 248 g, whilst the equivalent in this chapter was 345 g, and unlike in the current study, transportation modelled by Boberg et al.(168) did not include any air freight (responsible for around one-quarter of the carbon footprint of ports in this study).

The principle of using hybrid products in preference to single-use products and of minimising single-use components is likely generalisable to other laparoscopic products and other laparoscopic procedures. Other hybrid products currently available include hybrid laparoscopic articulating dissectors, retractor rings, electrocautery probes, and a variety of forceps on the market. Further research and innovation may expand this repertoire to enable further replacement of single-use products. Given that a mean average of two-thirds of the carbon footprint of hybrid products was due to the single-use components, it is likely that decreasing the single-use proportion of hybrid products would reduce environmental impact. However, I am aware of suboptimal anecdotal user experience associated with current hybrid solutions with higher reusable portions, for example delays due to reloading of reusable clip appliers with single polymer or titanium locking clips (contrasting with cartridge containing multiple clips modelled here), and higher levels of technical skills required to use a reusable pre-tied knot pusher. Whilst fully reusable laparoscopic scissors exist, these are reportedly less reliably sharp than single-use equivalents. Future innovation should therefore be targeted towards improving design of reusable laparoscopic equipment, minimising the single-use component as far as possible, and scheduling maintenance and repair for reusable components.

Limitations

There are alternative solutions to the products evaluated beyond the scope of this study as previously discussed. As with all LCAs, this analysis was limited by assumptions, the system boundary, parameter uncertainty, and model uncertainty. This is illustrated when comparing results for the three single-use products derived in this study to those estimated for the same products in CHAPTER 4 as a component of the carbon footprint evaluation of all products used across as laparoscopic cholecystectomy. Whilst figures derived in CHAPTER 4 were 37% - 44% lower per product than those of the current study (CHAPTER 5), the ratio of the carbon footprint between product categories were similar (for laparoscopic clip applier: laparoscopic scissors: ports, this was 2.2 : 1 : 3.1 in CHAPTER 5, compared with 2.4 : 1 : 3 in CHAPTER 4). Whilst the relative ratios of products were similar between studies, the absolute figures differed, and this is likely due to several factors. Firstly, there were differences in the system boundaries drawn, for example the detailed LCA study in the current chapter (CHAPTER 5) included all transportation involved across the life cycle, and processing of primary materials via injection moulding and metal working. Secondly, there were differences in granularity of activity data collated, for example in the current study, raw material extraction, transportation, and manufacture processes were adapted to specific countries and transport modalities, rather than using global average data as was necessary in CHAPTER 4. There were also differences in emission factor sources used between studies. Further, the wide range in results derived within the sensitivity analysis in the current study (CHAPTER 5) demonstrate how the absolute figures determined using carbon footprinting are dependent on a range of assumptions. This illustrates that results should be compared with caution between sources (for example across different research papers, and across studies in this thesis using different approaches), and instead the principal value of environmental accounting is in using this consistently in a given context to evaluate carbon hotpots, low carbon alternatives, or optimisation of processes.

Conclusion

CHAPTER 4 found the process contributing most to the carbon footprint of products used across five operations was the production of single-use products (mean average 54%). CHAPTER 4 also found that in a laparoscopic cholecystectomy 19% of the carbon footprint related to just three single-use products; laparoscopic clip applier, scissors, and ports. The current study (CHAPTER 5) evaluated the potential to mitigate this through switching to hybrid equivalents, finding this reduced the carbon footprint by around three-quarters, and the financial cost by around half. Given the global scale of laparoscopic surgery, adoption of hybrid products could play an important role in meeting carbon reduction targets in healthcare, whilst saving money. To reduce environmental impact of hybrid products further they should be used for their full lifespan, sterilised within existing laparoscopic instrument sets where possible, and manufactured, transported, and decontaminated using low carbon intensity methods.

CHAPTER 6 Minimising carbon footprint and financial costs of steam sterilisation and packaging of reusable surgical instruments

This chapter relates to the following publication:

- Rizan C, Lillywhite R, Reed M, Bhutta MF. Minimising carbon footprint and financial costs of steam sterilisation and packaging reusable surgical instruments. British Journal of Surgery. 2022; 109(2):200–210. PMID: 34849606. *Impact factor 6.94*

6.1. Introduction

CHAPTER 4 found that the largest contributing processes to the carbon footprint of products used across five common operations were production of single-use products (54%), sterilisation of reusable products (20%), and waste disposal of single-use products (8%). CHAPTER 5 focused on tackling the first hotspot process, taking the example of three high-carbon laparoscopic products, and finding approximately three-quarter reductions in carbon footprint through switching to hybrid equivalents that were mainly reusable. However, CHAPTER 5 found that when hybrid products were used most of the remaining carbon footprint related to the single-use component (mean 62%), followed by sterilisation (37%), and so strategies to reduce carbon footprint of hybrid products further might include reducing the single-use component and optimising the sterilisation process. As discussed in previous chapters, the majority of evidence indicates that reusable products used in the operating theatre have a lower carbon footprint than single-use equivalents, as supported by a previous systematic review.(78) However, where reusable products are used, the majority of the carbon footprint typically relates to sterilisation, for example illustrated by studies evaluating laryngoscopes,(72) laryngeal mask airways,(92) and surgical scissors.(91) This study (CHAPTER 6) estimates the carbon footprint of sterilisation and strategies for mitigation, focusing on the second largest carbon hotspot process across products used in common operations, identified in CHAPTER 4.

Reusable surgical instruments are typically grouped into sets containing instruments required for a specified procedure or group of procedures, and each set is placed in trays or baskets. After use, instruments go through a process of decontamination, which involves cleaning and subsequent microbial inactivation through disinfection and/or sterilisation.(159) Microbial inactivation for reusable instruments is most often achieved using steam (as modelled in this study),(169) although alternative low-temperature methods include ethylene oxide, vaporised hydrogen peroxide gas plasma, or ozone.(159) For the purpose of this study, the process of preparing reusable equipment for subsequent use is referred to as 'decontamination' to enable distinction between the two component processes (washing, and steam sterilisation), whilst in other chapters this process is referred to collectively as 'sterilisation', in line with common use within the healthcare sector.

Packaging of instruments for decontamination utilises 'sterile barrier systems', which permit permeation of the sterilisation agent, but prevent post treatment entry of microorganisms, to maintain sterility until point of use.(170) Options include tray wraps (usually 1-3 single-use layers, typically made of polypropylene and paper), reusable rigid containers (usually made of aluminium, stainless steel or plastics, with or without a filter) or flexible pouches (thermally sealed sleeves made of combinations of paper and plastics). These are the three packaging systems used at RSCH, and are the ones recommended by a WHO report on decontamination, which indicates that whilst reusable linen tray wraps are sometimes used as an alternative in some regions, the ability of reusable linen tray wraps to act as a microbial barrier is lower than single-use tray wraps, and so reusable linen tray wraps were not modelled in this study.(169)

An additional factor determining carbon footprint of decontamination and packaging is the composition of instrument sets. In some surgical procedures, additional individually wrapped instruments (not included in the set) may be opened, which are subsequently re-packaged and decontaminated. Conversely some instruments in a set may remain unused in a particular procedure. There has been a recent drive to streamline instruments included in reusable sets,(171, 172, 173, 174) whereby less commonly used instruments are removed from sets, and reclassified as individually wrapped instruments, to be opened only if specifically needed. Previous studies have suggested potential elimination of up to 60% of instruments in a paediatric set,(171) and 39% of instruments in minor urology sets through removal of instruments used less than 20% of the time.(172) Consolidating instrument sets may reduce costs(171, 172) and time spent assembling sets and performing peri-operative checks,(173, 174) but no studies have reported impact on carbon footprint. During a given operation surgeons frequently require additional instruments not included within an opened set, for example due to an instrument not being included in the original set, or an included instrument being dropped or de-sterilised. In this situation, surgeons can choose between obtaining the instrument as a an individually wrapped instrument or through opening a whole additional instrument set. The carbon impact of this has not previously been evaluated.

In summary, the carbon footprint and financial cost of preparing surgical instruments for reuse is determined by:

1. the decontamination processes
2. the sterile barrier system (packaging)
3. the composition of instrument sets, and the need to open individually wrapped instruments

Previous studies have evaluated the carbon footprint of steam sterilisation of specific instruments including a central venous catheter (Australia),(97) reusable ureteroscope (Australia),(96) and reusable laryngoscope blade (USA).(72) Electricity requirements have also been determined for decontamination of a caesarean section instrument tray (USA),(112) and electricity and water requirements for decontaminating one kilogram of linens and instruments (Australia).(157) Prior to the publication of this study (CHAPTER 6),(7) no studies had reported the carbon footprint and financial cost of different processes for decontamination and preparation of reusable surgical instruments, nor how such processes can be optimised.

The primary aim of this study (CHAPTER 6) was to estimate the carbon footprint and financial cost of decontaminating reusable surgical instruments. This in turn provided emission factors to account for decontamination of reusable instruments in CHAPTER 4, and decontamination activity data for LCAs of hybrid laparoscopic equipment in CHAPTER 5 and reusable scissors in CHAPTER 8. The secondary aim was to evaluate ways to mitigate the carbon footprint associated with decontamination, and in doing so this seeks to addresses the second hotspot identified at the level of products used across operations (CHAPTER 4) and a major contributor to the carbon footprint of hybrid equipment (CHAPTER 5). The ambition is that this will provide evidence for surgeons and sterile services department (SSD) personnel wishing to reduce the carbon footprint associated with decontamination and packaging of reusable surgical instruments.

The objectives were as follows:

- Estimate the carbon footprint of decontaminating reusable surgical instruments via washing and steam sterilisation, alongside packaging in alternative sterile barrier systems
    - Evaluate financial life cycle cost associated with the alternative models
    - Evaluate opportunities to mitigate the carbon footprint of decontamination; impact of preparing reusable instruments as sets versus individually wrapped instruments, altering machine loading, use of alternative energy sources for decontamination, and alternative waste streams
    - Evaluate carbon and financial cost impact of opening instruments during an operation, and of streamlining instrument sets

6.2. Methods

The method used for this study aligns with the approach outlined in CHAPTER 2, and this section only includes details specific to the current chapter.

Scope

Carbon footprint and financial costs were estimated from processes for decontamination and packaging reusable surgical instruments at the RSCH sterile services department (SSD), which provides services for University Hospitals Sussex NHS Foundation Trust (alongside a smaller SSD at the Princess Royal Hospital). When a reusable instrument set arrived at the SSD, it was first un-packaged, and instruments loaded into a washer/ disinfector machine. Any single-use packaging was disposed of, whilst reusable packaging was placed in the washer/ disinfector separate to the instruments. The instruments were then packaged in their sterile barrier system before undergoing sterilisation in the decontamination machine.

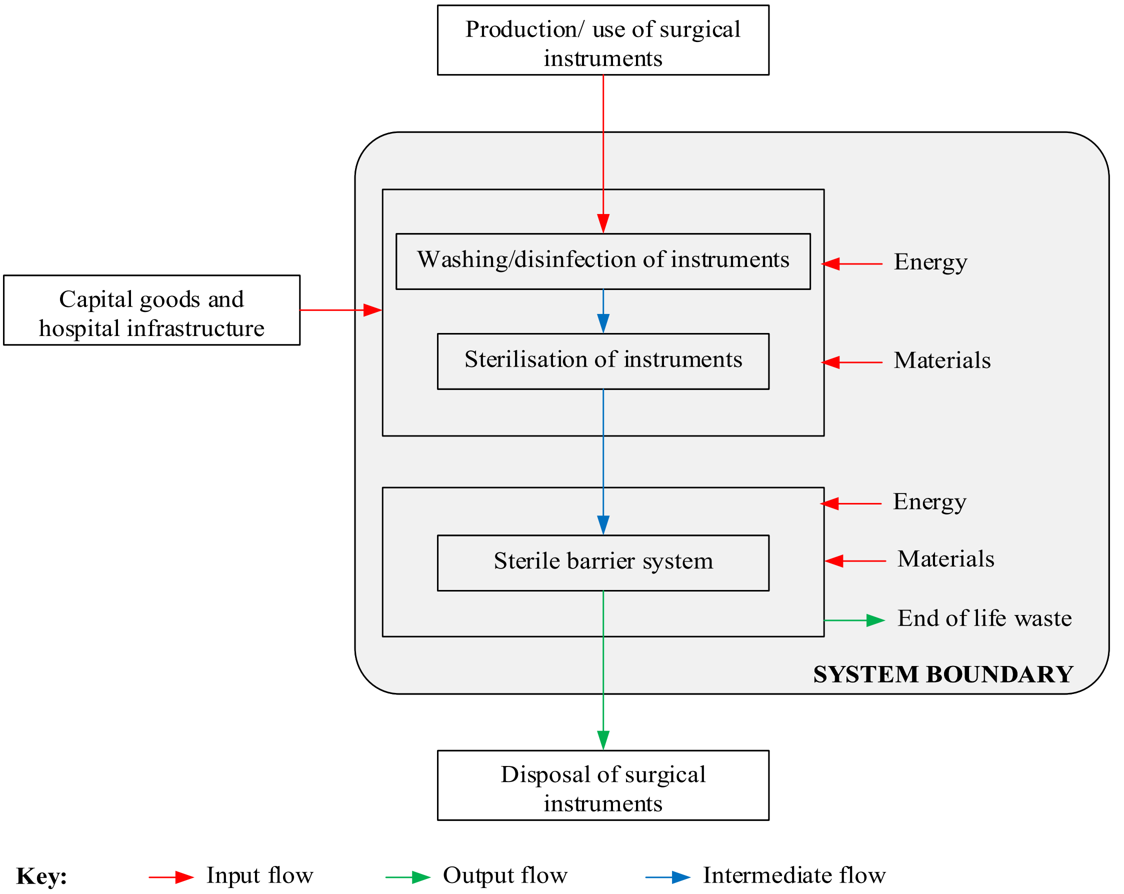
At RSCH there were two types of machines for decontamination; two washer/ disinfectors (Steelco TW300/3, Treviso, Italy) and four steam sterilisers (BMM Western V9934, Faversham, UK). The washer/ disinfector machines had 12 slots (each with capacity to hold a standard sized instrument set, with larger sets split across two slots) with instruments passing through three chambers each with capacity of 400 litres, and reaching 90 ºC – 95 ºC for around one minute during the decontamination cycle. The steam steriliser had 18 slots (each slot housing a standard to large sized set, or up to two small sets), with capacity of 1,250 litres, reaching 134ºC - 137 ºC for approximately three minutes. The number of individually wrapped instruments which could be housed in each slot depended upon the size of those instruments, and on hospital demand for such instruments at a given time (sometimes necessitating decontamination cycles to be run with the number of instruments loaded per slot below the maximum).

Three alternative packaging materials recommended by WHO(169) were modelled, based on specific examples available at RSCH. Set instruments were placed in a reusable stainless steel mesh basket, and in the first scenario housed in reusable aluminium containers, and in the second scenario within two layers of single-use tray wrap made of polypropylene and paper. In the third scenario, instruments were individually packaged in two single-use flexible peel pouches, each made of paper on one side and polyethylene on the other. Associated packaging and labelling of instruments were included for all scenarios. At the study site, around two-thirds of instruments sterilised (April 2017-March 2018) were instrument sets, and one-third individually wrapped instruments, with 85% of the former housed in reusable containers and the other 15% in single-use tray wraps.

The functional units assessed were one cycle of each decontamination machine, one surgical instrument (either as part of a set or individually wrapped), and one typically sized set (housed within a rigid container or tray wrap).

Processes included within the system boundary were energy and materials required by the washer/disinfector, steriliser, sterile barrier system, and waste disposal of materials (Figure 17). The system boundary for the production, use, and waste disposal of the sterile barrier system aligned with that outlined in the study of products used in whole operations (CHAPTER 4 Figure 9). Energy and materials for the sterile barrier system included any additional decontamination resulting from choice of packaging, which included washing of rigid containers in dedicated cycles in the washer/disinfector, but there was no additional impact from sterilisation of the sterile barrier system. Capital goods, hospital infrastructure, and production and disposal of surgical instruments were excluded. Vehicular transportation was not modelled, as this study assumed use of instruments at RSCH and sterilisation at the onsite SSD.

Figure 17: System boundary for carbon footprint of decontamination and packaging of reusable surgical instruments



Life cycle inventory

A process-based carbon footprint approach was used for all components using activity data, aside from the detergent, which was modelled using an EEIO analysis based on financial data.

Decontamination processes were determined through discussion with engineers, data managers, and senior staff at the SSD. Typical input requirements were determined for each machine per unit time of operation through technical specification sheets and direct contact with manufacturers (no primary data on energy or water consumption were collected). The mean duration of machine cycles was determined across three cycles of each process and used to calculate process activity data per cycle. Typical machine loading patterns were determined using a prospective audit of ten cycles on one day to record mean number of slots used, number of instruments per slot, and whether slots were filled with sets or individually wrapped instruments. Mean number of instruments per set was determined using a retrospective audit of RSCH instrument decontamination over one year (1/7/18- 30/6/19). Where typical carbon footprint and cost per set were estimated, these were derived using mean loading patterns and mean number of instruments per set.

The carbon footprint of packaging was estimated by determining material composition of each sterile barrier system (from manufacturer information where available, or expert knowledge), and the weight of each component was determined. The lifetime of stainless steel baskets was estimated at ten years, and plastic identification tags at four years (expert opinion of SSD senior staff and industry contacts), with a mean of 11.6 uses per year for both components (based upon one-year retrospective audit of RSCH decontamination of 67,080 instrument sets). Reusable aluminium containers were assumed to be used 1,000 times, in accordance with manufacturer information. Packaging and reusable products (at the end of reusable products' life) were assumed to enter domestic or non-infectious offensive waste streams (both processed using low temperature incineration with energy from waste), based on observed waste streams at the SSD.(8)

Impact assessment

The carbon footprint of decontamination and packaging was determined through applying best available emission factors (Supplementary table 39). These were sourced from the 2019 DEFRA/ BEIS database,(116) Inventory of Carbon and Energy database (version 3),(32) Small World Consulting Carbon Factors dataset (version 1.5),(117) and published findings from CHAPTER 7 on healthcare waste.(8)

Reusable containers were washed in dedicated cycles, with each washer/disinfector machine loaded with six containers per cycle, and the carbon footprint of this was allocated to the packaging itself. However, instruments were sterilised in the sterilisation machine within their packaging, with no additional sterilisation required for any sterile barrier system (unlike dedicated washing cycles required for reusable containers), and so the carbon footprint associated with sterilisation was allocated to the instruments themselves.

Life cycle costing

The financial cost of decontaminating instruments was based on the charge by SSD to surgical departments per set and per individually wrapped instrument. Purchase costs of sterile barrier systems were obtained from the SSD procurement team, and combined with the costs of decontamination to determine the financial implications of each scenario.

Sensitivity analysis

Alternative scenarios were modelled to determine sensitivity of carbon footprint results to key assumptions, and to determine strategies to mitigate carbon footprint of decontaminating and packaging reusable surgical instruments.

Altering decontamination machine loading

Scenario modelling and multiple linear regression was used to evaluate and compare the carbon footprint and cost of alternative processes for instrument decontamination, including different machine loading capacities (25%, 50%, 75%, 100%), and number of instruments per slot (5-30, at intervals of 5). The latter equates to the number of instruments on a standard set for instruments, or the number of instruments per decontamination machine slot for individually wrapped instruments. The carbon footprint of the lowest machine loading pattern observed during the audit was also estimated.

Altering sources of energy for decontamination

The SSD at RSCH used a natural gas fuelled steam generator to supply steam for both the washer/ disinfector and sterilisation machine. The generation of steam by electricity was modelled, as well as different sources for electricity and natural gas supply. This modelling was based upon Australian electricity, assuming a large proportion of non-renewable high carbon energy sources (coal), Icelandic electricity assuming predominantly low carbon renewable energy sources (geothermal and hydropower), alongside regions that use a mix of sources (US, European average, and global average). For natural gas, the carbon footprint of onsite combustion is relatively constant, but well-to-tank emissions show large geographical variations depending upon upstream processes for extraction, refining, and transportation and transmission via pipelines.(175) Well-to-tank emissions were modelled for US, European average (also used for Icelandic models due to lack of country specific data), and global average calculations (also used for Australian models). Water supply and detergent were responsible for <1% of the decontamination carbon footprint and so were not altered in this analysis. Region-specific emission factors for electricity and natural gas were extracted from SimaPro (version 9.10), using the Ecoinvent database (version 3.6, Supplementary table 39).(114)

Altering waste streams

The impact of sterile barrier system disposal via different waste streams was modelled, comparing high temperature incineration (as used for clinical waste) with recycling, to represent highest and lowest carbon modes of healthcare waste disposal respectively.(8) Emission factors derived in CHAPTER 7 were used for high temperature incineration, (8) and the recycled content method was used to account for recycling, which allocates the carbon footprint of the recycling process to the production of the recycled goods.(20)

Optimal processes

Using this sensitivity analysis, the optimum carbon footprint and cost of decontaminating and packaging an average instrument set were determined. The financial cost impact of changing the proportion of lower carbon energy was not modelled, but financial savings would likely align with carbon reductions, given that UK government data estimate that generating electricity using wind and solar technologies costs half that of gas turbines.(176)

Analysis for streamlining instrument sets and obtaining additional instruments intra-operatively

The impact of removing between one and ten instruments from a set on the carbon footprint and cost of decontamination and packaging was modelled. A standard operation was assumed to require a set containing 29 instruments (based on the RSCH retrospective audit of 67,080 instrument sets) housed in single-use tray wrap, with loading of the decontamination machine at mean values. It was assumed that each removed instrument would be required in 20% of operations (and obtained as an individually wrapped instrument), because prior studies on streamlining sets have suggested removal of instruments used less than 20% of the time.(172, 174) Obtaining one or more instruments either from a new set (assuming all subsequent additional instruments could be obtained from that set, housed in single-use tray wrap), or as individually wrapped instruments was also modelled, and thresholds determined at which carbon and financial costs reached parity in these scenarios.

6.3. Results

Decontamination

Sub-processes and associated inputs for decontamination machines are summarised in Figure 18 and Figure 19. The mean duration of the washer/ disinfector cycle was 45 minutes, and for the steriliser 54 minutes. Total inputs for decontamination (washer/disinfector and steriliser) per instrument set were 1.26 kWh electricity, 76 L water, 0.3 m^3 natural gas (=3.20 kWh), and £0.03 for detergent. The carbon footprint of one typical cycle of the washer/ disinfector and steriliser were 3.74 kg CO_2e per cycle and 12.13 kg CO_2e per cycle respectively (Table 19).

Audit of decontamination machines indicated mean average of 68% of washer/ disinfector and 69% of steriliser slots were occupied, and the majority of occupied machine slots were used for instrument sets rather than individually wrapped instruments (85% for the washer/ disinfector, and 92% for the steriliser; Table 20). Across 67,080 instrument sets processed by the SSD in the year, there was a mean of 29 instruments per set. Using mean machine loading and mean number of instruments per set, the carbon footprint of decontaminating surgical instruments was 52 g CO_2e per instrument as part of a set (1,531 g CO_2e per set), and 145 g CO_2e per instrument for individually wrapped instruments (Table 21).

The cost to decontaminate an average set (containing ≤ 30 instruments) was £25.53 per set, and £4.83 per instrument for individually wrapped instruments.

Figure 18: Processes involved in the washer/ disinfector cycle and input requirements
The washer/ disinfector machine (far right) was reliant on several other machines (grey boxes). The inputs (energy, fuels, water, and chemicals) for each machine are illustrated in white boxes, with the input requirements of each machine per cycle shown in red.

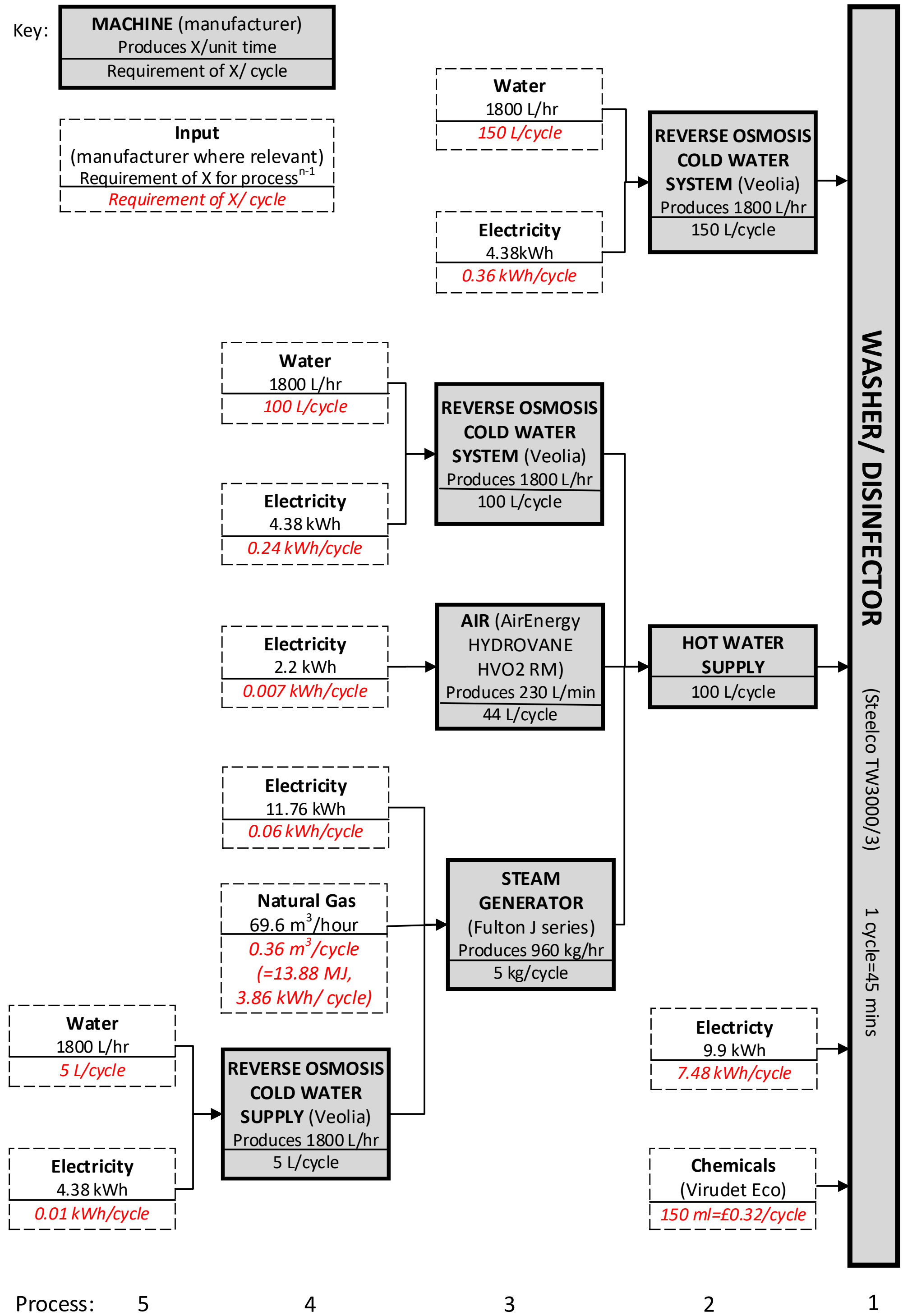


Figure 19: Processes involved in steriliser cycle and input requirements
The steriliser machine (far right) was reliant on several other machines (grey boxes). The inputs (energy, fuels, water and chemicals) for each machine are illustrated in white boxes, with the input requirements of each machine per cycle shown in red.

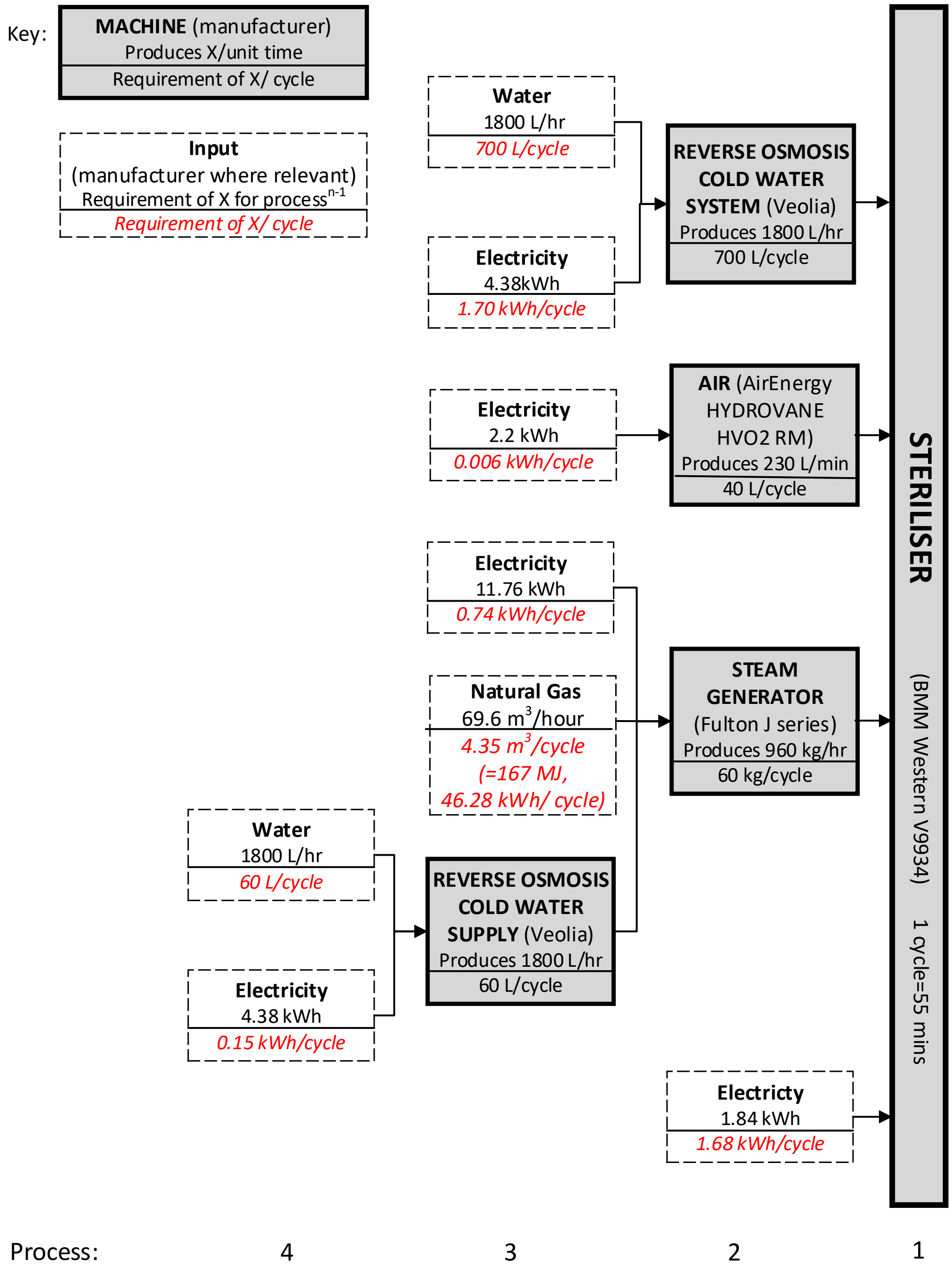


Table 19 Carbon footprint of washer/ disinfector and steam steriliser
Inputs for a single cycle of each decontamination machine and their carbon footprint. CO_2e= carbon dioxide equivalents

Component	Washer/ disinfector			Steam steriliser		
	Quantity used per cycle	Carbon footprint (kg CO_2e per cycle)		Quantity used per cycle	Carbon footprint (kg CO_2e per cycle)	
		Component	Total		Component	Total
Detergent	£0.32	0.05	3.74	-	-	12.13
Electricity	8.17 kWh	2.58		4.27 kWh	1.35	
Natural gas	0.36 m^3 (=13.88 MJ, 3.86 kWh)	0.83		4.35 m^3 (=167 MJ, 46.28 kWh)	9.98	
Water supply and treatment	255 L	0.27		760 L	0.80	

Table 20: Decontamination machine loading audit results
CI=confidence interval

Unit	Parameter (all per cycle)	Washer/ disinfector	Steriliser
Total number of instruments	Mean (95% CI)	159.00 (120.07-197.93)	309.90 (192.90-426.90)
Total slots used	Mean (95% CI)	8.10 (6.21-9.98)	11.33 (8.81-13.87)
	Mean proportion of slots available used (%)	67.50	68.54
Slots containing individually wrapped instruments	Mean (95% CI)	1.20 (0.24-2.16)	1.00 (0.23-1.77)
	Mean proportion of used slots (%)	14.81	8.11
Number of instruments per slot used for individually wrapped instruments	Mean (95% CI)	7.08 (3.75-10.42)	12.5 (7.06-17.94)
Slots containing instrument sets	Mean (95% CI)	6.9 (5.68-8.12)	11.34 (8.81-13.87)
	Mean proportion of used slots (%)	85.19	91.89
Number of instruments per slot used for instrument sets	Mean (95% CI)	21.81 (18.98-24.64)	23.88 (18.57-29.20)

Table 21: Carbon footprint of decontamination per instrument set and per instrument
Results in this table do not include the sterile barrier system. CO_2e= carbon dioxide equivalents

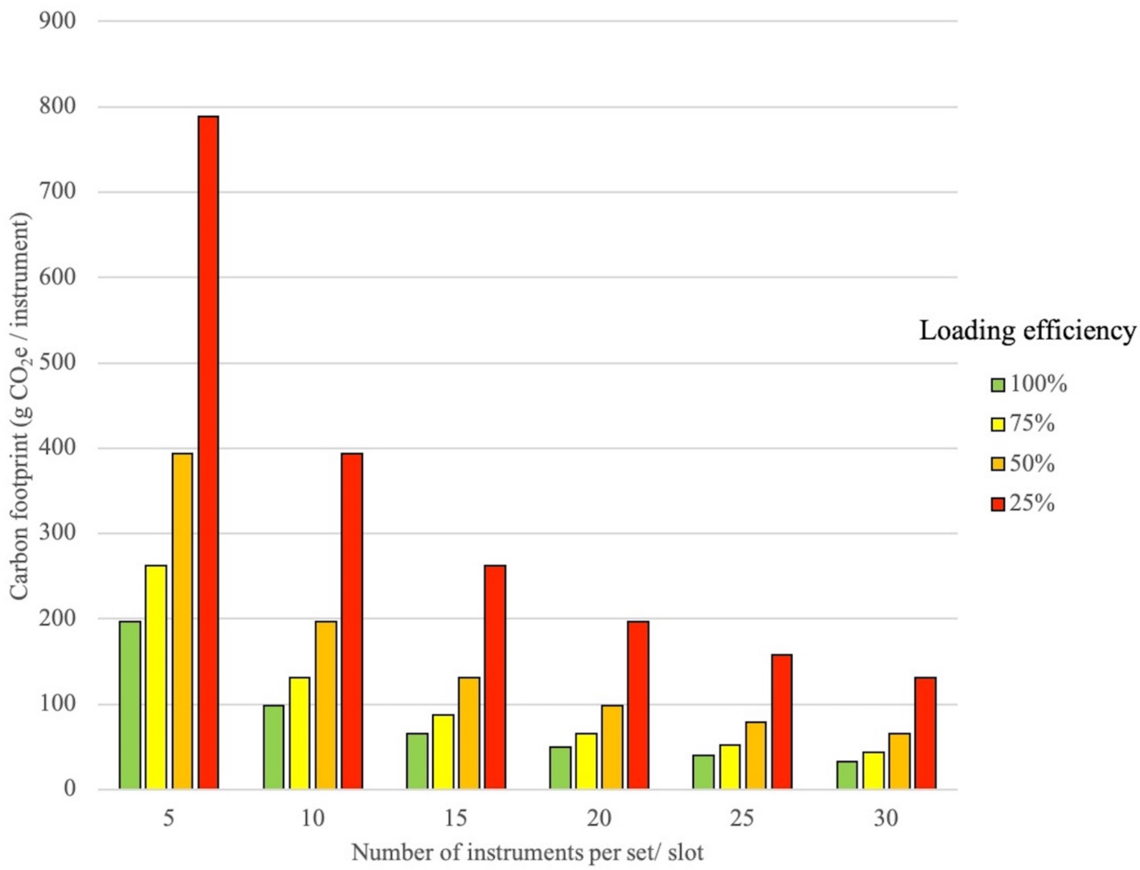
Functional unit	Carbon footprint (g CO_2e per functional unit)		
	Washer/ disinfector	Steriliser	Total
Instrument set	461	1,070	1,531
Instrument in instrument set	15.8	36.6	52.4
Individually wrapped instrument	59.8	85.6	145.4

Sensitivity analysis: altering decontamination machine loading

Modelling loading efficiencies (Figure 20) indicated that as the number of instruments per set (or per slot for individually wrapped instruments) increased, the carbon footprint decreased, and decreased further through improving loading efficiency (proportion of slots used). Both the number of slots used and number of instruments per slot significantly correlated to carbon footprint (R^2 = 0.678, p <0.001), with both variables adding significantly to the prediction (p<0.001). When the lowest observed loading was modelled (4/12 slots for the washer/ disinfector, and 6/18 slots for the steriliser, with 29 instruments per set), part-loading of machines increased carbon footprint by a factor of 2.6 compared to typical loading (3,967 versus 1,531 g CO_2e per set, and 137 versus 52 CO_2e per instrument). The lowest carbon footprint (33 g CO_2e per instrument) was achieved where loading efficiency was 100% and there were 30 instruments per set.

Figure 20: Carbon footprint of decontaminating instruments under different loading scenarios

This figure did not include the sterile barrier system. CO_2e= carbon dioxide equivalents



Sensitivity analysis: altering sources of energy for decontamination

The carbon footprint of decontamination (without packaging) per instrument set using natural gas to power the steam generator (Figure 21, Table 22) ranged from 1,222 g CO_2e in Iceland, to 2,536 g CO_2e in Australia, with a global average of 2,166 g CO_2e (compared with baseline natural-gas powered UK model at 1,531 g CO_2e). Where electricity was used to power the steam steriliser, the carbon footprint of decontamination ranged from 421 g CO_2e in Iceland (low carbon energy source) to 6,020 g CO_2e in Australia (high carbon energy source), with a global average of 4,431 g CO_2e. In most regions the carbon footprint of decontamination was higher when electricity was used to power the steam steriliser rather than natural gas, due to additional steps in generation and distribution of electricity.

Figure 21: Altering sources of energy for decontamination

Total carbon footprint of decontamination (washer/disinfector plus steriliser), modelling steam generated using either natural gas or electricity, and alternative regions. *=base scenario, CO_2e= carbon dioxide equivalents

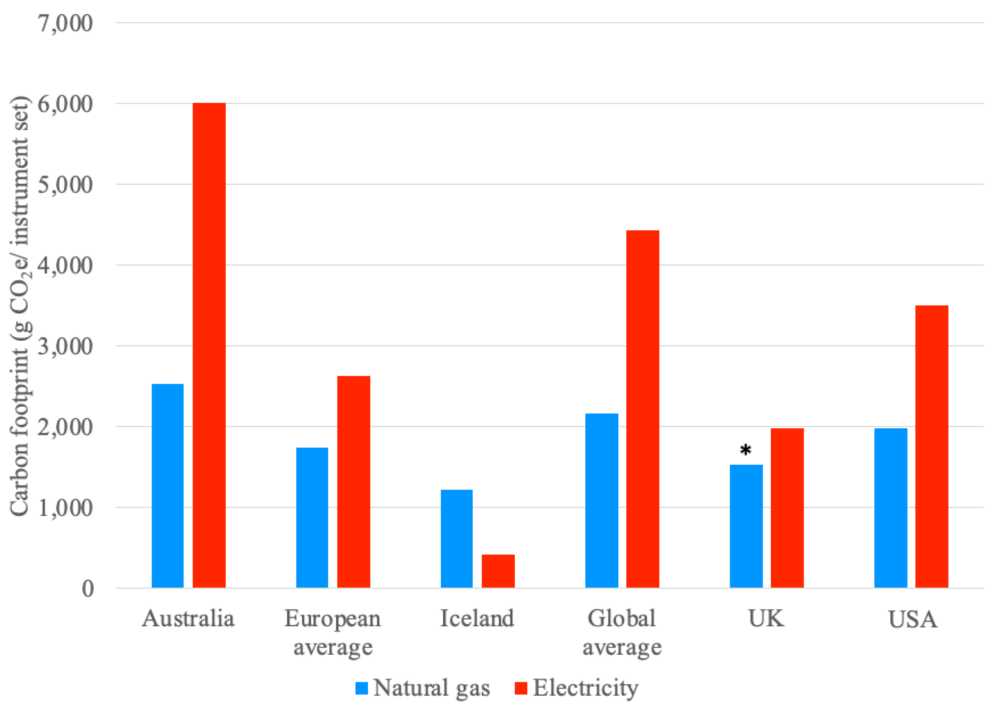


Table 22: Altering sources of energy for decontamination
Carbon footprint of decontamination (washer/disinfector plus steriliser), modelling steam generated using either natural gas or electricity, and alternative regions. *=base scenario, CO_2e= carbon dioxide equivalents

Region	Steam generation energy source	Carbon footprint (g CO_2e per functional unit)		
		Instrument set	Instrument in instrument set	Individually wrapped instrument
Australia	Natural gas	2,536	87	260
	Electricity	6,020	206	557
European average	Natural gas	1,739	60	168
	Electricity	2,639	90	244
Iceland	Natural gas	1,222	42	108
	Electricity	421	14	40
Global average	Natural gas	2,166	74	217
	Electricity	4,431	152	410
UK	Natural gas*	1,531	52	145
	Electricity	1,989	68	184
USA	Natural gas	1,990	68	195
	Electricity	3,499	120	324

Sterile barrier systems

The carbon footprint of the sterile barrier system per typical instrument was 25 g CO_2e for reusable aluminium containers, 13 g CO_2e for single-use tray wraps, and 44 g CO_2e for flexible pouches (Table 23).

The cost of two layers of single-use tray wrap was £1.18. The flexible pouch cost approximately £1.51 per instrument. The outlay cost of the aluminium container was £682.80, and £0.68 per use. Cost of the aluminium container achieved parity with tray wrap after 591 uses, and with flexible pouches after 454 uses.

Table 23: Carbon footprint of sterile barrier systems
Additional decontamination relates to washing of reusable containers in dedicated washer/ disinfector cycles. There was no washing involved in single-use options, and no additional impact from sterilisation of any of the packaging options (allocated to instruments inside of packaging). *Total carbon footprint of sterile barrier system (packaging) per instrument using mean number of instruments per set, CO_2e= carbon dioxide equivalents, HDPE= high density polyethylene

Sterile barrier system	**Component**	**Sub-unit material**	**Weight (g)**	**Assumed number of uses**	**Carbon footprint (g CO_2e per use)**				
					Materials	**Additional decontamination**	**Disposal**	**Total per sterile barrier system**	**Total per instrument ***
Reusable rigid container	Basket	Stainless steel	1,053.09	116	95	623	4	721	25
	Container	Aluminium	2,996.54	1,000					
	Identification tag	HDPE resin	8.21	46					
	Filter paper	Paper	3.55	1					
	Kit list	Paper	4.85	1					
	Tamper proof tags	General plastic	1.78	1					
Single-use tray wrap	Basket	Stainless steel	1,053.09	116	362	N/A	24	387	13
	Identification tag	HDPE resin	8.21	46					
	Inner wrap	Polypropylene	55.95	1					
	Kit list	Paper	4.85	1					
	Label + indicator tape	Paper	7.90	1					
	Outer wrap	Paper	64.02	1					
Flexible pouch	Identification tag	HDPE resin	8.21	46	39	N/A	5	44	44
	Outer pouch	Paper	4.10	1					
		General polyethylene	5.96	1					
	Inner pouch	Paper	3.68	1					
		General polyethylene	4.83	1					

Sensitivity analysis: altering waste disposal

Compared with the baseline (which assumed use of low temperature incineration with energy from waste), disposal via high temperature incineration increased the carbon footprint of reusable rigid containers across their life cycle by only 3% (to 25.4 g CO_2e per instrument), and recycling reduced carbon footprint by only 0.5% (to 24.5 g CO_2e per instrument). Larger differences were found for single-use sterile barrier systems (Table 24), with a 33% increase in total carbon footprint with high temperature incineration for single-use tray wrap (to 18 g CO_2e per instrument) and 55% increase for flexible pouches (to 68 g CO_2e per instrument). There was a 6% decrease in carbon footprint associated with use of recycling for tray wrap (to 12 g CO_2e per instrument) and 10% decrease for flexible pouches (to 39 g CO_2e per instrument).

Table 24: Altering waste disposal for sterile barrier system

Total results presented here relate to materials, additional decontamination plus waste disposal of sterile barrier systems (packaging), under two alternative waste disposal scenarios. CO_2e= carbon dioxide equivalents

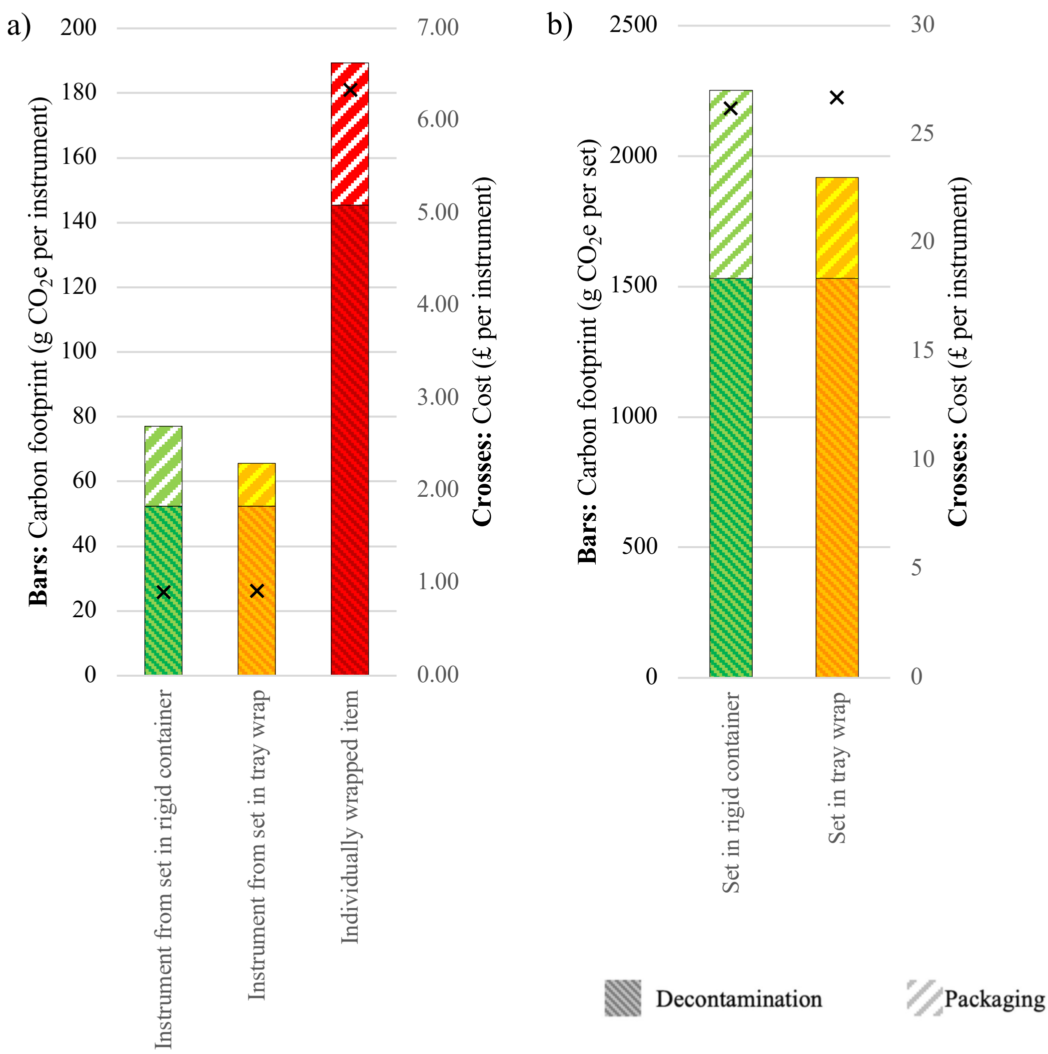
Sterile barrier system	Carbon footprint (g CO_2e per use) of sterile barrier system			
	Per instrument set		Per instrument	
	High temperature incineration	Recycling	High temperature incineration	Recycling
Reusable rigid container	741	717	25	25
Single-use tray wrap	515	362	18	12
Flexible pouch	N/A	N/A	68	39

Total carbon footprint and cost of decontamination and packaging

Total carbon footprint and cost of decontaminating and packaging instruments (Figure 22, baseline model and assumptions) was 77 g CO_2e (£0.90) per instrument housed in aluminium containers (2,252 g CO_2e, £26.21 for the whole set), 66 g CO_2e (£0.92) per instrument in tray wrap (1,918 g CO_2e, £26.71 for the whole set), and 189 g CO_2e (£6.34) per individually wrapped instrument. In summary, both the carbon footprint and financial cost of an individually wrapped instrument was greater than an instrument from a set packaged in a rigid container, which in turn had a greater carbon footprint per use than an instrument from a set packaged in tray wrap (and substantially the same financial cost).

Figure 22: Total carbon footprint and cost of decontaminating and packaging reusable instruments a) per instrument, and b) per set

Bar graph shows carbon footprint and crosses indicate financial cost a) per instrument and b) per instrument set. Each bar is split in two to demonstrate the contribution of the decontamination process and the packaging to the carbon footprint. CO_2e= carbon dioxide equivalents



Optimal processes

The carbon footprint and cost of instrument decontamination and packaging was optimised through four strategies (Figure 23); 1) processing instruments in sets rather than individually wrapped, 2) maximal loading of the decontamination machine (100% slots used, 30 instruments per slot), 3) increasing the proportion of low carbon energy supply, and 4) recycling of the sterile barrier system. The choice of a reusable rigid container for housing the set was associated with lowest financial cost (marginally lower than using single-use tray wrap), whilst use of single-use tray wrap resulted in the lowest carbon footprint. Optimum financial costs (assuming use of reusable rigid containers) equated to £26.21 per set, and £0.87 per instrument, and optimum carbon footprint (assuming use of a single-use tray wrap in the UK) was 1,348 g CO_2e per set, and 45 g CO_2e per instrument. Where Icelandic electricity was modelled, carbon footprint was reduced further to 633 g CO_2e or 1,141 g CO_2e per set (assuming electricity, or natural gas fuelled steam generation respectively), equating to 21 g CO_2e or 38 g CO_2e per instrument.

Streamlining instrument sets and obtaining extra instruments intra-operatively

Removing instruments from a set proportionately increased the carbon footprint and financial cost of decontaminating and packaging reusable instruments (Figure 24). For operations requiring the removed instrument(s) as individually wrapped instruments (20% of cases), this generated an additional 189 g CO_2e and cost an extra £6.34 per instrument. Carbon footprint increased by a mean average of 38 g CO_2e (costing an additional £1.27) per instrument removed across all operations requiring the streamlined set.

When obtaining extra instruments intra-operatively, the carbon footprint of decontamination and packaging was lower when additional instruments were obtained as individually wrapped instruments when ≤ 10 instruments were required, and costs lower when ≤ 4 instruments were required. Above these thresholds carbon and financial costs were lower when instruments were obtained by opening an additional set.

Figure 23: Optimising carbon footprint and financial cost of decontaminating and packaging reusable instruments
Low carbon energy models assumed electricity powered steam generation. CO_2e= carbon dioxide equivalents, SBS= sterile barrier system

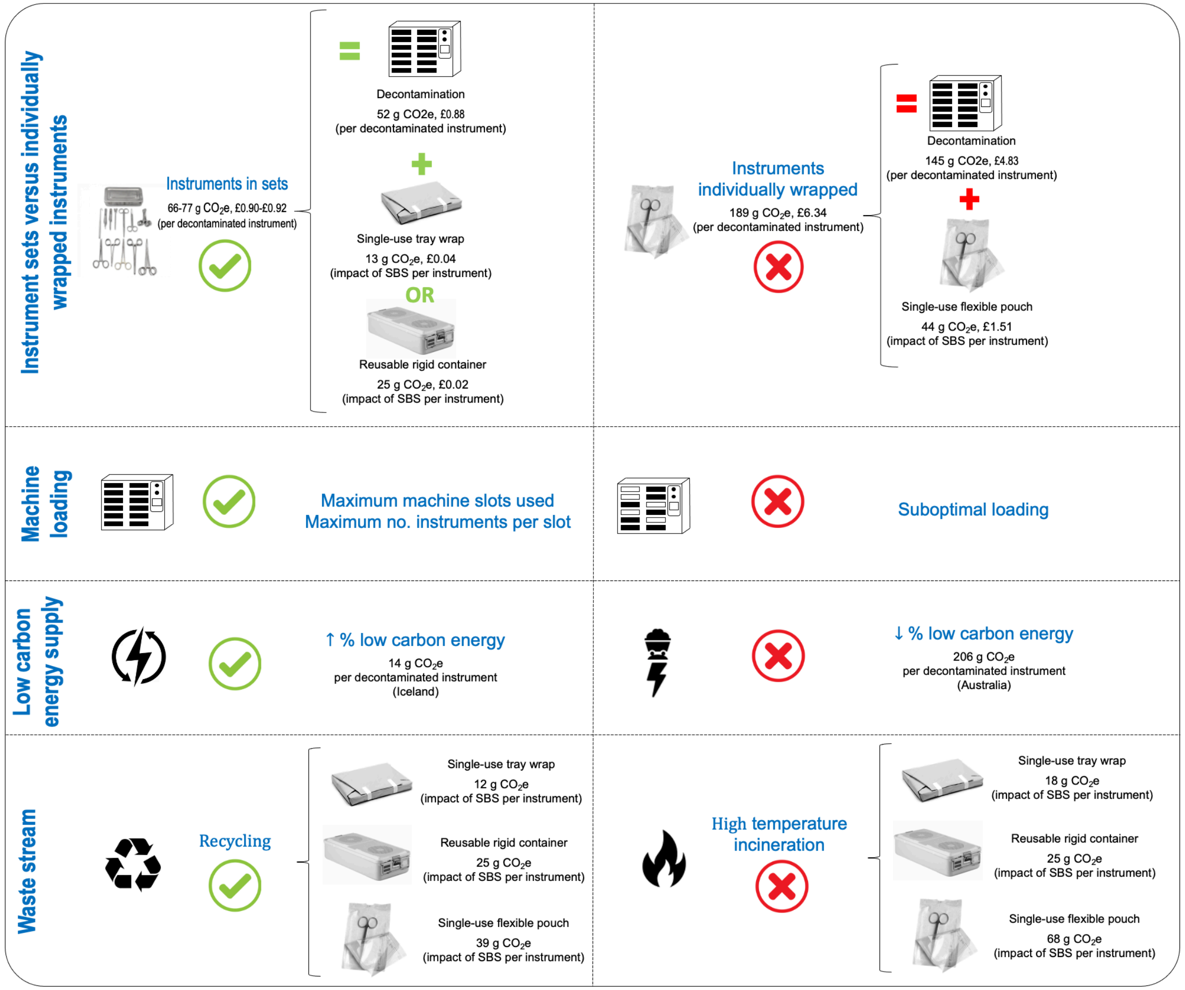
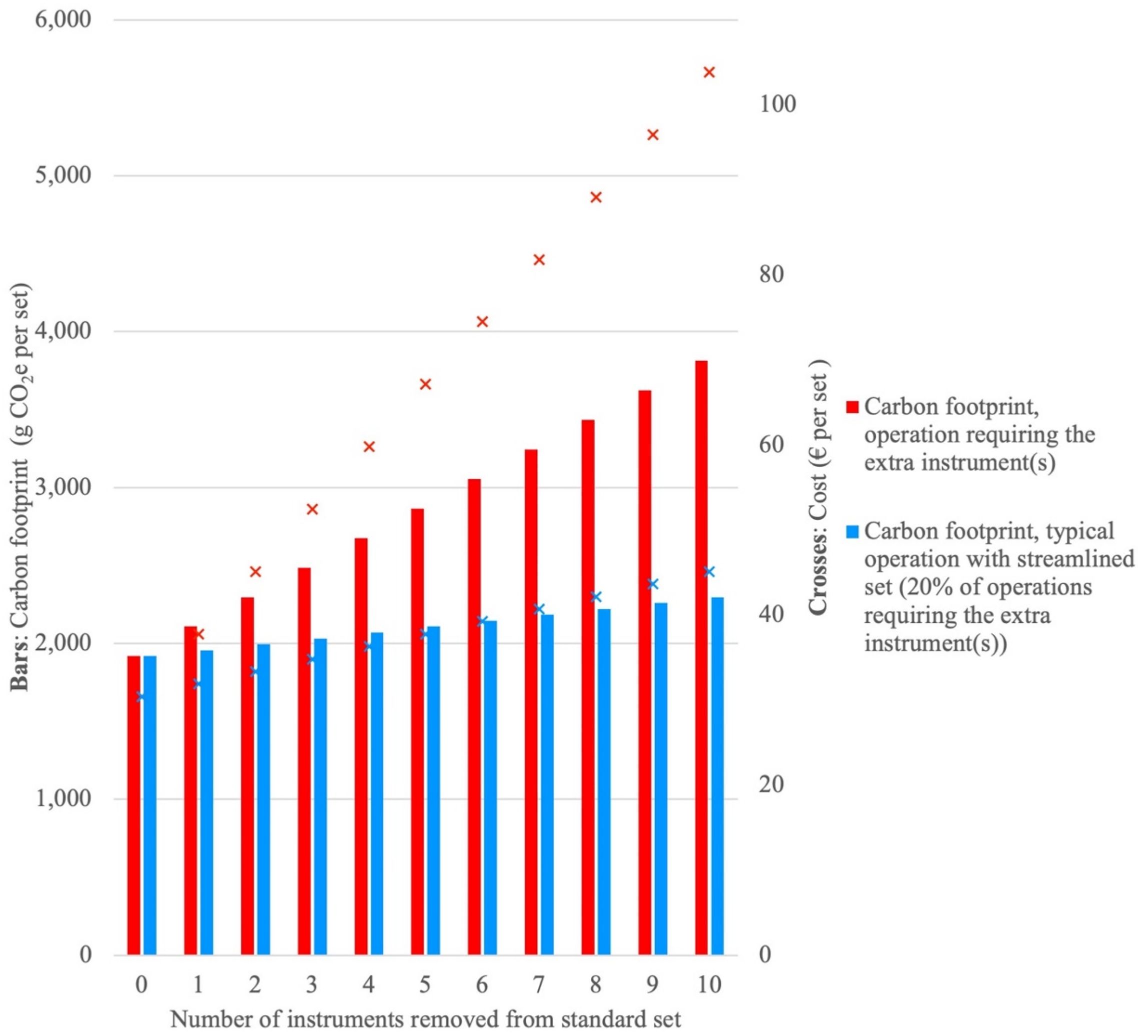


Figure 24: Impact of streamlining instrument sets on the carbon footprint and cost of decontamination and packaging of reusable instruments
Based upon standard set containing 29 instruments, housed in single-use tray wrap, with loading of the decontamination machine at mean values. Bar graph shows carbon footprint and crosses indicate financial cost. CO_2e= carbon dioxide equivalents



6.4. Discussion

The principal determinant of the carbon footprint of reusable surgical instruments is typically the decontamination process, for example responsible for up to 85% of the carbon footprint of reusable surgical scissors,(91) and almost all GHG emissions associated with reusable laryngoscope blades and handles.(72) The carbon footprint of processes upstream and downstream of decontamination (e.g. product manufacture, distribution, and waste) apportioned per instrument use can be reduced by increasing the number of uses, but the decontamination process will remain a constant hotspot. To minimise environmental impact of reusable instruments, it is important therefore to understand how to mitigate this impact.

This study found the carbon footprint of decontaminating and packaging an average reusable instrument in the UK could be reduced to 45 g CO_2e, achieved through processing instruments as part of sets (housed in single-use tray wraps which were recycled after use), and maximising loading of decontamination machines. This 'optimal process' represents a 31% - 42% reduction compared with average loading of instrument sets (packaged in single-use tray wrap and reusable aluminium containers respectively), and a 76% reduction compared with individually wrapped instruments. The absolute carbon footprint of decontamination was also dependent on the energy source used, and so could be further optimised through use of lower carbon energy sources.

The preparation of instruments, either as individually wrapped instruments (189 g CO_2e per instrument), or in sets (66 g CO_2e - 77 g CO_2e per instrument) had a two-to-three-fold impact on carbon footprint. Instruments are typically individually wrapped because of infrequent use, convenience, or habit. Several authors have suggested that the environmental impact of an operation can be reduced through streamlining instrument sets,(177, 178) but the results of this study do not support those assertions. Here, streamlining sets was found to counterintuitively increase carbon footprint and financial costs. When decontamination of instruments is undertaken through loading of sets into a machine, the carbon footprint of that decontamination cycle is almost unaffected by the number of instruments on that set, but processing instruments separately significantly increased per-instrument financial cost and carbon footprint. If one additional individually wrapped instrument were required 20% of the time across the 313 million annual surgical procedures performed globally,(74) based upon the UK data in this study, this would generate an additional 11,850 t CO_2e (equivalent to a single passenger flying from London to New York return approximately 4,900 times).(31) Surgeons should therefore request that instruments even occasionally used in an operation should remain on sets (although instruments never or very rarely used can be removed), and that individually wrapped instruments are integrated into appropriate sets where possible. Where integration into existing sets is not possible (e.g. due to size or number of additional instruments) and more than ten instruments are frequently required, those instruments should be collated to form a new set (although this will depend on the size of instruments).

This finding does not preclude the notion that some individually wrapped instruments should remain available in case they are needed due to intra-operative instrument damage or loss of sterility, because associated carbon footprint remains preferable to opening a whole new set when ≤ 10 instruments are required, and ≤ 4 from a financial perspective. These data apply to reusable instruments, and in contrast, for single-use pre-prepared sets, streamlining may confer benefits, for example reducing the carbon footprint of a hysterectomy by up to 46%.(134) Reducing the number of reusable instruments on a set may also reduce carbon footprint of sterilisation where this enables those instruments to be housed in a smaller container, for example such that two trays can be placed in a decontamination machine slot in place of one.

The carbon footprint of decontaminating and packaging reusable instruments was sensitive to machine loading. Whilst it is inevitable that machine slots may sometimes be unfilled to meet operational demands, this should be minimised. These findings are consistent with those reported by McGain et al., who found heavier machine loads were more efficient,(157) although the number of instruments housed per slot would not be perfectly correlated to the weight of those instruments. Surgeons can work with colleagues in sterile services departments and the wider surgical team to optimise instrument flow and stock levels, minimising the need for last-minute decontamination using partially filled machines.

The purchase and disposal cost per use of using a reusable rigid container was around half that of single-use trap wrap per use. Depending on local arrangements (and use of onsite versus offsite decontamination services) this may confer a financial saving: for example one hospital in the USA estimated savings of US $51,000 (£42,110; exchange rate 22nd August 2022) per year by switching from tray wrap to reusable containers.(179) Switching to reusable packaging may also help meet obligations to reduce plastic use within healthcare, as the outer layer of tray wrap is typically made of plastics such as polypropylene, and so switching to reusable metal containers would also reduce waste disposal costs (120 g less waste per set). However, the carbon footprint of using single-use tray wraps (13 g CO_2e per instrument, 387 g CO_2e per set) was around half of using reusable aluminium containers as the sterile barrier system (25 g CO_2e per instrument, 721 g CO_2e per set), and a three-fold reduction compared to wrapping instruments individually in pouches (44 g CO_2e per instrument). The carbon footprint of using reusable containers was principally determined by the washing process (86% of the impact of the reusable container itself), and this may be reduced through use of larger washer/disinfector machines manufactured specifically for the washing of reusable rigid containers which are likely more efficient, and through ensuring the tray is of smallest sufficient size.

An LCA study by Friedericy et al. published since submission of my publication based on this study(7) found that the carbon footprint of reusable rigid containers was 85% less than that of single-use tray wraps.(180) The estimate for single-use tray wraps (374 g CO_2e)(180) was similar to those derived in this study (387 g CO_2e), but the estimate for reusable rigid containers (57 g CO_2e per use)(180) was significantly lower than estimates in this study (721 g CO_2e per use). The study by Friedericy included washing and sterilisation of the reusable container, including electricity consumption which was estimated at 0.11 kWh per reusable container (assuming 1,996 MJ per 5,000 cycles, no additional energy from other sources). Meanwhile in the current study, the energy consumed by the washer/ disinfector alone was 2 kWh per reusable container (including energy via electricity and natural gas, and assuming 6 reusable containers were washed at once, and assigning impacts of sterilisation to instruments). McGain et al. has previously estimated that steam sterilisation of one kg of materials (which included linens and instruments) required 1.9 kWh of electricity,(157) whilst Campion et al. found that 2.57 kWh of electricity was required to decontaminate a caesarean section instrument tray.(112) Whilst Friedericy et al.(180) included both washing and sterilisation of the reusable container, it is unclear how such energy efficiencies could be achievable.

Individually wrapped instruments are often double wrapped within two flexible pouches, in part because of convenience for theatre staff, yet the Association of Surgical Technologists recommends this practice only when packaging multiple instruments or multi-component instruments.(181) Outer flexible pouches for individually wrapped instruments are typically one size larger than the inner pouch, therefore switching to single pouches more than halves associated carbon footprint, financial cost, and waste. A comparison of the clinical performance of different sterile barrier systems is outside the scope of this discussion, but if (as would be expected) these comply with sterility assurance standards,(170) housing instruments in sets rather than individually within flexible pouches should be standard hospital policy wherever feasible.

Recycling was associated with 6-10% reduction in carbon footprint of single-use sterile barrier systems (tray wrap and flexible pouches respectively). The DEFRA/BEIS database defines closed-loop recycling as the process by which waste is recycled into the same original product, and open-loop where this is into a different product.(116) This study assumed an open-loop recycling model whereby waste materials were ‘downcycled’ and used for generation of other items (often in other industry sectors), for example production of toolboxes, bottles and bins from polypropylene tray wrap.(182) Manufacture of sterile barrier systems from recycled materials in a closed-loop model would further reduce the carbon (due to the reduced acquisition of virgin raw materials), and innovation towards this should be encouraged. Conversely, use of high temperature incineration (common for clinical waste) increased the carbon footprint of tray wraps by one-third, and of flexible pouches by over half, highlighting opportunity to explore optimal waste disposal.(8) The carbon footprint of decontamination also varied due to differences in carbon intensity of energy and natural gas supply, with a fourteen-fold difference between high and low carbon energy sources when using electricity-fuelled generation of steam. This illustrates that optimising processes to reduce the carbon burden is still at the mercy of national energy strategy, and that increasing the availability of lower carbon electricity must be an allied strategy in attempts to reduce carbon footprint.

Optimising the decontamination and packaging of surgical instruments at scale could help us meet Net Zero carbon within surgery, and save money. The recommendations of this study are broadly generalisable, although country or region-specific figures should be applied by those wishing to evaluate data specific to their context. The findings on ‘optimal process’ are applicable to decontamination of instruments used outside of the operating theatre, including for example instruments used in outpatient settings, or laryngoscope blades used in anaesthesia. The recommendation of optimising machine loading and utilising low carbon energy can also be applied to mitigating carbon footprint of laundering reusable linens such as surgical gowns and drapes.

Limitations

This study has a number of limitations, including those in common with other evaluations of carbon footprint such as those relating to system boundaries and assumptions. The decontamination machines modelled were around 10 years old, and newer versions may be more efficient or have differing loading capacities. The frequency and annual volume of decontamination may differ at other hospital sites, as well as the composition of instrument sets, or of specific sterile barrier systems. Some hospitals use centralised offsite services, rather than the onsite services modelled here, but when additional transportation for offsite sterilisation was modelled based on a 160 km round trip by road, this increased carbon footprint by only 1% - 6% (Table 25). Whilst such differences in process would change values for the data presented in this study, it seems unlikely they would alter the overall optimal strategy for decontamination outlined here. The financial life cycle cost was limited, with cost calculations based on amounts charged to surgical departments, with no direct measure of staff time in the sterilisation department or the operating theatre.

This study included material and energy flows associated with sterilisation cycles, and omitted those associated with decontamination machine standby time. McGain et al. found that standby time was responsible for a considerable proportion of a steam steriliser's daily total energy and water consumption (40% and 20% respectively), despite the hospital study site providing emergency surgery overnight.(157) The extent of decontamination machine idle standby time will depend on the setting, including whether emergency out of hours operations take place, and will vary on a daily basis depending on surgical case-loads and also on staffing levels available to load machines. At the study site, the SSD operated 24 hours a day, processing instruments used within emergency overnight surgical cases alongside backlogs from the day. The study site ran decontamination machine test- runs (to check sterility assurance standards were met) loaded with instruments which were then put into circulation for clinical use provided the test passed (as per vast majority of cases), whilst if sterilisation facilities operate empty test-runs, this would result in additional emissions. Running decontamination machine test-runs loaded with sets which can be used provided the test passes, alongside switching off idle decontamination machines may represent additional strategies to reduce carbon footprint further, with the latter previously modelled to save around a quarter electricity and 13% water consumption of steam sterilisers.(183)

This study focused on steam sterilisation which is a standard method in the UK.(159) Other methods of microbial inactivation will have differing environmental and financial costs. For example, a study in Australia included an estimate of the carbon footprint of ethylene oxide sterilisation during manufacture of a single-use ureteroscope, finding this had a carbon footprint of just 7% of that for steam sterilisation of a reusable equivalent.(96) A study in India estimated electricity consumption of rapid high pressure steam sterilisation (also known as flash autoclaving, or benchtop sterilisation) at around one-quarter that of standard steam sterilisation.(79) Such methods are not widely used in the UK: flash autoclaving is less reliable than standard steam sterilisation,(184) and ethylene oxide sterilisation is usually used only for sensitive materials in part because this compound poses risks to human and environmental health.(185)

Table 25: Carbon footprint of transport to offsite decontamination site
The mean weight of instruments across three typical sets used for common operations (tonsillectomy set, minor op set used for carpal tunnel decompression, and basic major orthopaedic set) was 66.7 g. The mean number of instruments per set was 29 (determined using a retrospective audit of instrument decontaminations over one year at the Royal Sussex County Hospital, conducted 1/7/18- 30/6/19). A typical instrument set was therefore assumed to contain 2 kg instruments, and a single instrument was assumed to weigh 66.7 g. The offsite decontamination centre was assumed to be located 80 km away from the hospital, and transportation assumed to involve 160 km round trip in an average diesel heavy goods vehicle (average laden). CO_2e= carbon dioxide equivalents

Functional unit	**Weight (g) including sterile barrier system and instrument(s) within**	**Carbon footprint of transportation (g CO_2e per functional unit)**
Instrument set housed in reusable rigid container	6,068	132.69
Instrument set housed in single-use tray wrap	3,194	69.84
Individually wrapped instrument housed in flexible pouch	93	2.04

Conclusion

In conclusion, integrating individually wrapped instruments into sets (instead of streamlining sets), optimising decontamination machine loading, using lower carbon energy supplies, alongside recycling sterile barrier systems are strategies which can be used to reduce carbon emissions and financial costs associated with sterilising reusable surgical instruments. Industry is also recommended to investigate development of larger, more efficient washers to optimise decontamination of reusable rigid containers.

CHAPTER 7 Minimising carbon footprint and financial costs of healthcare waste

This chapter relates to the following publication:

- Rizan C, Bhutta MF, Reed M, Lillywhite R. The carbon footprint of waste streams in a UK hospital. Journal of Cleaner Production. 2021;286:125446. doi.org/10.1016/j.jclepro.2020.125446. *Impact factor 11.07*

7.1. Introduction

The previous two studies evaluated ways to reduce the carbon footprint of products used in the operating theatre through switching from single-use laparoscopic products to predominantly reusable equivalents (CHAPTER 5) and optimising reusable instrument sterilisation (CHAPTER 6). These two studies related to the two largest carbon hotspots identified in the evaluation of products used across five operations in CHAPTER 4; production of single-use products (54%) and sterilisation of reusable products (20%). This study (CHAPTER 7) focuses on the next largest hotspot identified in CHAPTER 4; waste (mean average 8% of carbon footprint of products used in five common operations). Waste was also found to be a large contributor to the carbon footprint of products and processes evaluated in other studies; CHAPTER 4 found that the mean average contribution of waste to the carbon footprint of three single-use laparoscopic products was 14%, and in the previous study (CHAPTER 6), waste was found to be responsible for 6% of the carbon footprint of a single-use tray wrap across the life cycle. Waste and water have together been associated with around 5% of the carbon footprint of the NHS in England,(3) whilst Healthcare without Harm estimated waste alone accounts for 3% of healthcare carbon emissions globally.(2) The NHS in England produced 1.2 Mt of waste in 2020 - 2021 (around double the volume from the previous year, prior to the COVID-19 pandemic), costing £143 million to dispose of.(186) The surgical operating theatre generates high volumes of waste, with mean average 7.6 kg - 16.4 kg waste per operation (in UK and Canadian settings respectively).(28) Understanding the carbon footprint of different healthcare waste streams is therefore an important component in mitigating carbon footprint of products used in the surgical operating theatre.

There are a number of different waste streams that can be used in healthcare settings including the operating theatre, each with a different disposal route and, as a consequence, different associated carbon footprint. The carbon footprint of disposing of healthcare waste will depend upon the material contents, alongside the method of disposal, and options for this will depend on the nature of the waste. The principal healthcare waste streams used within the UK are domestic, offensive, dry mixed recycling, infectious, clinical, medicinally contaminated sharps and anatomical waste (Table 26), although more specialist waste streams are also described,(187) and classifications will vary by country.

Table 26: Principal healthcare waste streams
Based upon UK Government Department of Health guidelines (187)

Waste stream		Waste receptacle	Suitable for	Examples of appropriate waste
Non-hazardous waste	Dry mixed recyclable waste	Clear bag	Dependent on local recycling facilities	Sterile packaging, plastic bottles, paper, cardboard
	Domestic waste	Black bag	Products equivalent to municipal waste generated by households	Hand towels, food, drink
	Non-infectious offensive waste	Yellow/black striped bag	Products which 'may cause offense' e.g. due to the presence of body fluids, odour, or association with healthcare services	Non-infectious gloves, aprons, incontinence pads, empty fluid bags
	Infectious waste	Orange bag	Products arising from a patient known (or suspected) to have a disease caused by a microorganism or associated toxins, not fulfilling criteria of hazardous waste	Infectious surgical dressing, gloves, aprons, masks
Hazardous waste	Clinical waste	Yellow bag	Infectious waste contaminated with chemicals or pharmaceuticals	Medicated intravenous bags/ lines, medicinally contaminated syringes
	Medical contaminated sharps waste	Yellow lidded yellow box	Sharp products contaminated with medications	Needles, cannulas
	Anatomical waste	Red lidded yellow container	Body parts, including anatomical waste which is infectious or contaminated with chemicals	Diagnostic specimens, placenta
	Medicinal waste	Blue lidded yellow box	Unused (or part used) medicines	Tablets, creams, liquids, patches

Regulations surrounding safe disposal of each of these waste streams differ.(187) Domestic and non-infectious 'offensive' waste may be disposed of via recycling, landfill, or low temperature incineration.(187) In low temperature incineration, domestic healthcare waste is incinerated alongside other household municipal waste, reaching temperatures of ≥ 850 °C.(188) This process can incorporate energy and material recovery, for example, recovery of heat and materials (such as bottom ash and slag metal), and is then referred to as an energy from waste (EfW) process. Infectious or hazardous waste (e.g. anatomical waste, sharps, pharmaceuticals, clinical waste, or waste that is cytotoxic or cytostatic) may be disposed of via high temperature incineration, which uses temperatures ≥ 1,100 °C(187) and may also involve EfW. Alternative high temperature methods less commonly used include pyrolysis, gasification, and plasma technology, which all heat waste to generate liquid or synthesised gas fuels that can be used to generate electricity or steam. The former two methods heat the waste to 1,100 °C, in a fully inert atmosphere for pyrolysis, and using small amounts of oxygen for gasification, whilst plasma technology uses electricity and an inert atmosphere to generate heats of around 6,000 °C.(187) Infectious waste and certain sharps may alternatively be decontaminated prior to disposal (via recycling, landfill, or low temperature incineration) using an autoclave, steam auger, dry heat, micro-/macrowaves or chemical disinfection, prior to disposal alongside non-hazardous waste streams (e.g. via recycling, landfill, or low temperature incineration).(187) NHS waste in England is most frequently processed via EfW (37%), followed by incineration (25%), recycling (23%), and landfill (15%).(189)

Whilst there is clear guidance on safe disposal of healthcare waste, information on associated carbon footprint is sparse. Evaluating carbon footprint of healthcare waste may help inform strategies to reduce associated GHG emissions, and is also an important component of a product life cycle to take into account when evaluating the cradle to grave carbon footprint of products used within the operating theatre. At the time this research was developed (2018-2019), the emission factors used to account for waste streams varied widely. Supplementary table 40 summarises the state of knowledge at the time of the publication associated with this chapter(8) from a number of geographical regions and clinical contexts, including plastic surgery in Chile,(26) urology in Australia,(96) ophthalmology in the UK,(27) minimally invasive surgery in the USA,(131) obstetrics and gynaecology in the USA,(30) and surgery (across specialties) in Canada, UK, and USA,(28) renal services in China,(190) the UK,(191) and Australia,(192) alongside dentistry in the UK.(193) There was a wide range of carbon emission factors used, in particular for landfill (10 kg CO_2e - 1,100 kg CO_2e) and recycling (12 kg CO_2e - 9,000 kg CO_2e), which is largely explained by differing materials and carbon footprint methodology, particularly allocation methods. For example, paper disposed to landfill has relatively high emissions because (unlike inert products such as metals and glass) it decomposes and releases GHGs, most notably CO_2 and methane. For recycled materials there are differences in the method by which the net benefit of reduced virgin acquisition of energy and materials is allocated, and it is also dependent upon the type of material offset through recycling, for example the production of metals and plastics have higher carbon footprints than paper.

The majority of example studies highlighted in Supplementary table 40 used the UK Government GHG Conversion Factors for Company Reporting (DEFRA/BEIS) database as the source of waste emission factors. Some studies used older versions of the DEFRA/BEIS database (for example the 2009 version(191) and 2011 version)(27) which differ significantly from the latest version. For example, the GHG emissions offset by recycling products, or from EfW, were attributed to the user of the recovered product in the 2021 version,(31) rather than the institution generating the waste, as in older versions. The current version does not reflect the net GHG emissions of waste, and authors of the DEFRA/BEIS database warn that it should not be used to compare the carbon footprint of different waste streams.(31) Two studies(192, 193) referenced Connor et al.(191) as the source of emission factors for clinical waste (who in turn used the DEFRA/BEIS database). These two studies used Australian(192) and US(193) government reports for other waste streams, and the latter was also used by McPherson et al.(194). Another study used a single emission factor of one kg CO_2e per kg waste across all solid waste disposal,(96) referencing reports on disposal of plastic bags, steel and laptops, and a publication on rubber production. This conversion factor was also used for municipal landfill by Woods et al., citing US reports and online calculators.(30) A different online calculator, estimating the carbon footprint of incineration of plastic, was used as the source of emission factor for laparoscopic instrument biomedical waste.(131) A further study collected primary activity data (enabling healthcare specific carbon footprint estimations) for autoclaving but did not publish results,(28) whilst another referenced a healthcare manufacturer document which could not be sourced.(194) Other LCA healthcare studies used emission factors embedded in libraries restricted to database licence holders such as the Tool for the Reduction and Assessment of Chemical and Other

Environmental Impacts software,(112) Ecoinvent,(91) and Packaging Industry Research Association Environmental Management System software.(135)

The primary aim of this study was to estimate and compare the carbon footprint of healthcare waste streams, in order to evaluate ways to mitigate the carbon footprint associated with disposal of healthcare products such as those used in the operating theatre. The secondary aim was that this would collate and provide emission factors for healthcare waste streams and that this could be used to inform future carbon footprinting studies wishing to account for associated healthcare waste (and these were used when evaluating carbon footprint of products used in common operations [CHAPTER 4] and sterile barrier systems [CHAPTER 6]). The objective of this study was to determine the waste streams used at the study site and their mode of waste disposal, and in turn evaluate the carbon footprint of healthcare waste undergoing high temperature incineration, low temperature incineration with energy from waste (plus sterilisation via waste autoclave where necessary), and recycling.

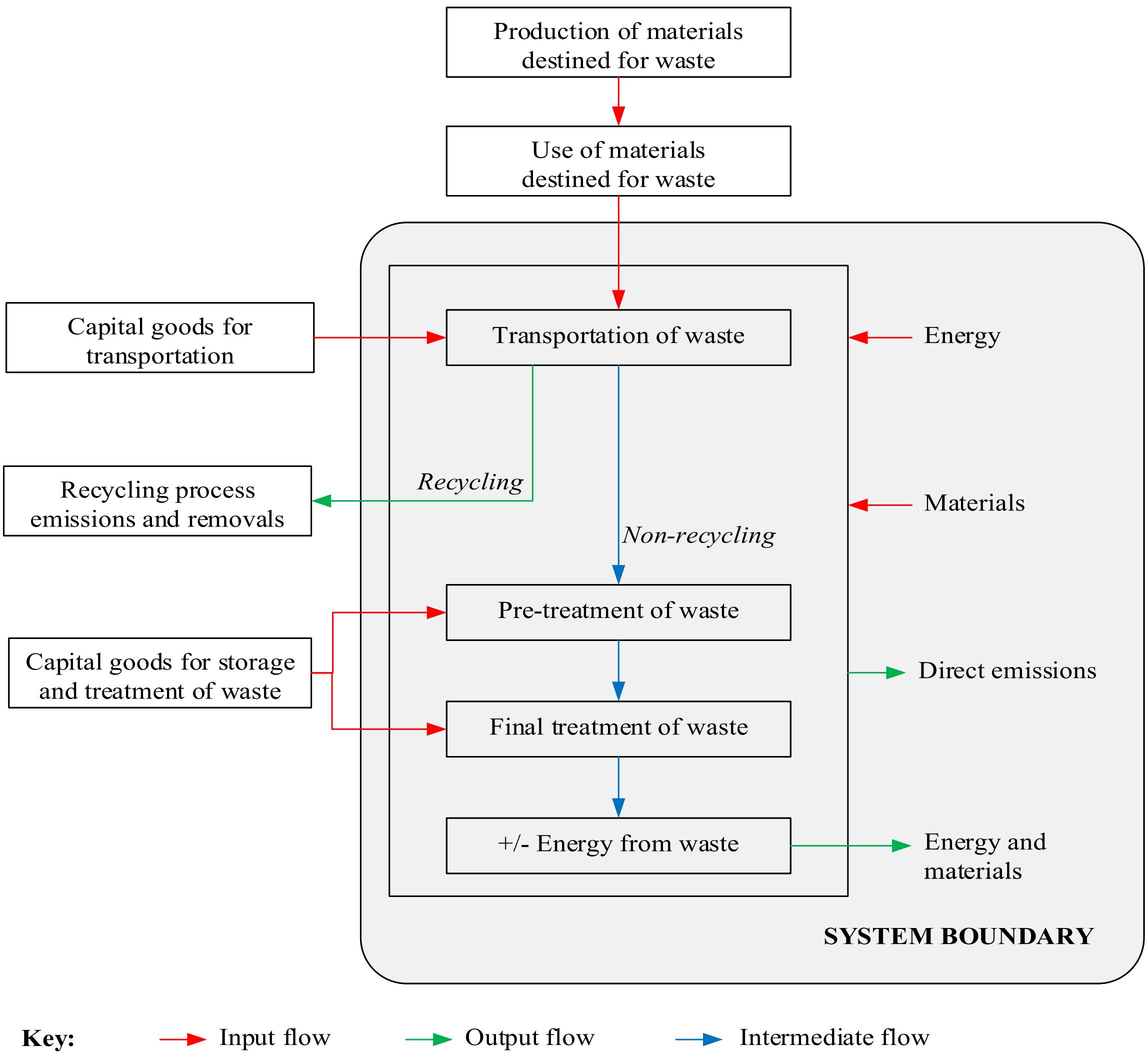
7.2. Methods

The method used for this study aligns with the approach outlined in CHAPTER 2, and this section only includes details specific to the current chapter.

Scope

The carbon footprint of hospital waste streams was modelled on waste processing at University Hospitals Sussex NHS Foundation Trust, which included three hospital sites (RSCH, Princess Royal Hospital, and Lewes Victoria Hospital), and waste was handled by three companies (Medisort, Tradebe, and Veolia). The functional unit was the disposal of one t of waste generated in each waste stream. The system boundary is detailed in Figure 25, and processes included were transportation of waste from hospitals to waste handling sites, energy and water for pre-treatment of waste and final waste processing, and direct GHG emissions. Capital goods involved in the waste management and associated infrastructure were excluded.

Figure 25: System boundary for carbon footprint of healthcare waste



For EfW the net benefit of reduced virgin acquisition of energy and materials was allocated to the waste material through subtracting the estimated avoided GHG emissions (due to recovery of energy and materials) from the carbon footprint.(120) For recycling processes, and due to uncertainty about the amount of material recycled from hospital recycling waste streams, the 'recycled content method' specified in the GHG Protocol Product Standard was used.(20) Accordingly, subsequent emissions of the recycling process and net reduction of virgin material acquisition were attributed to the production of the recycled goods and so these were excluded from the system boundary.

Life cycle inventory and impact assessment

A process-based carbon footprint of the healthcare waste streams at the study site was estimated using primary activity data alongside secondary data sources. The life cycle inventory and impact assessment method are presented together in the methods section of this study (unlike other chapters) to improve clarity, and emission factors used for impact assessments within this study are detailed in Supplementary table 41.

The steps involved in the processing of each of the waste streams were determined through discussion with the hospitals' waste manager and waste contractors, and were illustrative of processes used in 2019. The waste streams were processed either through low temperature incineration (with prior sterilisation via autoclave steam sterilisation where necessary), high temperature incineration, or recycling. No waste was sent to landfill from the study site.

Transportation

Distance travelled for each waste stream was defined as the mean distance between each waste processing site and the three hospitals. The registration plate of typical delivery vehicles were determined, enabling the vehicle weights to be established using the Driver & Vehicle Licensing Agency website.(195) The 2019 DEFRA/BEIS database(116) was used to determine the carbon footprint of travelling the calculated distances in these vehicles (depending on vehicle weight), and this was allocated according to the weight of waste carried. The average weight of the loads carried by the trucks for each waste type were obtained over a one-month period (April 2019, for waste streams processed by Medisort), or using company reported averages where such data were unavailable (all other waste streams). The carbon footprint of transportation was included in the emission factors used for recycling so was not calculated separately.

Autoclave sterilisation

Annual electricity, gas oil, and water consumption were determined for the site sterilising the hospital's infectious waste stream (Medisort, 1 January- 31st December 2018). Here, a steam sterilisation autoclave was used to sterilise infectious waste (at temperatures ≥ 146 °C for at least 2 minutes). The autoclave was pressurised with steam produced via an industrial boiler, and at the end of the cycle steam was extracted using a vacuum pump that ensured the resultant waste was as dry and compact as possible, reducing the cost (and carbon footprint) of onward transportation. The carbon footprint of gas oil, water, and electricity consumption at the site was allocated across the weight of infectious waste handled at the site annually.

Thermal treatment

The direct emissions associated with burning of waste during thermal treatment (i.e. low temperature incineration with energy from waste, and high temperature incineration, at temperatures of ≥ 850 °C and 1,000 °C respectively) were determined using the Greenhouse Gas Protocol Emissions from Waste Management Activities database (version 5) emission factors,(118) referred to hereon in as the 'GHG Protocol Waste database'. Direct emissions reported here relate to the CO_2 released where fossil fuel derived carbon within a waste product combines with oxygen. The direct emissions quoted in the GHG Protocol Waste database for 'non-hazardous industrial waste' were assumed to relate to low temperature incineration, and those for 'hospital waste' were assumed to relate to high temperature incineration.(118) Other (non-carbon) direct emission GHGs considered in the GHG Protocol Waste database(118) were not included, as volatile compounds such as nitrous oxides were likely to be responsible for <0.1% of hospital waste emissions, and other GHGs such as hydrofluorocarbons, perfluorochemical, and sulphur hexafluoride are not relevant to medical waste.(196) Biogenic emissions were not estimated as these emissions refer to those relating to biological sources, and for healthcare waste these may be relevant to a relatively small proportion of waste including paper and cardboard. Biogenic emissions release the carbon temporarily stored within plant and animal matter, unlike carbon emissions associated with the burning of fossil fuels, and so wherever biogenic emissions are accounted for they must be reported separately,(20) and were excluded here, in line with a previous LCA study evaluating incineration and landfill of medical waste.(197)

Emissions relating to energy and water consumption associated with thermal processing of waste were also included. The consumption of gas oil and water for low temperature incineration with EfW were estimated using the Waste and Resources Assessment Tool for the Environment (WRATE) database,(198) based on data from the Veolia Chineham EfW plant. The latter is a site which is run by the same company as the study site low temperature incineration with EfW plants (Veolia Newhaven, and Veolia Portsmouth), and using comparable processes. The electricity consumed during processing of waste via low temperature incineration with EfW was accounted for by using net electricity generation figures from the WRATE database.(198) Electricity and water consumption during high temperature incineration was extracted from the Tradebe UK Corporate Sustainability Report, which is specific to the Tradebe site at which University Hospital Sussex NHS Foundation Trust hazardous waste is processed,(199) and the plant was assumed to operate for 8,000 hours per year.(200) The high temperature incineration site was powered by electric motors, and no additional fuel consumption was accounted for. Bottom ash and air pollution control residues generated during high temperature incineration were sent to deep burial landfill sites, the impact of which was beyond the scope of this study.

EfW involves thermal treatment of waste, with generation of electricity, slag metal and bottom ash. Avoided emissions were calculated through offsetting the carbon footprint of generated products (electricity and slag metal) against that of incineration. Bottom ash generated was not included, as the GHG Protocol Waste database reports that the use of this in road construction does not equate to any GHG savings.(118) The net electricity generated per t of waste was determined using the WRATE database.(198) The metal component of theatre waste was assumed to be 2.2%, based on an audit of total knee arthroplasty waste,(201) and these were assumed here to be ferrous metals. The recycling factor (amount actually recycled) for ferrous metal recovery was set at 55%, based on the WRATE database.(198) Together, this means that for every t of waste processed via EfW, an estimated 12 kg of slag metal was recovered. The carbon footprint offset of slag metal generated was estimated using GHG Protocol Waste database emission factors.(118)

Recycling

The end-of-life disposal routes for reusable surgical linens, surgical instruments, and batteries were identified through the external surgical linens supplier (Elis), internal sterilisation services, and internal waste department. The GHG Protocol Waste database(118) allocates emissions associated with recycling to the original product, and so DEFRA/BEIS database emission factors(116) were used instead as these only take into account the transportation of waste to recycling facilities, in line with the 'recycled content method' specified in the GHG Protocol Product Standard.(20)

7.3. Results

Waste stream overview

Eight principal waste streams (with a number of recycling sub-streams) were in use at the hospital sites, in line with those identified in Table 26. The processes for each of the waste streams are summarised in Figure 26, including the mean distance between sites. Dry mixed recyclable and domestic waste streams were both taken from hospital sites to Newhaven (Veolia) and processed via low temperature incineration with EfW. Non-infectious offensive waste was taken from hospital sites and bulked up at a transit site in

Littlehampton (Medisort), from where it was taken to Portsmouth (Veolia) and processed via EfW. Infectious waste was taken from hospital sites to Littlehampton (Medisort), where it was decontaminated using a steam sterilisation autoclave, after which it was compacted through a bulking process, and then taken for EfW in Portsmouth (Veolia). All EfW sites relevant to the NHS organisation used low temperature incineration. Clinical waste, anatomical waste, medicinal contaminated sharps, and medicinal waste were taken from hospital sites to be bulked up at the Littlehampton site (Medisort) prior to being sent for high temperature incineration at a Tradebe site in Fawley. The weight of waste carried by vehicles travelling from hospitals to the Medisort site during the month of April 2019 is provided in Figure 26 (journey A-B). The average weight of waste carried during all other journeys was a mix of observed and modelled data based on company estimates (Figure 26).

The majority of reusable stainless steel surgical instruments and batteries were sent for recycling at the end of life, although a small proportion of surgical instruments were sent for reuse in low- and middle-income countries. In this study, all instruments were assumed to be sent for recycling. At the end of life, reusable surgical linens (such as scrubs, gowns and drapes), were sent to ‘ragging merchants’ and downcycled, for example, as sound insulation materials.

Transportation

The carbon footprint of transportation associated with each waste stream was between 5 kg CO_2e per t of waste and 125 kg CO_2e per t of waste, depending on waste type, distances travelled, vehicle type, and the mean weight of waste transported per journey (Table 27). The vehicle weight capacity was largely determined by whether the waste was transported in its original form, or whether waste was compacted allowing bulk-loading, and this was the primary determinant of the variation between the carbon footprint of transportation between waste streams.

Figure 26: Process map of healthcare waste streams

Different waste streams listed on the left, within coloured boxes reflecting the colour of the waste receptacle where possible. The final waste process is indicated in dark grey boxes to the right, with intermediate processes in boxes with a red outline. The start and end location of each leg of the journey specific to each waste stream is denoted by circled letters, corresponding to locations in the key. The distance of each of these journeys, vehicle type and average load carried is indicated in ovals. HGV= heavy goods vehicle, temp=temperature

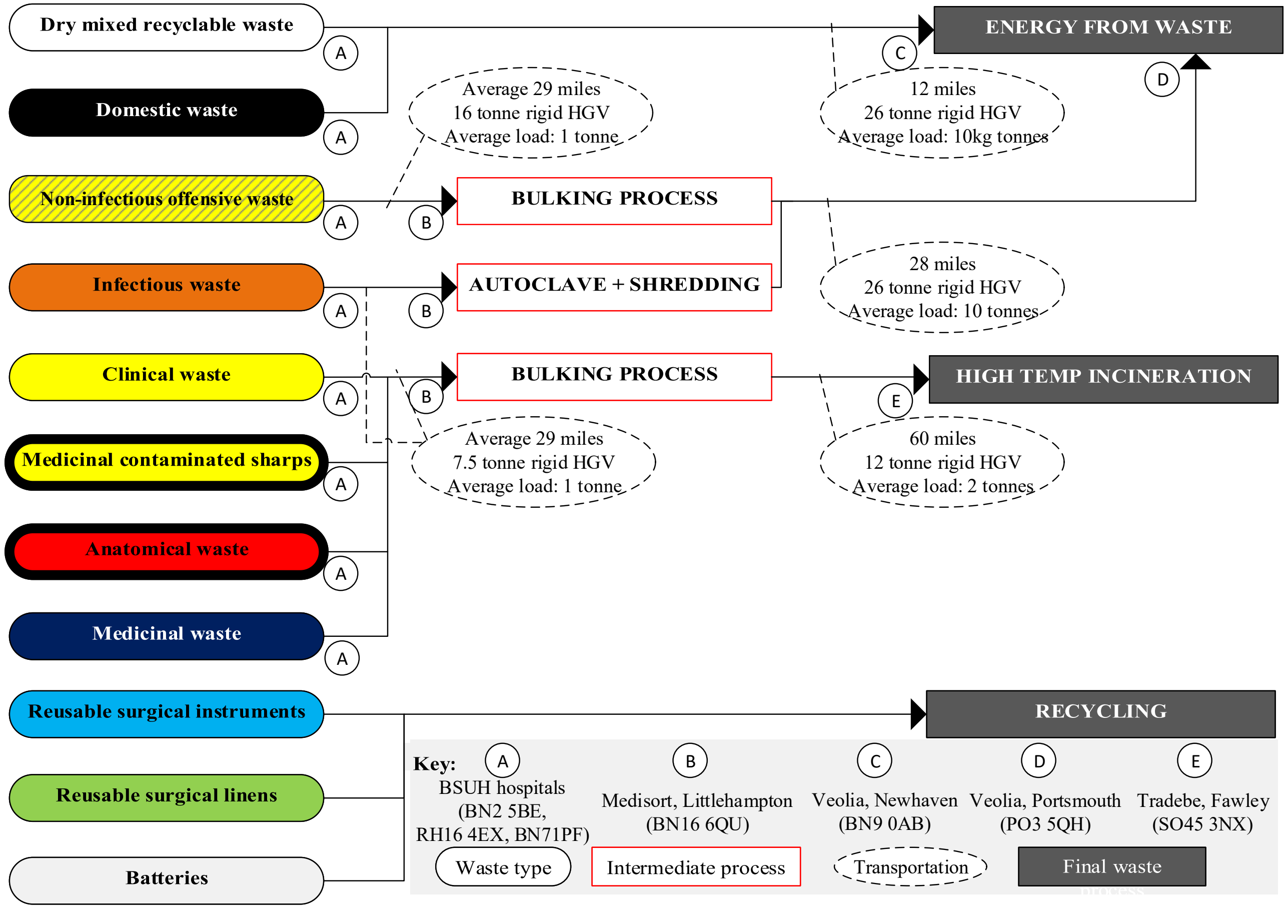


Table 27: Carbon footprint of transportation of healthcare waste
CO_2e= carbon dioxide equivalents, HGV= heavy goods vehicle

Waste stream	Mean round trip distance (miles)	Vehicle type	Weight of transported waste (t)	Carbon footprint (kg CO_2e per t waste)	
				Sub-total	Total for waste stream
Dry mixed recyclable waste transportation	24	26 t HGV rigid diesel	10	4.56	4.56
Domestic waste transportation	24	26 t HGV rigid diesel	10	4.56	4.56
Non-infectious offensive waste transportation	58	16 t HGV rigid diesel	0.98	71.03	81.71
	56	26 t HGV rigid diesel	10	10.68	
Infectious waste transportation	58	7.5 t HGV rigid diesel	1.07	53.21	63.89
	56	26 t HGV rigid diesel	10	10.68	
Clinical waste, medicinal contaminated sharps, anatomical waste, and medicinal waste transportation	58	7.5 t HGV rigid diesel	1.07	53.21	125.17
	120	12 t HGV rigid diesel	2	71.96	

Autoclave sterilisation

The carbon footprint of the electricity, gas, and water used during sterilisation of healthcare waste via autoclave sterilisation is summarised in Table 28, totalling 338 kg CO_2e per t of waste, with the majority (92%) of this due to use of gas oil.

Table 28: Carbon footprint of sterilisation of healthcare waste
CO_2e= carbon dioxide equivalents

Input	Quantity used per t of waste	Carbon footprint (kg CO_2e per t waste)	
		Sub-total	Total for sterilisation
Electricity	74.78 kWh	23.63	338.20
Gas oil	92.17 L	312.54	
Water supply and treatment	1.93 m^3	2.04	

Thermal treatment

Emissions due to processing of waste via low temperature incineration with EfW produced an estimated 338 kg CO_2e per t of waste (Table 29). This was offset by 170 kg CO_2e per t of waste due to electricity generation and recycled slag metal, with net generation of 167 kg CO_2e per t of waste processed. The carbon footprint of high temperature incineration totalled 949 kg CO_2e per t, and Tradebe confirmed that there were no avoided emissions during this process.

Table 29: Carbon footprint of emissions, and avoided emissions, for incineration
CO_2e= carbon dioxide equivalents

	Input	**Quantity used per t waste**	**Carbon footprint (kg CO_2e per t waste)**	
			Sub-total	**Total**
Low temperature incineration with energy from waste	Direct emissions from burning waste	N/A	332	337.62
	Gas oil	1.34 kg	5.33	
	Water supply and treatment	0.29 m^3	0.29	
	Output	**Quantity generated per t waste**	**Carbon footprint (kg CO_2e per t waste)**	
			Sub-total	**Total**
	Net electricity	482.34 kWh	-152.41	-170.40
	Slag metals recycled	12.10 kg	-17.99	
			Net	167.22
High temperature incineration	**Input**	**Quantity used per t waste**	**Carbon footprint (kg CO_2e per t waste)**	
			Sub-total	**Total**
	Direct emissions from burning waste	N/A	880	948.96
	Electricity	195.56 kWh	61.79	
	Water supply and treatment	6.81 m^3	7.17	

Overall carbon footprint of disposing of healthcare waste

The total estimated carbon footprint of healthcare waste disposal (including waste processing and transportation) via each of the waste streams is detailed in Table 30 and compared in Figure 27. The carbon footprint per t of healthcare waste was lowest when it was recycled (21 kg CO_2e - 65 kg CO_2e), followed by low temperature incineration with energy from waste (172 kg CO_2e - 249 kg CO_2e). When the waste was additionally decontaminated using an autoclave prior to low temperature incineration with energy from waste, the carbon footprint increased to 569 kg CO_2e per t of waste. The highest carbon footprint was associated with the disposal of waste via high temperature incineration (1,074 kg CO_2e per t of waste).

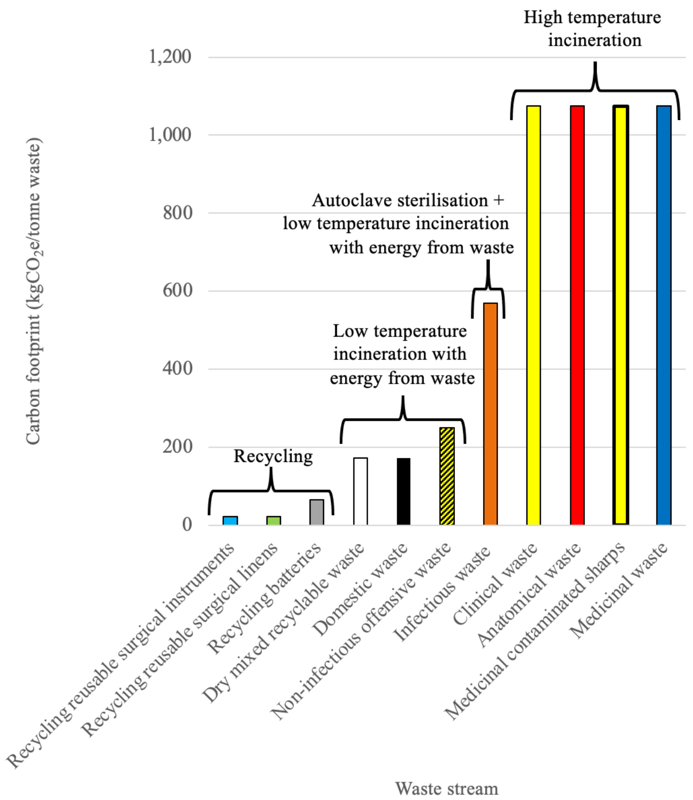
Table 30 Carbon footprint of disposing of healthcare waste

*=included in waste process, CO_2e= carbon dioxide equivalents, EfW= energy from waste

Waste stream		Carbon footprint (kg CO_2e per t waste)		
	Waste process		Transportation	Total
Recycling reusable surgical instruments	Recycling scrap metal	21	0*	21
Recycling reusable surgical linens	Recycling clothing	21	0*	21
Recycling batteries	Recycling batteries	65	0*	65
Dry mixed recyclable waste	Low temperature incineration with EfW	167	5	172
Domestic waste	Low temperature incineration with EfW	167	5	172
Non-infectious offensive waste	Low temperature incineration with EfW	167	82	249
Infectious waste	Autoclave sterilisation	338	64	569
	Low temperature incineration with EfW	167		
Clinical waste, medicinal contaminated sharps, anatomical waste, medicinal waste	High temperature incineration	949	125	1,074

Figure 27: Carbon footprint of healthcare waste streams

The colour of bars reflects the colour of the waste stream receptacle where relevant. CO_2e= carbon dioxide equivalents



7.4. Discussion

This study estimated the carbon footprint of waste streams used at the study site and found considerable variation between them. Disposing of hospital waste via high temperature incineration generated the highest carbon footprint at 1,074 kg CO_2e per t, and this disposal method was used for clinical waste, medicinal contaminated sharps, anatomical waste and medicinal waste, as mandated in Department of Health guidelines.(187) The carbon footprint of low temperature incineration with EfW (as used for domestic, dry mixed recyclable, and non-infectious offensive waste) was only 16-23% of this (172-249 kg CO_2e per t), and recycling of linens and surgical instruments only 2% of that (21 kg CO_2e per t). Where pre-treatment with decontamination of infectious waste was required prior to EfW, the carbon footprint of waste disposal was 53% that of high temperature incineration (569 kg CO_2e per t). This variation suggests that careful segregation of waste streams is required to prevent unnecessary carbon burdens.

The figure derived for high temperature incineration of healthcare waste was in close alignment with a previous LCA study by Zhao et al.,(197) estimated at 1,190 kg CO_2e per t.(197) Zhao et al. found that generating energy from waste from high temperature incineration (at 15% efficiency, considered in the study as 'conventional'), was associated with 42% reductions in carbon footprint.(197) Whilst energy was recovered from waste only for low temperature incineration in this study (CHAPTER 7), the offset due to energy from waste was similar at 50%. Previous carbon footprinting studies highlighted in Supplementary table 40 included 'incineration' (although did not specify associated temperatures), sourcing figures from 2009(191) and 2011(27) DEFRA/BEIS databases (1,800 and 1,833 kg CO_2e per t respectively). These older carbon footprint estimates may be higher than those derived in this study due to national reductions in emissions associated with energy, travel, and improved efficiencies in incinerators. Meanwhile the 2021 DEFRA/BEIS database (31) estimated the carbon footprint of waste incineration at 21 kg CO_2e per t, significantly lower due to assignment of all associated emissions (aside from transport) to the recovered energy from waste. The carbon footprint of sharps waste autoclave sterilisation (for example needles and scalpels) was previously estimated by McPherson et al. at 125 kg CO_2e per t,(194) (using secondary data on energy consumption from a waste company which could not be sourced) whilst the impact was estimated in this study at 338 kg CO_2e per t. The carbon footprint associated with recycling of waste is dependent on the method used to allocate emissions associated with the handling of waste and processing of materials into those that can be used again. In the current study these emissions were assigned to the products manufactured using recycled materials, in accordance with the recycled content method.(20) For example, where stainless steel instruments are recycled into materials used for construction, the associated GHG emissions and offsets due to reduced need for virgin material acquisition are assigned to the construction industry. In contrast other studies highlighted in Supplementary table 40 used the alternative closed loop method,(20) which assigns the associated emissions and offsets to the original product which is recycled.

The proportion of operating theatre waste that is potentially recyclable has previously been estimated at 55% by weight.(105) This would be higher if infectious waste was decontaminated before recycling, and I am aware of innovative services which decontaminate stainless steel surgical instruments prior to using the steel within the construction industry, and the potential to expand this to other healthcare waste materials and applications should be explored. This indicates considerable potential to reduce the contribution of waste to the carbon footprint of products used across whole operations (9%; CHAPTER 4). NHS national data indicate that incineration holds the highest financial cost (£189 per t of waste), followed by landfill (£149 per t), EfW (£129 per t), and recycling (£100 per t).(189) Furthermore, there are reports of recycling schemes (including for plastics used in the operating theatre) where the recycling company will not charge healthcare providers for waste removal and processing.(202) This indicates that on both carbon and financial grounds, hospital waste should be recycled where possible, and where this is not possible and products are sent for incineration these should recover energy from waste. The associated savings could be large, for example if the proportion of the 1.2 Mt of waste generated in 2020-2021 by NHS England(186) that was recycled rather than incinerated at high temperatures increased by 5% of total waste, this would save an estimated 63,000 t CO_2e (based on figures derived in this study), and cost savings of over £ 5.3 million (based on NHS national data).(189)

A survey of UK and Australian anaesthetists found that the major perceived barriers to recycling theatre waste were inadequate facilities (49%), staff attitudes (17%), and inadequate information (16%).(203) In order to shift the disposal of hospital waste disposal routes towards those with lower associated carbon footprint, it is important that healthcare staff have access to appropriate waste disposal routes, alongside better education on how to use these appropriately. There is much variability in the waste streams available in comparable clinical settings, even within a given hospital, and these could be standardised at a national level. For example, there were operations captured in CHAPTER 4 (Supplementary table 16 - Supplementary table 20) in which different waste streams were available in different operating theatres within the same NHS Trust for disposal of the same products for the same operation, with similar contamination risk. Alongside standardising available waste streams, there are also opportunities to improve segregation of waste into appropriate waste streams; an audit of anaesthetic waste found 16% of waste disposed of in infectious waste streams was not contaminated, whilst 7% of waste disposed of in general waste streams was infectious.(204) Correct segregation of waste into waste receptacles could be improved through centralised simplification of waste terminology using intuitive language designed to improve appropriate waste segregation. For example, the waste stream for infectious waste contaminated with chemicals is commonly confusingly labelled ‘clinical waste’. Within CHAPTER 4, operations were observed in which clinical waste streams were used as the principal waste stream within the operating theatre, where either non-infectious offensive waste streams or domestic waste streams would have been more appropriate for much of the theatre waste in accordance with guidelines,(187) and this could have reduced the carbon footprint and cost of disposal.

The recycling potential of healthcare products could be increased through encouraging manufacturers to design products which are modular (can be easily disassembled), with as few different material types as possible, with clear labelling to facilitate recycling. Whilst recycling reduces the need for virgin materials, the recycled content method for allocation stipulates that the benefit is assigned to the industry in which products are used.(20) For example a recycling scheme was piloted for PVC anaesthetic masks, oxygen masks and tubing, which were downcycled into horticultural products such as tree ties,(205) and any carbon reductions associated with using recycled materials would be assigned to the tree ties. In order for recycling to make a larger impact in the transition to net zero surgery, the recycled content of surgical products themselves would need to increase, and this might start with low-risk products that do not contact non-intact mucous membranes such as aprons.

There will be differences in the carbon footprint of alternative methods of waste disposal not included in this study. For example, a life cycle assessment study by Hong et al. (2017) found that the carbon footprint of steam sterilisation of infectious waste in China was five times greater, and more expensive, than chemical disinfection.(206) The study in this chapter (CHAPTER 7) did not include landfill of hospital waste, as University Hospital Sussex NHS Trust had a zero to landfill policy, but a number of sources have estimated the carbon footprint of sending waste to landfill. Ahmad et al. undertook an LCA to compare landfill to high temperature incineration of typical healthcare waste and found a 4% difference in normalised 'climate change' results between the two waste streams (with landfill slightly greater impact), but did not report the carbon footprint.(207) This study referenced emissions data from three sources examining non-medical waste and a healthcare specific source from 1996 which is likely outdated as incineration technology has changed since then.(207) Zhao et al. estimated that high temperature incineration of healthcare waste generated 1,190 kg CO_2e per t (a figure in agreement with the estimate in this study as discussed), and that sending healthcare waste to landfill following autoclaving generated 461 kg CO_2e per t (with minimal contribution from the sterilisation process, and authors did not include transportation for any waste streams).(197) When authors modelled 30% energy recovery from waste, high temperature incineration became preferable to landfill.(197) The carbon footprint of landfill of healthcare waste relative to incineration is likely to be largely dependent on the carbon content of materials disposed of, and the proportion of biogenic versus fossil fuel derived carbon. This is reflected in figures within the DEFRA/ BEIS database,(31) which estimates 9 kg CO_2e associated with landfill per t for scrap metal and average plastics, and 1,042 kg CO_2e per t for paper.(31)

Caution should be taken when comparing the emission factors estimated here with those used in previously published papers due to differences in study boundaries. However, these studies also illustrate there are wider factors beyond GHG emissions which also need to be taken into account when comparing the environmental impact of different waste streams, and the preferable option may differ between impact categories examined. For example the LCA studies comparing landfill to high temperature incineration both found that landfill had a lower impact on human toxicity and photochemical oxidation.(197, 207) Conversely both studies found high temperature incineration had a lower impact on terrestrial ecotoxicity (and Ahmad et al.(207) also found this was the case for marine aquatic eco-toxicity). The evidence was conflicting between studies for acidification potential, climate change/ global warming, eutrophication, and freshwater eco-toxicity.(197, 207)

Limitations

There are some limitations to this study. As with all carbon footprinting studies, the findings are limited by the system boundaries and assumptions. The extent to which results can be generalised to other healthcare settings may be limited as the activity data was modelled on waste processes found at one organisation and associated waste handling sites, and emission factors applied were country specific where possible (e.g. based on UK energy supply). Considerable variability has previously been identified in the carbon footprint of 110 French municipal solid waste incinerators due to differences in characteristics of sites, for example dependent on energy recovery rates, site capacity, and age of incinerator.(208)

This study was limited by use of the GHG Protocol Waste database as the source of direct emissions relating to burning of waste in thermal treatment, alongside exclusion of biogenic emissions.(118) The differences in the direct emissions reported here for incineration of alternative waste streams may relate to differences in the assumed composition of waste, impacting the fossil fuel derived carbon content associated with different waste streams (alongside small differences in combustion efficiency and resulting carbon content of bottom ash generated). Further, differences in composition would impact the calorific value of the waste (amount of energy released when burnt), which in turn would affect the additional energy required from fuel to maintain the incinerator temperatures. The finding that low temperature incineration had a significantly lower carbon footprint than high temperature incineration is reflected by figures within Ecoinvent (version 3.6), which suggest that incineration of one t of municipal solid waste is associated with 519 kg CO_2e, whilst one t of hazardous waste is associated with 2,650 kg CO_2e.(114) Further, if the same direct emissions estimated for high temperature incineration (800 kg CO_2e per t) were assumed across other waste streams, the total carbon footprint of low temperature incineration with energy from waste would be 720 kg CO_2e per t -797 kg CO_2e per t (depending on transportation), remaining lower than high temperature incineration (1,074 kg CO_2e per t) principally due to recovery of energy from waste. However, whilst infectious waste undergoes additional sterilisation, the carbon footprint would increase to 1,117 kg CO_2e per t, exceeding that of high temperature incineration. Whilst the results reported in this study may reflect the carbon footprint of disposing typical waste, the extent to which the results can be used to determine the carbon footprint of disposing of a given product via alternative waste streams is limited. Future research should evaluate the direct and biogenic emissions associated with incineration of different material types via different waste streams.

Conclusion

Healthcare waste constitutes a small proportion of the overall carbon footprint of healthcare services, equating to an estimated 3% of healthcare carbon emissions globally.(2) However, this study found that the choice of waste stream has up to 50-fold impact on the carbon footprint, and it is important that handling of waste is optimised. Healthcare waste policies should encourage processes with lowest impact such as recycling or energy from waste and to explore the option of decontaminating infectious waste prior to recycling, conferring both carbon and financial savings. Alongside this, further research and enterprise is required, focusing on designing products and systems enabling recycling of medical products. Whilst the strategy outlined would maximise disposal through low carbon intensity methods, this must be done in parallel with efforts to reduce resource consumption and to shift the reliance on single-use products towards reusables (or hybrids, as per CHAPTER 5) where possible, minimising the generation of waste.

CHAPTER 8 Minimising carbon footprint and financial cost of reusable surgical scissors through repair

This chapter relates to the following publication:

- Rizan C, Brophy T, Lillywhite R, Reed M, Bhutta MF. Life cycle assessment and life cycle cost of repairing surgical scissors. International Journal of Life Cycle Assessment. 2022;27:780–795. *Impact factor 5.23*

8.1. Introduction

The operating theatre is resource-intensive,(28) and as such transitioning products to a circular economy model will be especially important in this setting. Previous studies in this thesis evaluated ways to mitigate carbon footprint associated with surgical products, through increasing the proportion of reusable components within three laparoscopic products (CHAPTER 5), optimising sterilisation of reusables (CHAPTER 6), and choice of waste stream (CHAPTER 7), with these three studies relating to the three largest hotspot processes identified in products used across five common operations in CHAPTER 4. Repair is another mechanism that can be used to extend the lifespan of equipment already in circulation, and which may result in net reduction in resource use. For example, use of repair may reduce the carbon footprint associated with production and disposal of reusable products, estimated together to contribute 8% (mean average) of the carbon footprint of reusable products used at the level of whole operations (CHAPTER 4, Table 11).

Maintenance and repair are especially important for products such as surgical instruments because intra-operative failure or instrument breakage impacts on the safety of care. Poor quality instruments have been associated with patient safety incidents.(209) Common problems with surgical instruments amenable to repair include sharpness (e.g. cutting edges of scissors, osteotomes, levers, scrapers), setting issues (e.g. misalignment and/ or ratchet defects of needle holders, artery forceps, tissue forceps) and missing components (e.g. screws). In the UK, very few hospitals have surgical instrument repair centres onsite, and repair is more commonly provided offsite by a small number of external contractors which typically receive instruments from across the country. There are only five such companies in the UK, which either contract directly with hospital sites, or subcontract through industry partners. Alternatively, repair may be performed by instrument manufacturers, or end users.(210)

The benefits of repairing surgical instruments include potential cost savings(100) and improved safety including reduced surgical site infection rates.(209) However, prior to the publication associated with this chapter,(9) the environmental impact of repairing reusable equipment had not previously been evaluated in a surgical context, and financial implications had not been formally analysed. In this study, environmental LCA and life cycle costing were used to estimate environmental and financial impact of repairing reusable surgical scissors. General surgical scissors were chosen as the unit of study as these were the most commonly repaired instrument at the study site (comprising 52% of all surgical instruments repaired at the Royal London Hospital, UK, between 2008 and 2019). Examples of general surgical scissors which are commonly used across a variety of surgical specialties include Mayo, McIndoe, and Metzenbaum (each can be curved or straight), and 17 cm straight Mayo scissors were pragmatically chosen for the study in this chapter following discussion with two surgical instrument manufacturers who both indicated that these scissors held the highest volume sales.

The aim of this study was to evaluate the potential role that repair may play in mitigating carbon footprint of surgical products, focusing on scissors as these were the most commonly repaired surgical instrument. The primary objective of this study was to evaluate the environmental impact (using life cycle assessment) and financial cost of repairing surgical scissors, comparing onsite versus offsite repair. The secondary objective was to model alternative scenarios to determine the generalisability of findings, including altering the number of uses of scissors, number of repairs, distance to offsite repair centre, alternative sources of electricity, and alternative waste handling processes. The final objective was to evaluate the scope for repair of surgical instruments beyond Mayo scissors.

8.2. Methods

The method used for this study aligns with the approach outlined in CHAPTER 2, and this section only includes details specific to the current chapter.

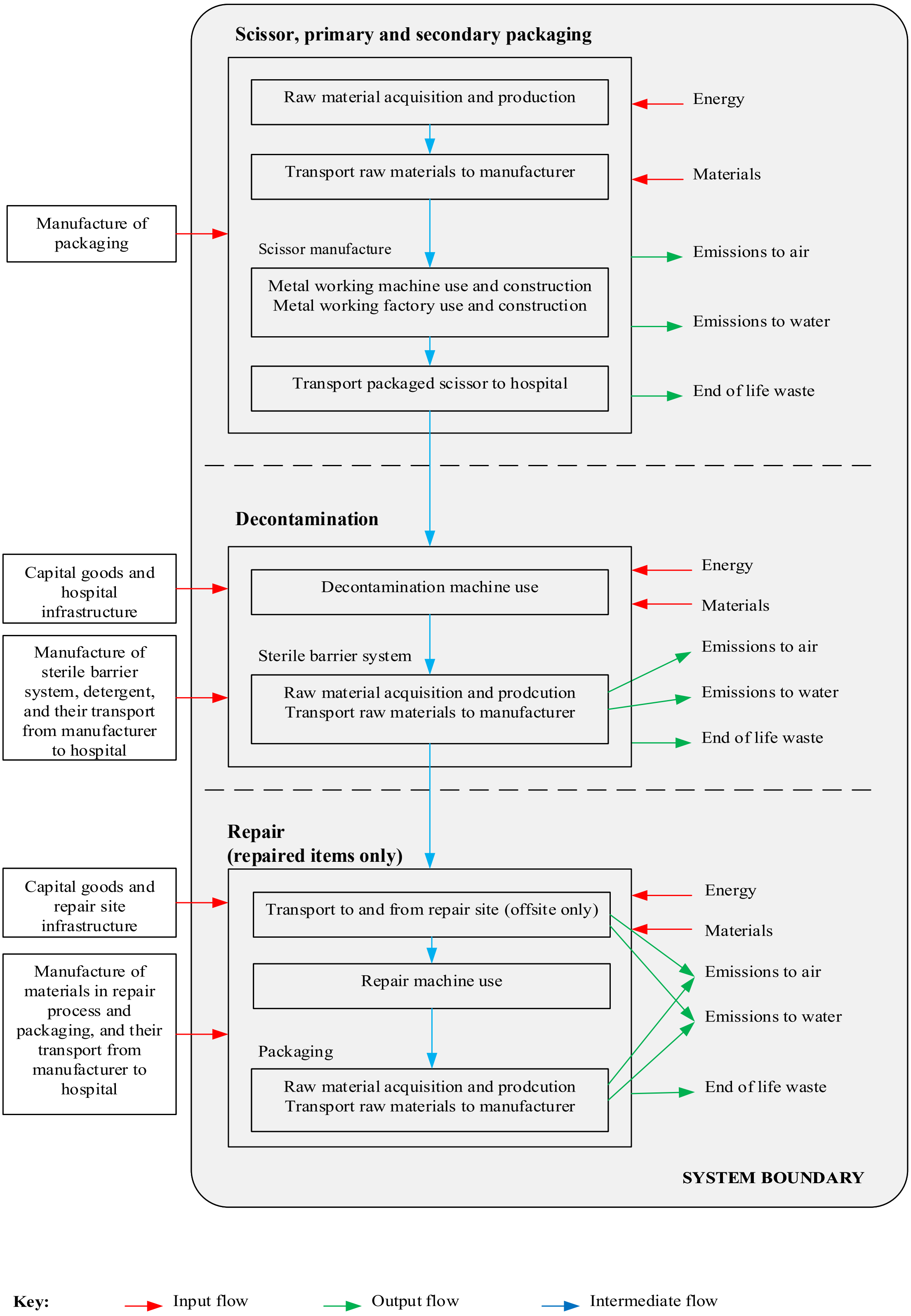
Scope

The functional unit chosen was one use of a 17 cm straight Mayo reusable surgical scissors (the term ‘use’ is used in this study to refer to the scissors being used for a single surgical procedure), manufactured in Germany and supplied by Ream Surgical Ltd (Dartford, UK; AS1116017). Three base scenarios were modelled for these reusable scissors: firstly no repair, secondly onsite repair, and lastly offsite repair.

In determining the reference flows, the following assumptions were made; a pair of scissors were used for 40 surgical procedures before disposal or repair was required; that each repair would provide a further 40 uses; and that scissors could be repaired up to nine times before disposal (giving total 400 uses of scissors where repaired nine times). These assumptions were based upon the experience of the lead technologist at the Royal London Hospital and expert opinion (surgical instrument industry personnel, and staff at the RSCH sterilisation services department). The life cycle inventory was built based upon 400 uses of surgical scissors as this was the lowest common denominator across scenarios using these reference flows, and all results were reported based upon one use of a pair of scissors in a single surgical procedure. Providing 400 uses of surgical scissors could be achieved through using one reusable scissors replaced nine times (total ten scissors, used 40 times each, no repair); or one reusable scissors repaired nine times (enabling 400 uses for individual reusable scissors), with repair either onsite at the hospital or offsite with an external contractor. Scissors must be sterilised before each use, and so 400 uses of scissors required 400 sterilisations. An additional sterilisation cycle was required after scissors were repaired and before they could be used,(211) and so 400 uses of scissors repaired nine times required a total of 409 sterilisations.

This was a cradle to grave LCA, starting with raw material extraction and manufacture of materials used within the scissors and their primary and secondary packaging, and the system boundary is outlined in Figure 28.

Figure 28: System boundary for repair of reusable scissors



The manufacture of scissors themselves was included, alongside transport associated with distributing the packaged scissors from the manufacturing site to the hospital. Energy and materials used by sterilisation and repair machines (used for grinding and buffing) were included, alongside transportation to the offsite repair site. Raw material extraction and production of materials within packaging involved in the sterilisation and repair processes were included, alongside transport of raw materials to the packaging manufacturer. Waste disposal was accounted for throughout the scissors' life cycle. Emissions to air and water were included for all processes where these were built into the life cycle inventory databases in SimaPro.(114) Capital goods and building infrastructure were excluded for both the sterilisation and repair site.

Life cycle inventory

The Ecoinvent database (version 3.6) was used for all processes aside from production of steam, which was modelled using the European Life Cycle Database (version 3.2).(114) Each included material was weighed, and manufacturer information was used to determine the material composition, or expert knowledge where such information was not available. The inventory was developed through matching these materials with closest materials included within the Ecoinvent version 3.6 database (materials and processes selected are outlined in Supplementary table 42), which provided material specific global average values associated with the raw material extraction, production, and transport to the 'end user' (in this case the manufacturer).

Manufacture of scissors was modelled using Ecoinvent version 3.6 data, which includes global average energy and auxiliary inputs for the metal working factory, metal working machine, construction of the metal working factory, manufacture of the metal working machine, and chromium steel lost within the process. Ecoinvent version 3.6 data on chromium steel production in Europe was adapted to German specific electricity, water, and natural gas sources.

Transportation of scissors from the site of raw material extraction to the distributor was modelled based on the locations and mode of travel specified by the supplier. For road travel, the first and last 8 km was assumed to be via courier, and the remaining distance via heavy goods vehicles. The distance between both the distributor and hospital, and between the offsite repair site and the hospital was assumed to be 80 km.

Scissors were assumed to be integrated into a reusable instrument set alongside other instruments (with instrument weight assumed to total 2 kg, as per assumptions detailed in Table 25), with the set contained within single-use tray wrap. Reusable scissors were sterilised at the hospital site before each use, including the first use, as scissors were not sterilised by the manufacturer. Energy and material inputs for sterilisation of reusable equipment were modelled based upon material and energy flows from CHAPTER 6(7) (Supplementary table 43), with environmental impact of sterilising scissors allocated according to weight (65.67 g scissor, within a set containing 2 kg of instruments).

The repair of reusable scissors was modelled based upon onsite repair at The Royal London Hospital (which provides repairs across Barts Health NHS Trust, London, UK), and offsite repair at Ream Surgical (Dartford, UK). Materials and inputs were determined through direct observation and discussion with repair site personnel. Electricity consumption of repair equipment was estimated using the power rating (highest power allowed to flow through the device) and the duration of use. This method potentially overestimates electricity consumption but would have negligible impact on results because electricity was responsible for only a small proportion of the overall environmental impact of the repair process itself. All waste was assumed to be disposed of via high temperature incineration.

Impact assessment

The ReCiPe Midpoint Hierarchist method (version 1.1) was used to characterise emissions from the lifecycle inventory assessment and combine these into 18 midpoint impact categories, with the global warming impact category results as the primary outcome measure. Results were weighted using aggregated midpoint impact categories via the ReCiPe Endpoint Hierarchist method (version 1.1), with midpoint and endpoint results normalised using Hierarchist normalisation factors (using the method defined in CHAPTER 2).(33)

Sensitivity analysis

To evaluate the generalisability of findings, eight alternative scenarios were modelled, changing just one parameter in each scenario.

1. Scenario 1 modelled the impact of reducing the number of reuses of scissors to 10, since in practice some reusable scissors may be used or repaired less often, for

example due to scissors being lost, damaged beyond repair, or placed on infrequently used instrument sets.

2. Scenario 2 modelled the impact of increasing the number of scissors reuses to 400.
3. Scenario 3 assumed that scissors were repaired just once before disposal and replacement.
4. Scenario 4 examined the impact of increasing the distance from the hospital to an offsite repair centre from 80 km to 800 km, assuming this was fulfilled via heavy goods vehicle, with the first and last 8 km assumed to be via courier.
5. Scenario 5 modelled the impact of sterilising reusable scissors using an Australian source of electricity, which has a high proportion of electricity sourced from fossil fuels.
6. Scenario 6 assumed that all waste was recycled, using the 'recycled content method' to account for associated emissions and environmental impacts.(20)
7. Scenario 7 assumed enhanced waste segregation, with sharps waste (scissors) sent for high temperature incineration (as per base model), cardboard and paper sent for recycling, and all other waste sent to landfill.
8. Scenario 8 was the same as 7 but with 'other' waste sent for municipal (low temperature) incineration. Alternative waste handling processes for scenario 6 – 8 are outlined in Supplementary table 44.

Life cycle costing

The purchase cost of the reusable scissors indicated by the supplier was used as the cost of manufacture and distribution. Cost of sterilisation was based on the rate charged by RSCH local sterilisation services department (£25.53 per reusable instrument set), apportioned according to the weight of reusable scissors (65.67 g out of 2 kg). The cost of repairing a pair of scissors was based on information provided by repair sites. End of life waste disposal was assumed to be £617 per t of waste, based on the average price of clinical waste incineration in the UK.(124)

Scope and feasibility for repair of surgical instruments

To determine the scope for repair of instruments beyond surgical scissors, a dataset was retrospectively reviewed which captured all instrument repairs conducted over an 11-year period (February 2008-February 2019) at the onsite repair centre (The Royal London Hospital), which also sends instruments for offsite repair where more specialist equipment is required. Here the types of instruments repaired were analysed, alongside the proportion of these that could be repaired onsite versus those which needed to be sent for offsite repair, and the rate at which products were irreparable (based on onsite repair data). Due to lack of instrument tracing, it was not possible to determine the number of repairs a given instrument underwent across its lifespan. The delay between batches of instruments being sent for repair and them being returned and ready for use was evaluated, using datasets from the Royal London Hospital (for onsite repair, July 2018-March 2019), and data from RSCH (for offsite repair, January 2018-January 2019). Any missing data was omitted from analysis.

8.3. Results

The repair process is summarised in Figure 29. Material and energy inputs for manufacture and distribution of surgical scissors are outlined in Table 31, and repair in Table 32.

Figure 29: Principal processes involved in repair of surgical scissors

Scissor decontaminated
after use

↓

Packaged

↓

Transport from user to repair site

↓

Sharpening
(grinding machine)

↓

Polishing
(buffing machine)

↓

Inspection

↓

Burrs removed
(using diamond lap or cloth)

↓

Testing (drop test and cutting
ability using tissue/ low density
polyethylene bag)

↓

Setting (screwdriver or
hammer)

↓

Oil to lubricate

↓

Packaged to send to
customer

↓

Transport from repair
site to user

↓

Scissor decontaminated
before use

Table 31: Parameters for supply of reusable 17 cm straight Mayo scissors

Process	Sub-process	Input	Amount (per scissor)	Notes
Acquisition stainless steel	Raw material	Stainless steel	65.67 g	Extracted in Solingen, Germany
	Transport from raw material extraction site to scissors manufacturing site	Train	497 km	Solingen to Tuttlingen, Germany
Packaging of scissors	Primary packaging	Low density polyethylene	3.57 g	Secondary packaging allocated by number of products within package (total of 50 assumed)
	Secondary packaging	Cardboard	6.11 g	
		Polystyrene	0.79 g	
Transport from scissors manufacturer to end user	Travel from scissors manufacturer to distributor	Courier	16 km	Tuttlingen to Dartford, UK (first and last 8 km via courier)
		Heavy goods vehicle	886 km	
	Travel from distributor to hospital	Courier	16 km	Assumed distance total 80 km (first and last 8 km via courier)
		Heavy goods vehicle	64 km	

Table 32: Parameters for repair of surgical scissors.
LDPE= low density polyethylene

Energy process	**Subprocess**	**Onsite repair**				**Offsite repair**			
		Input	Power rating (kW)	Duration (seconds per scissor)	Estimated electricity consumption (kWh per scissor)	Input	Power rating (kW)	Duration (seconds per scissor)	Estimated electricity consumption (kWh per scissor)
Sharpening	**Grinding**	Electricity	0.9	29	0.00725	Electricity	0.9	25	0.00625
	Buffing		0.33	7	0.00064		0.8	34	0.00756
Materials process	**Subprocess**	Input	Amount (g)	Number of scissors used across	Amount (g per scissor)	Input	Amount (g)	Number of scissors used across	Amount (g per scissor)
Test of sharpness	**Tissue**	Tissue paper	2.11	10	0.21	Tissue paper	2.17	10	0.22
	LDPE bag	N/A				LDPE	0.33	10	0.03
Oil spray		Paraffin oil	1.5	1	1.5	Paraffin oil	1.5	1	1.5
Packaging (used to send products for repair)	**Outer bag**	LDPE	5.27	10	0.53	LDPE	4.37	1	4.37
		Paper	5.61	10	0.56	Paper	3.53	1	3.53
	Inner bag	LDPE	5.63	10	0.56	N/A			
Packaging (used to return products to end user)		N/A- above packaging re-used				Polypropylene	3.05	1	3.05
Transport process		N/A				Input	Distance (km)		
Transport from end user to repairer (round trip)						Courier	16		
						Heavy goods vehicle	64		

Environmental life cycle assessment

The carbon footprint of using a pair of reusable scissors once was 70.3 g CO_2e per use, assuming scissors were replaced with new reusable scissors after 40 uses. This was reduced by 20% through use of onsite repair every 40 uses instead of replacement (56.3 g CO_2e per use), and by 19% for offsite repair (57.0 g CO_2e per use). Reusable scissors repaired offsite were associated with reductions (when compared with no repair) across all 18 midpoint environmental impact categories (Table 33), with mean average reductions across categories of 30% relative to no repair (range: 2% for marine eutrophication, to 73% for mineral resource scarcity). There were notable reductions through use of repair (compared with no repair) in mineral resource scarcity, marine ecotoxicity, freshwater ecotoxicity, and fine particulate matter, with the difference driven mainly by use of ferronickel (for all four impact categories), and ferrochromium (for fine particulate matter generation) within the manufacture of chromium steel for replacement scissors (Supplementary figure 13 -Supplementary figure 16). Notable reductions were also seen in human carcinogenic impacts through use of scissors that were repaired offsite, as this reduced the need for manufacture of chromium steel with human carcinogenic impacts driven by the generation of dust by furnaces used in the steel-making process and treatment of associated waste (Supplementary figure 17).

There were small additional reductions associated with onsite repair, with a mean additional reduction in environmental impact (compared with offsite repair) of 1.6% across impact categories (range: 0.1% for marine eutrophication, to 2.4% for land use). The reduction in land use and carbon footprint associated with switching from offsite to onsite repair was driven by differences in quantity of paper and low-density polyethylene respectively used within packaging used to send scissors for repair. Scissors were individually packaged when sent for offsite repair, whilst bulk packaging across multiple scissors was used where repair was conducted onsite.

Table 33: Environmental impact of one use of surgical scissors (midpoint categories, baseline scenarios)
Categories with greatest reductions (≥ 40%) associated with repair highlighted in bold. 1,4-DCB =dichlorobenzene, Bq Co-60 eq = becquerel Cobalt-60, CFC11= Trichlorofluoromethane, CO_2e= carbon dioxide equivalents, Cu= copper, eq= equivalents, m^2a = square metre years, N= nitrogen, NO_x= nitrous oxides, P=phosphate, PM2.5 = particulate matter <2.5 micrometres, SO_2= sulphur dioxide.

Impact category	Unit	Reusable scissors, no repair	Reusable scissors, offsite repair (% reductions relative to no repair)	Reusable scissors, onsite repair (% reductions relative to offsite repair)
Global warming	g CO_2e	70.3	57.0 (19%)	56.3 (1%)
Stratospheric ozone depletion	g CFC11 eq	0.000026	0.000021 (18%)	0.000021 (1%)
Ionizing radiation	Bq Co-60 eq	10	10 (3%)	10 (1%)
Ozone formation, Human health	g NO_x eq	0.11	0.09 (25%)	0.08 (2%)
Fine particulate matter formation	g PM2.5 eq	0.08	**0.05** (41%)	**0.05** (2%)
Ozone formation, Terrestrial ecosystems	g NOx eq	0.12	0.09 (25%)	0.09 (2%)
Terrestrial acidification	g SO_2 eq	0.15	0.10 (30%)	0.10 (2%)
Freshwater eutrophication	g P eq	0.02	0.01 (36%)	0.01 (2%)
Marine eutrophication	g N eq	0.02	0.02 (2%)	0.02 (0.1%)
Terrestrial ecotoxicity	g 1,4-DCB	395	124 (68%)	122 (2%)
Freshwater ecotoxicity	g 1,4-DCB	2.0	**1.1** (44%)	**1.1** (2%)
Marine ecotoxicity	g 1,4-DCB	2.7	**1.5** (45%)	**1.5** (2%)
Human carcinogenic toxicity	g 1,4-DCB	4.8	**2.1** (56%)	**2.1** (1%)
Human non-carcinogenic toxicity	g 1,4-DCB	47	29 (37%)	29 (2%)
Land use	m^2a crop eq	0.0051	0.0049 (4%)	0.0048 (2%)
Mineral resource scarcity	g Cu eq	1.3	**0.3** (73%)	**0.3** (0.5%)
Fossil resource scarcity	g oil eq	23	21 (9%)	21 (2%)
Water consumption	m^3	0.0006	0.0005 (8%)	0.0005 (2%)

Normalised results (Table 34) indicated that the carbon footprint of using a pair of reusable scissors once (no repair) equated to the GHG emissions generated in around 4 minutes and 38 seconds by a global average person, whilst switching to a pair that undergoes repair instead of replacement saves the equivalent of around one minute of a global average person's GHG emissions. The impact of using scissors (no repair) relative to a global average person's environmental impact was greatest for freshwater ecotoxicity (equating to equivalent impact generated in 14 hours by a global average person), human carcinogenic toxicity (15 hours), and marine ecotoxicity (23 hours), whilst repair reduced these impacts to 8, 7, and 13 hours respectively (Figure 30).

Table 34: Environmental impact of surgical scissors (midpoint categories): normalised results

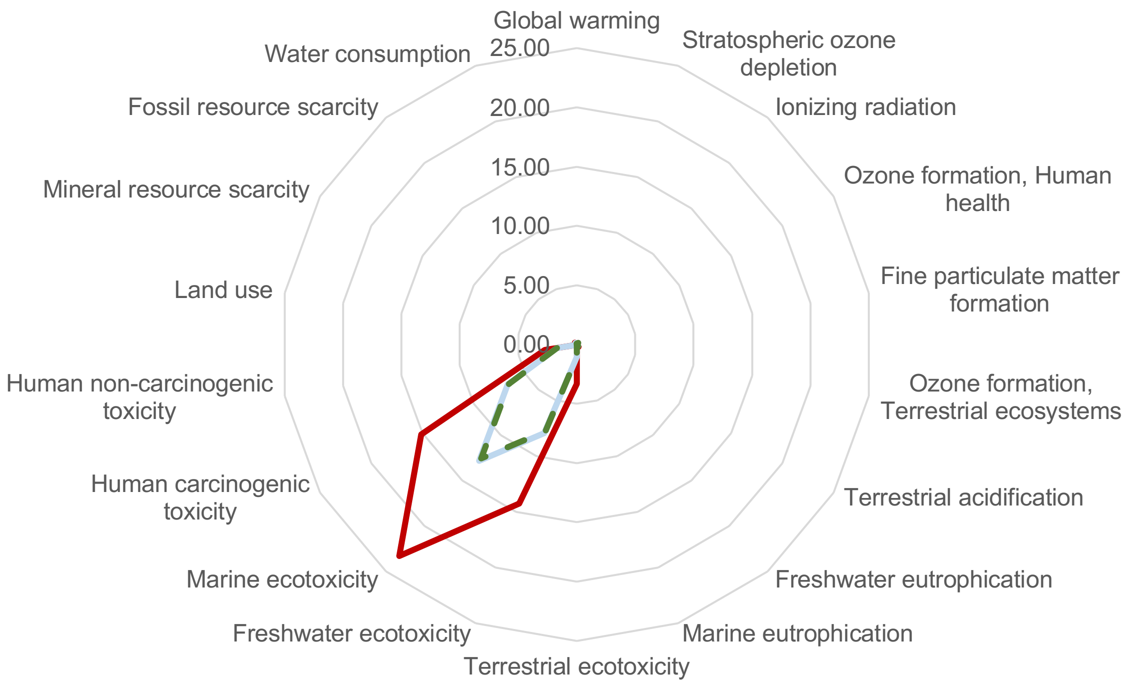
Normalised results reported as environmental impact per scissors use relative to the global average person's contribution to impact category over one hour.

Impact category	Reusable scissors, no repair	Reusable scissors, offsite repair	Reusable scissors, onsite repair
Global warming	0.08	0.06	0.06
Stratospheric ozone depletion	0.00	0.00	0.00
Ionizing radiation	0.19	0.19	0.18
Ozone formation, Human health	0.05	0.04	0.04
Fine particulate matter formation	0.03	0.02	0.02
Ozone formation, Terrestrial ecosystems	0.06	0.04	0.04
Terrestrial acidification	0.03	0.02	0.02
Freshwater eutrophication	0.23	0.14	0.14
Marine eutrophication	0.03	0.03	0.03
Terrestrial ecotoxicity	3.34	1.05	1.04
Freshwater ecotoxicity	14.25	7.96	7.79
Marine ecotoxicity	23.28	12.81	12.54
Human carcinogenic toxicity	15.17	6.70	6.63
Human non-carcinogenic toxicity	2.74	1.71	1.68
Land use	0.01	0.01	0.01
Mineral resource scarcity	0.00	0.00	0.00
Fossil resource scarcity	0.21	0.19	0.19
Water consumption	0.02	0.02	0.02

Figure 30: Environmental impact of surgical scissors (midpoint categories): normalised results

Normalised results reported as environmental impact relative to the global average person's contribution to the impact category over one hour, comparing baseline scenarios. All results reported per scissors use. Red line= reusable scissors with no repair, blue line=

reusable scissors with offsite repair, green dashed line= reusable scissors with onsite repair



Total damage to human health from one use of reusable scissors (no repair) was $1.46e^{-7}$ DALYs (disability adjusted life years) equating to five disability adjusted life seconds (endpoint environmental impact results: Table 35). The impact on ecosystems was $3.12e^{-10}$ species.year (loss of local species per year), and the impact on resource depletion equated to US $0.007 involved in future mineral and fossil resource extraction. These three endpoint environmental impacts were reduced by 32%, 19%, and 8% respectively through use of scissors repaired offsite, whilst those that were repaired onsite were associated with a further 1% - 2% reduction across the three endpoint categories relative to offsite repair. Normalised endpoint results indicated that use of surgical scissors had greatest impact on the human health endpoint impact category across all base scenarios, relative to activities of a global average person (Table 36).

Table 35: Environmental impact of one use of surgical scissors (endpoint categories, baseline scenario)
DALYs= disability adjusted life years, species.year=loss of local species per year, US $= extra costs involved for future mineral and fossil resource extraction. All results reported per scissors use.

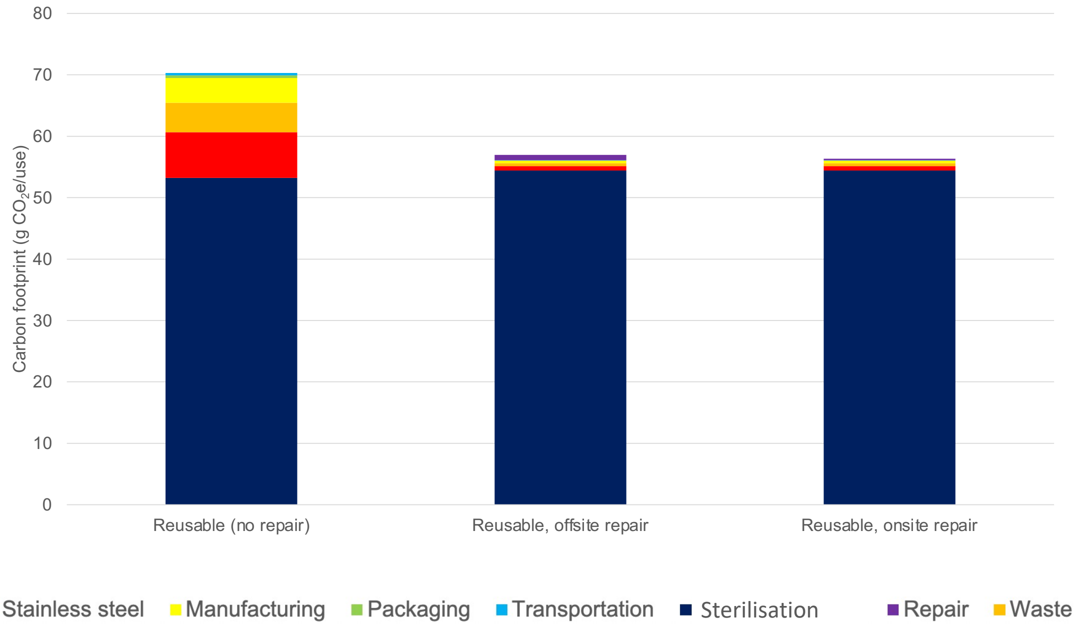
Damage category	Unit	Reusable scissors, no repair	Reusable scissors, offsite repair (% reductions relative to no repair)	Reusable scissors, onsite repair (% reductions relative to offsite repair
Human health	DALY	$1.46e^{-7}$	$9.92e^{-8}$ (32%)	$9.77e^{-8}$ (1%)
Ecosystems	species.yr	$3.12e^{-10}$	$2.51e^{-10}$ (19%)	$2.47e^{-10}$ (2%)
Resources	US $	0.0078	0.0072 (8%)	0.0071 (2%)

Table 36: Environmental impact of surgical scissors (endpoint categories): normalised results
Normalised results reported as environmental impact relative to the global average person's contribution to the impact category over one hour, comparing baseline scenarios. All results reported per scissors use.

Damage category	Reusable scissors, no repair	Reusable scissors, offsite repair	Reusable scissors, onsite repair
Human health	0.0539	0.0366	0.0360
Ecosystems	0.0038	0.0031	0.0030
Resources	0.0024	0.0022	0.0022

Figure 31 provides a breakdown of processes contributing to the carbon footprint of one use of surgical scissors, and Supplementary figure 18 - Supplementary figure 20 demonstrate the drivers of the carbon footprint of each baseline scenario in more detail. Sterilisation was the largest contributor to the carbon footprint, whether the reusable scissors were repaired or not. For non-repaired reusable scissors, sterilisation constituted the majority of the carbon footprint (76%, 53 g CO_2e per use). The carbon footprint of sterilisation increased to 54 g CO_2e per use for those repaired either offsite (95% of impact) or onsite (97%), as the scissors required sterilisation both before and after repair, although this was apportioned across the additional uses afforded by repair. The impact of repair was 1.5% of the total carbon footprint of scissors for those repaired offsite (0.9 g CO_2e per use, which included associated transport associated with offsite repair), and 0.4% of the total for scissors repaired onsite (0.2 g CO_2e per use). The carbon footprint of raw material extraction, manufacture, packaging, transportation and waste (in relation to scissors) totalled 17 g CO_2e per use for reusable scissors which were not repaired, and use of repair instead of replacement reduced this by 90% (to 2 g CO_2e per use).

Figure 31: Contribution of processes to carbon footprint of one use of surgical scissors
Stainless steel= raw material extraction of stainless steel; manufacturing= production of surgical scissors from stainless steel; packaging= primary and secondary packaging of scissors; transportation= transport from raw material extraction through to delivery of scissors to hospital; sterilisation = sterilisation within single-use tray wrap; repair= processes involved in repair, including any associated packaging and transportation; waste= high temperature incineration of all waste throughout life cycle.



Analysis of the repair process itself indicated that where this was conducted offsite, the majority of GHGs generated were associated with use of low density polyethylene (62%) and paper (14%) relating mainly to packaging (Supplementary figure 21), whilst use of bulk packaging at the onsite repair site reduced the relative contributions of these to 39% and 9% respectively (Supplementary figure 22).

Sensitivity analysis

Within each of eight alternative scenario models, the carbon footprint was highest for non-repaired scissors and lowest for those repaired onsite (Figure 32). Similar patterns were seen across all other midpoint environmental impacts (Table 37 A-C) with highest impact where scissors were not repaired and lowest where they were repaired onsite, indicating that environmental impact reductions associated with repair were robust to alternative scenario analysis.

Across all scenarios, the highest carbon footprint was associated with scissors which were only used ten times and were not repaired (122 g CO_2e per use; scenario 1), whilst the lowest carbon footprint was associated with scissors which were used 400 times before repair onsite (53.5 g CO_2e per use; scenario 2). The carbon footprint of scissors which were not repaired but which were used 400 times (54.9 g CO_2e per use) was only marginally greater than those that were repaired (narrowing the gap between those that were repaired onsite versus offsite to 52.5 g CO_2e and 53.6 g CO_2e per use respectively), indicating the number of uses was an important factor. Where scissors were repaired only once (either on or offsite), this resulted in an 11% carbon reduction compared with no repair (scenario 3). Increasing the distance between the hospital and offsite repair centre (from 80 km to 800 km; scenario 4) made very little difference to the results. However, modelling Australian electricity for the sterilisation component significantly increased the carbon footprint, to the extent that using a reusable surgical scissors which underwent repair but was sterilised in Australia (scenario 5) had a greater carbon footprint than using one which was not repaired in the UK (baseline scenario). The only alternative waste scenario which had an impact of ≥ 1% was recycling of all waste, and in turn this only had an impact where scissors were not repaired (scenario 6).

Figure 32: Scenario modelling of repair of surgical scissors
Waste segregation (scenario 7) = sharps waste (scissors) sent for high temperature incineration, cardboard and paper sent for recycling, and all other waste sent to landfill. Waste segregation (scenario 8) = sharps waste (scissors) sent for high temperature incineration, cardboard and paper sent for recycling, and all other waste sent to municipal incineration. CO_2e= carbon dioxide equivalents.

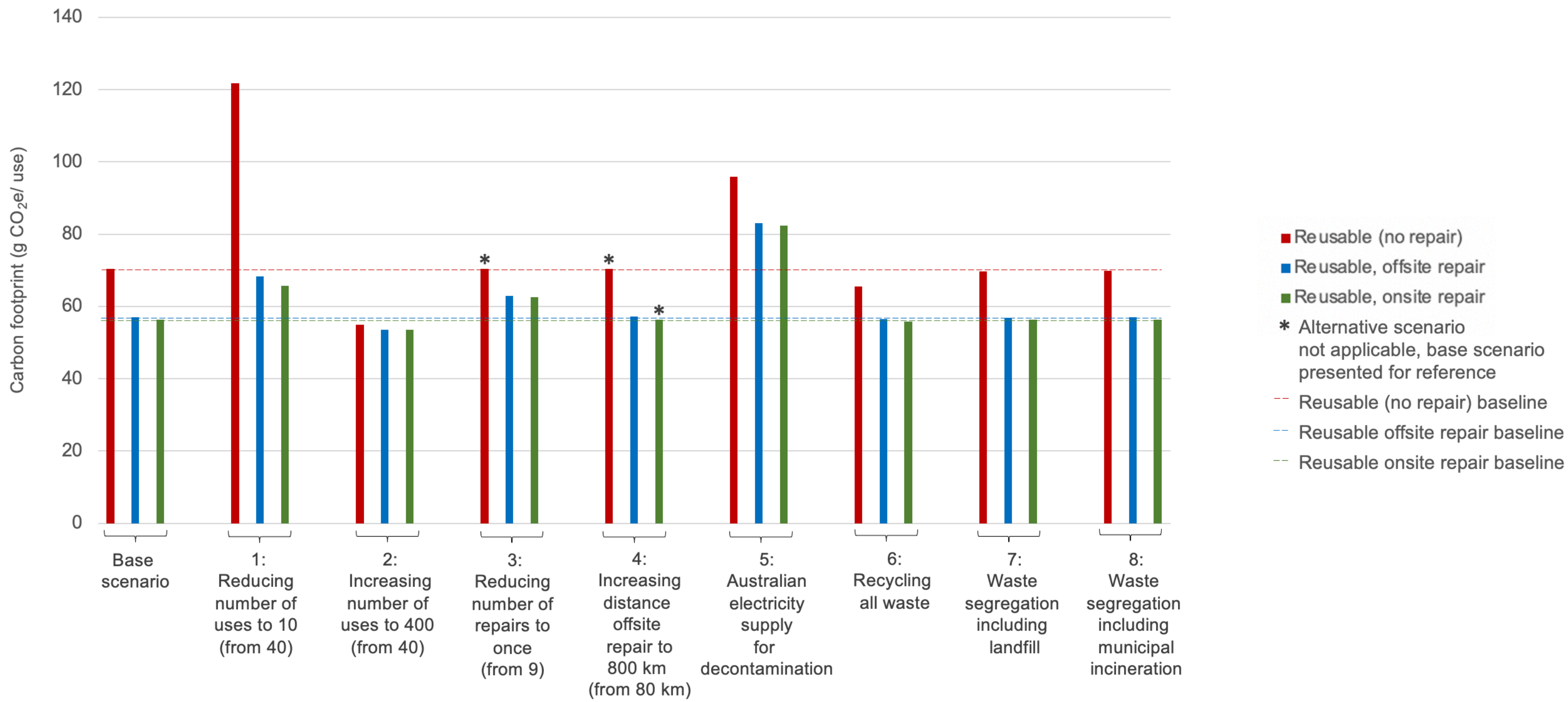


Table 37: Environmental impact of one use of surgical scissors-sensitivity analysis

Missing number indicates that alternative scenario was not applicable. All results reported per scissors use. 1,4-DCB =dichlorobenzene, CFC11= Trichlorofluoromethane, Bq Co-60 eq = becquerel Cobalt-60, CO_2e= carbon dioxide equivalents, Cu= copper, eq= equivalents, m^2a = square metre years, N= nitrogen, NO_x= nitrous oxides, P=phosphate, PM2.5 = particulate matter <2.5 micrometres, SO_2= sulphur dioxide.

Base scenarios are compared with the following models, in which only one assumption is changed.

- Scenario 1: reducing number of reuses of reusables to 10 (from 40)
- Scenario 2: increasing number of reuses of reusables to 400 (from 40)
- Scenario 3: reducing number of repairs to once (from nine)
- Scenario 4: increased distance of travel for offsite recycling to 800 km (from 80 km)
- Scenario 5: electricity supply with lower proportion of renewables (Australian) assumed for sterilisation of reusable instruments
- Scenario 6: all waste assumed to be recycled
- Scenario 7: waste segregation, with sharps waste (scissors) sent for high temperature incineration, cardboard and paper sent for recycling, and all other waste sent to landfill
- Scenario 8: waste segregation, with sharps waste (scissors) sent for high temperature incineration, cardboard and paper sent for recycling, and all other waste sent to municipal incineration

Table 37 A: Reusable scissors (no repair) base scenario and alternative assumption models

Impact category	Unit	Base scenario	1	2	5	6	7	8
Global warming	g CO_2e	70.3	121.7	54.9	95.8	65.5	69.7	69.9
Stratospheric ozone depletion	g CFC11 eq	0.000026	0.000044	0.000021	0.000050	0.000024	0.000026	0.000026
Ionizing radiation	Bq Co-60 eq	10	13	10	2	10	10	10
Ozone formation, Human health	g NO_x eq	0.11	0.22	0.08	0.16	0.11	0.11	0.11
Fine particulate matter formation	g PM2.5 eq	0.08	0.21	0.05	0.11	0.08	0.08	0.08
Ozone formation, Terrestrial ecosystems	g NOx eq	0.12	0.23	0.08	0.17	0.11	0.12	0.12
Terrestrial acidification	g SO_2 eq	0.15	0.31	0.10	0.24	0.14	0.15	0.15
Freshwater eutrophication	g P eq	0.02	0.04	0.01	0.08	0.02	0.02	0.02

Marine eutrophication	g N eq	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	395	1,310	120	401	390	394	394
Freshwater ecotoxicity	g 1,4-DCB	2.0	5.1	1.1	3.6	1.9	2.0	2.0
Marine ecotoxicity	g 1,4-DCB	2.7	7.1	1.4	5.0	2.6	2.7	2.7
Human carcinogenic toxicity	g 1,4-DCB	4.8	13.9	2.1	8.1	4.3	4.7	4.7
Human non-carcinogenic toxicity	g 1,4-DCB	47	109	28	112	44	46	46
Land use	m^2a crop eq	0.0051	0.0066	0.0046	0.0035	0.0051	0.0051	0.0051
Mineral resource scarcity	g Cu eq	1.3	4.4	0.3	1.3	1.3	1.3	1.3
Fossil resource scarcity	g oil eq	23	34	20	28	23	23	23
Water consumption	m^3	0.0006	0.0008	0.0005	0.0006	0.0006	0.0006	0.0006

Table 37 B: Reusable scissors repaired offsite, base scenario and alternative assumption models

Impact category	**Unit**	**Base scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Global warming	g CO_2e	57.0	68.3	53.6	62.9	57.1	83.1	56.5	56.9	56.9
Stratospheric ozone depletion	g CFC11 eq	0.000021	0.000025	0.000020	0.000023	0.000021	0.000046	0.000021	0.000021	0.000021
Ionizing radiation	Bq Co-60 eq	10	11	10	10	10	1	10	10	10
Ozone formation, Human health	g NO_x eq	0.09	0.11	0.08	0.10	0.09	0.14	0.09	0.09	0.09
Fine particulate matter formation	g PM2.5 eq	0.05	0.07	0.04	0.07	0.05	0.08	0.05	0.05	0.05
Ozone formation, Terrestrial ecosystems	g NOx eq	0.09	0.11	0.08	0.10	0.09	0.14	0.09	0.09	0.09
Terrestrial acidification	g SO_2 eq	0.10	0.13	0.09	0.12	0.10	0.19	0.10	0.10	0.10
Freshwater eutrophication	g P eq	0.01	0.01	0.01	0.01	0.01	0.08	0.01	0.01	0.01
Marine eutrophication	g N eq	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	124	229	93	245	127	131	124	124	124
Freshwater ecotoxicity	g 1,4-DCB	1.1	1.6	1.0	1.5	1.1	2.8	1.1	1.1	1.1

Marine ecotoxicity	g 1,4-DCB	1.5	2.2	1.3	2.1	1.5	3.8	1.5	1.5	1.5
Human carcinogenic toxicity	g 1,4-DCB	2.1	3.2	1.8	3.3	2.1	5.5	2.1	2.1	2.1
Human non-carcinogenic toxicity	g 1,4-DCB	29	39	26	37	29	96	29	29	29
Land use	m^2a crop eq	0.0049	0.0058	0.0046	0.0050	0.0049	0.0033	0.0049	0.0049	0.0049
Mineral resource scarcity	g Cu eq	0.3	0.7	0.2	0.8	0.3	0.3	0.3	0.3	0.3
Fossil resource scarcity	g oil eq	21	25	20	22	21	26	21	21	21
Water consumption	m^3	0.0005	0.0006	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005

Table 37 C: Reusable scissors repaired onsite: base scenario and alternative assumption models

Impact category	Unit	Base scenario	1	2	3	5	6	7	8
Global warming	g CO_2e	56.3	65.7	53.5	62.5	82.4	55.8	56.2	56.3
Stratospheric ozone depletion	g CFC11 eq	0.000021	0.000024	0.000020	0.000023	0.000045	0.000021	0.000021	0.000021
Ionizing radiation	Bq Co-60 eq	10	11	10	10	1	10	10	10
Ozone formation, Human health	g NO_x eq	0.08	0.10	0.08	0.10	0.14	0.08	0.08	0.08
Fine particulate matter formation	g PM2.5 eq	0.05	0.07	0.04	0.06	0.08	0.05	0.05	0.05
Ozone formation, Terrestrial ecosystems	g NOx eq	0.09	0.10	0.08	0.10	0.14	0.09	0.09	0.09
Terrestrial acidification	g SO_2 eq	0.10	0.12	0.09	0.12	0.19	0.10	0.10	0.10
Freshwater eutrophication	g P eq	0.01	0.01	0.01	0.01	0.08	0.01	0.01	0.01
Marine eutrophication	g N eq	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	122	221	93	243	129	122	122	122
Freshwater ecotoxicity	g 1,4-DCB	1.1	1.5	1.0	1.5	2.8	1.1	1.1	1.1
Marine ecotoxicity	g 1,4-DCB	1.5	2.0	1.3	2.0	3.8	1.5	1.5	1.5
Human carcinogenic toxicity	g 1,4-DCB	2.1	3.1	1.8	3.3	5.5	2.0	2.1	2.1
Human non-carcinogenic toxicity	g 1,4-DCB	29	37	26	37	95	28	29	29
Land use	m^2a crop eq	0.0048	0.0053	0.0046	0.0049	0.0032	0.0048	0.0048	0.0048

Mineral resource scarcity	g Cu eq	0.3	0.7	0.2	0.8	0.3	0.3	0.3	0.3
Fossil resource scarcity	g oil eq	21	23	20	22	26	21	21	21
Water consumption	m^3	0.0005	0.0006	0.0005	0.5425	0.0005	0.0005	0.0005	0.0005

Life cycle financial cost

The financial cost of purchasing a new pair of reusable scissors was £23.45, and sterilising cost £0.84 per pair, with a small additional cost associated with disposal (£0.05 per pair). The cost to repair scissors offsite was £2.20, whilst onsite repair cost £2.50. The cost of repair was significantly cheaper (89-91% for onsite and offsite repair respectively) than purchasing a new pair of scissors. The life cycle cost per use for reusable scissors (£1.43) was reduced by 32% when repaired, with marginally lower life cycle costs for offsite repair (£0.965) compared with onsite repair (£0.972) (Table 38).

Table 38: Life cycle cost of scissors

<table>
<tr><th></th><th>Process</th><th>Reusable scissors, no repair</th><th>Reusable scissors, offsite repair</th><th>Reusable scissors, onsite repair</th></tr>
<tr><td rowspan="5">Cost per use: £

(Cost per 400 uses: £)</td><td>Manufacture and distribution</td><td>0.59
(234.50)</td><td>0.06
(23.45)</td><td>0.06
(23.45)</td></tr>
<tr><td>Sterilisation</td><td>0.84
(335.31)</td><td>0.86
(342.86)</td><td>0.86
(342.86)</td></tr>
<tr><td>Repair</td><td></td><td>0.05
(19.80)</td><td>0.06
(22.50)</td></tr>
<tr><td>Disposal</td><td>0.00
(0.47)</td><td>0.00
(0.05)</td><td>0.00
(0.05)</td></tr>
<tr><td>Total</td><td>1.43
(570.28)</td><td>0.97
(386.15)</td><td>0.97
(388.85)</td></tr>
</table>

Scope of instrument repairs

Over an 11 year period at Barts Health NHS Trust, 14,210 out of 20,150 (70.5%, Wilson binomial confidence interval 69.9%- 71.2%) of instruments sent for repair were successfully repaired, of which the majority (13,241 instruments: 93% of those repaired) were repaired internally onsite, and the remainder (969: 7%) were repaired offsite via an external contractor (Table 39). The majority of the instruments which needed to be repaired offsite were endoscopic scopes (36%), needle holders (21%), and endoscopic instruments (10%). Of those instruments successfully repaired (either on or offsite), over half were general surgical scissors such as Mayo, Metzenbaum or McIndoe scissors (7,320: 52%), followed by osteotomes (866: 6%), needle holders (853: 6%), retractors (553:4%), and clamps (520: 4%). Of those instruments that were considered irreparable, 46% was due to normal expected wear, 30% due to damage by external force (incorrect use), 21% due to corrosion, and 2% were not repaired at the time due to insufficient sterilisation. The average turnaround time was 3.6 days (range 1-28 days) for onsite repair, and 31.6 days for offsite repair (range 9 - 57 days).

Table 39 Scope of instrument repairs conducted at a single centre
Total number of repairs successfully completed across an 11-year period at Barts Health NHS Trust, by instrument type, indicating those performed at onsite repair centre versus those repaired externally offsite. 'Further information/ parts' indicates that the repair centre was unable to identify fault, or that instruments were sent with missing or incorrect parts.

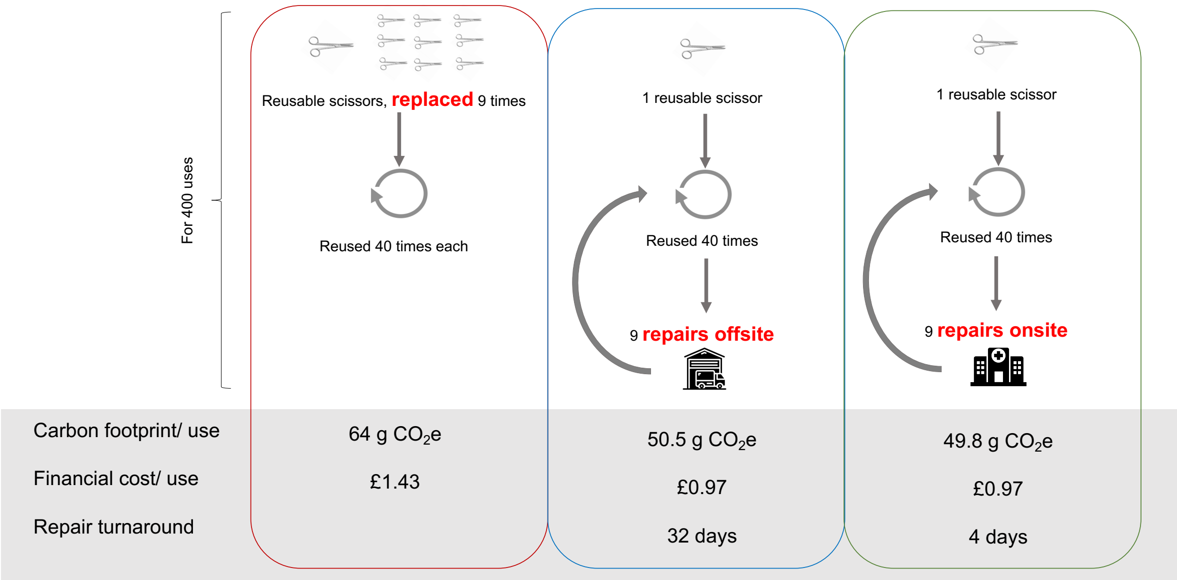
Instrument	**Repaired onsite**		**Repaired offsite**		**Total repairable**		**Further information/ parts**		**Irreparable (corrosion, damage, unusable)**		**Irreparable (require further sterilisation)**		**Total**
	Count	**%**	**Count**	**%**	**Count**	**%**	**Count**	**%**	**Count**	**%**	**Count**	**%**	**Count**
General scissors	7318	84.6	2	0.0	**7320**	**84.6**	17	0.2	1281	14.8	30	0.3	8648
Osteotomes/ chisels/ mallets	861	86.9	5	0.5	**866**	**87.4**	7	0.7	108	10.9	10	1.0	991
Needle holders	652	34.8	201	10.7	**853**	**45.5**	147	7.8	863	46.0	12	0.6	1875
Retractors	515	56.0	38	4.1	**553**	**60.2**	104	11.3	259	28.2	3	0.3	919
Clamps	481	51.1	39	4.1	**520**	**55.2**	103	10.9	313	33.2	6	0.6	942
Vessel scissors	506	87.5	1	0.2	**507**	**87.7**	3	0.5	63	10.9	5	0.9	578
Artery forceps	501	46.1	0	0.0	**501**	**46.1**	64	5.9	516	47.5	5	0.5	1086
Endoscope telescopes	15	3.5	349	80.8	**364**	**84.3**	65	15.0	3	0.7	0	0.0	432
Micro scissors	340	83.5	6	1.5	**346**	**85.0**	6	1.5	55	13.5	0	0.0	407
Micro forceps	314	60.6	8	1.5	**322**	**62.2**	27	5.2	166	32.0	3	0.6	518
Tissue forceps	212	49.6	1	0.2	**213**	**49.9**	42	9.8	168	39.3	4	0.9	427
Levers/ rasps/ curettes	203	44.2	5	1.1	**208**	**45.3**	30	6.5	219	47.7	2	0.4	459
Dissecting forceps	201	49.5	2	0.5	**203**	**50.0**	23	5.7	177	43.6	3	0.7	406

Endoscope instruments	95	32.9	94	32.5	**189**	**65.4**	40	13.8	54	18.7	6	2.1	289
Bone cutting/ holding	136	52.1	35	13.4	**171**	**65.5**	20	7.7	63	24.1	7	2.7	261
Rongeurs	154	66.1	12	5.2	**166**	**71.2**	16	6.9	45	19.3	6	2.6	233
Picks/ probes/ hooks	159	56.2	1	0.4	**160**	**56.5**	39	13.8	83	29.3	1	0.4	283
Pliers/ cutters/ benders/ spanners	129	50.6	31	12.2	**160**	**62.7**	28	11.0	67	26.3	0	0.0	255
Punches	77	68.1	6	5.3	**83**	**73.5**	13	11.5	17	15.0	0	0.0	113
Air/ battery tools	31	46.3	24	35.8	**55**	**82.1**	5	7.5	5	7.5	2	3.0	67
Scalpels/ knives/ snares	51	37.8	4	3.0	**55**	**40.7**	16	11.9	59	43.7	5	3.7	135
Debakey forceps/ clamp	53	50.5	0	0.0	**53**	**50.5**	36	34.3	15	14.3	1	1.0	105
Dilators/ introducers/ catheters	36	20.1	11	6.1	**47**	**26.3**	30	16.8	102	57.0	0	0.0	179
Electro-medical	14	19.4	25	34.7	**39**	**54.2**	5	6.9	28	38.9	0	0.0	72
Measuring / jigs	26	50.0	7	13.5	**33**	**63.5**	8	15.4	11	21.2	0	0.0	52
Needles	27	77.1	4	11.4	**31**	**88.6**	0	0.0	4	11.4	0	0.0	35
Fibre lights	7	11.1	23	36.5	**30**	**47.6**	20	31.7	13	20.6	0	0.0	63
Skin graft	16	47.1	12	35.3	**28**	**82.4**	4	11.8	2	5.9	0	0.0	34
Biopsy forceps	20	31.7	7	11.1	**27**	**42.9**	9	14.3	23	36.5	4	6.3	63
Suction	24	52.2	0	0.0	**24**	**52.2**	7	15.2	15	32.6	0	0.0	46
Syringes	14	23.0	3	4.9	**17**	**27.9**	17	27.9	27	44.3	0	0.0	61
Sterilisation cases	11	61.1	4	22.2	**15**	**83.3**	2	11.1	1	5.6	0	0.0	18

Table accessories	10	38.5	5	19.2	**15**	**57.7**	6	23.1	5	19.2	0	0.0	26
Trocar/ cannula	12	46.2	2	7.7	**14**	**53.8**	3	11.5	9	34.6	0	0.0	26
Laparoscopic scissors	12	66.7	1	5.6	**13**	**72.2**	0	0.0	5	27.8	0	0.0	18
Complete sets and kits	4	36.4	1	9.1	**5**	**45.5**	4	36.4	2	18.2	0	0.0	11
Vein strippers	2	50.0	0	0.0	**2**	**50.0**	1	25.0	1	25.0	0	0.0	4
Air tools	1	50.0	0	0.0	**1**	**50.0**	1	50.0	0	0.0	0	0.0	2
Measuring	1	50.0	0	0.0	**1**	**50.0**	1	50.0	0	0.0	0	0.0	2
Optical instrument	0	0.0	0	0.0	**0**	**0.0**	0	0.0	9	100.0	0	0.0	9
Total	**13,241**	**65.7**	**969**	**4.8**	**14,210**	**70.5**	**969**	**4.8**	**4,856**	**24.1**	**115**	**0.6**	**20,150**

Figure 33 summarises study findings including turnaround time.

Figure 33: Environmental impact and financial cost of repairing reusable surgical scissors
CO_2e= carbon dioxide equivalents



8.4. Discussion

The study in this chapter was the first to evaluate the environmental and financial impact of repair in the context of surgical products, finding that using surgical scissors that had undergone repair reduced the carbon footprint by around one-fifth, and the financial cost by approximately one-third. Repairing scissors once achieved an 11% reduction in carbon footprint and 15% lower financial cost relative to replacing these with a new pair, indicating over half of the carbon and financial reductions associated with repair as modelled in the baseline scenario could be achieved through a single repair. The repair of scissors was compared offsite versus onsite, and this study found that surprisingly this did not make a significant impact to the carbon footprint, whilst factors relating to sterilisation and number of uses across the scissors' lifespan were important determinants of the carbon footprint.

The value of the global surgical scissors market was previously estimated at US \$331 million (£273 million; exchange rate 12th August 2022) in 2019, of which approximately two-thirds were reusable and one-third single-use.(212) Assuming the purchase cost and use profile used in this study (CHAPTER 8) are representative, and that the rate at which new scissors were purchased was equal to the rate at which they were disposed of (with no change in stock levels), this implies an estimated 364 million uses of reusable scissors each year. Repairing these scissors at offsite centres would save approximately 4,847 t CO_2e (equivalent to flying as a passenger from London to New York return over 2,000 times)(31) and around £166 million each year. Previous research from three hospitals in the Netherlands found one-sixth of single-use stainless steel instruments destined for waste could potentially be refurbished, and that repairing or remanufacturing instead of purchasing new products saved almost €39,000 over a six month period (£33,070; exchange rate 12th August 2022).(106)

The reduction in environmental impact associated with repair was robust to reducing number of reuses, reducing number of repairs, increasing the distance to the offsite repair site, and using an electricity supply with lower proportion of renewables (Australian) for the sterilisation process. Increasing the number of uses of scissors from 40 to 400 times before disposal reduced the carbon footprint by a similar proportion (around one-fifth) to reductions associated with repairing those used 40 times. It is therefore important to maximise the number of uses of scissors between repair or before disposal. The barriers, enablers, and carbon footprint implication of extending the number of uses of surgical instruments across their lifetime is an important area of future research. Extending instrument lifetime duration may be facilitated by improving robustness at design stage, developing objective measures to evaluate functional failure, and proactive maintenance.

Sterilisation made the biggest contribution to the carbon footprint across all baseline scenarios, ranging from three-quarters of the carbon footprint of scissors which were not repaired, up to almost all of the carbon footprint of repaired scissors. This analysis highlights that whilst repair can be used to reduce the carbon footprint associated with obtaining new scissors (including raw material extraction, manufacture, and distribution), sterilisation remains a key hotspot responsible for 95% - 97% of the carbon footprint of repaired scissors. Optimising the carbon footprint of sterilisation in line with principles outlined in CHAPTER 5 is therefore important, such as preparing instruments as part of a set (rather than individually wrapped instruments), optimising sterilisation machine loading (number of instruments per machine slot), and recycling of associated packaging.(7) Adopting these strategies would reduce the carbon footprint of the sterilisation phase by around one-third across all three base scenarios in the current study, resulting in similar carbon savings across the scissors' life cycle to those associated with adopting repair. There is also opportunity to reduce the carbon footprint associated with the repair process for surgical scissors; this study found around three-quarters of the GHGs associated with the offsite repair process itself were attributed to use of low-density polyethylene and paper predominantly within packaging, and so use of bulk packaging or reusing packaging could significantly reduce the environmental impact of the repair process itself.

A previous study by Ibbotson et al.(91) evaluated the carbon footprint of reusable scissors, assuming that these were repaired every 750 uses (repaired a total of five times, providing 4,500 uses across the scissors' life cycle). This contrasts with the model in this study (CHAPTER 8), which assumed that repair was required every 40 uses, and that repair was undertaken nine times, totalling 400 uses across the scissors' lifespan. The more conservative use profile assumptions in this study are aligned with a study using radio frequency identification for tracking, which indicated that Cooper scissors were used 10-120 times before instrument failure (which included the need for repair).(213) Ibbotson et al.(91) included the cost of repair within their analysis and assumed this was 75% of the cost of purchasing a new pair of scissors, whilst the current study used primary data based on amount charged by two repair centres. The study by Ibbotson et al.(91) did not evaluate the impact of repair itself, and unlike the current study, made no comparison to scenarios in which scissors were replaced instead of repaired. However, unlike the study in this chapter, the study by Ibbotson et al. evaluated the impact of switching from single-use surgical scissors to reusable equivalents, and whilst figures were not reported directly, these can be estimated from a graph indicating the carbon footprint reduced from around 2,200 g CO_2e per use for single-use scissors to around 66 g CO_2e per use for reusable scissors (including repair).(91) This is supported by studies of other equipment used in the operating theatre, for example 16 to 18 fold reductions have been associated with switching single-use to reusable laryngoscope handles.(72) The large difference in carbon footprint of single-use versus reusable surgical scissors related to the increased requirements for raw material extraction, manufacture, distribution, and waste associated with the single-use scissors.(91) The figure derived by Ibbotson et al.(91) for reusable scissors was similar to the baseline scenario estimates in the study in this chapter (56 g CO_2e - 70 g CO_2e), although difficulty in interpreting the graph by Ibbotson et al. limits the extent to which the carbon footprint estimated for reusable scissors can be compared to those in this study (CHAPTER 8).

There were similar reductions in the carbon footprint and financial cost associated with both onsite versus offsite repair, indicating that the important message is that reusable scissors are sent for repair, whether that is onsite at the hospital or offsite with an external contractor. The carbon footprint of transporting the scissors for repair offsite was minimal, even where an 800 km journey to the repair centre was factored in (scenario 4), although this was modelled using data on average couriers and heavy goods vehicles, and so the exact contribution would depend on how efficiently these are loaded. There were other minor differences in the processes used for repair conducted onsite versus offsite such as use of bulk packaging when scissors were repaired onsite, and use of different materials to test scissors' sharpness. Whilst onsite repair may offer faster turnaround times (which may be especially important for instruments used frequently), offsite repair potentially offers the ability to repair more complex instruments (such as electrosurgical and endoscopic products), requiring more specialist equipment and expertise. Encouraging uptake of offsite repair centres is likely more feasible than individual hospitals creating repair services, and purchase or loan of spare equipment can be used to minimise disruption (and loan is already offered by some repair companies).(210)

Maintenance and repair services have been established in low-resource settings such as public hospitals in Honduras to meet demand for safe surgical instruments in the absence of resources to fund new equipment.(214) However in high-income nations repair services are anecdotally under-utilised, resulting in premature obsolescence. When surgical instruments fail, they are usually disposed of, and so education amongst users (such as theatre staff), and those involved in processing (such as sterilisation personnel) will be important when introducing and expanding repair contracts. Attempts to provide repair services for instruments must also be aligned with education to minimise avoidable instrument damage (including correct handling, sterilisation processes, and instrument maintenance) and proactive onsite quality checking to identify damaged or sub-optimally performing instruments.

Limitations

In common with other studies, this analysis was limited by parameter, scenario, and model uncertainty (as discussed in CHAPTER 2). Whilst primary process activity data was collected and used wherever possible throughout the product life cycle, global average data embedded within Ecoinvent (version 3.6)(114) were used for production of chromium steel and metal working due to difficulties in obtaining reliable primary data on the manufacture of surgical scissors from stainless steel. Whilst this limits the specificity of the results in relation to the case study pair of scissors, this approach improves generalisability of findings through use of global average data aggregated from multiple sources.

The impact of key methodological assumptions was evaluated through formal sensitivity analysis, finding conclusions were robust to alternative scenarios which improves the generalisability of results to other settings. This study examined the scope to repair surgical instruments beyond scissors, and whilst this highlights the feasibility of repair across a range of commonly used surgical instruments, the environmental impact of such repair relative to purchasing new instruments will depend upon packaging, equipment required for repair, alongside sterilisation processes. Whilst findings may extend to other simple stainless steel instruments such as needle holders and forceps, repair of complex equipment such as electrosurgical or endoscopic equipment may be associated with greater environmental impact. Repair has the potential to play an important role in mitigating environmental impacts of products used within healthcare, but the extent to which this applies across other medical products requires further research.

Conclusion

The environmental impact of repairing products instead of buying new ones has previously been evaluated in other contexts,(101, 102) but this study was the first to explore the role of repair within a surgical setting. This study focused on surgical scissors, finding that repairing these at the end of their functional life instead of replacing them with a new pair could reduce environmental and financial cost. Minimal differences were found in the environmental impact or financial cost associated with onsite and offsite repair centres, indicating that development of regional or national repair centres would be as good a strategy as developing local repair centres.

Whilst sterilisation was responsible for almost all of the carbon footprint of repaired scissors (and up to three-quarters of those that were not repaired), it is important to optimise the sterilisation process, in line with findings from CHAPTER 6.(5) Evidence from Ibbotson et al.(91) point to significant reductions in carbon footprint associated with switching from single-use to reusable scissors (estimated at around 33-fold). The principle of reduce and reuse must be prioritised, with single-use products switched to reusable or hybrid equivalents (CHAPTER 7)(6) where appropriate, and where evidence supports this. Once reusable products are in place, strategies for further reductions in carbon footprint then include optimising sterilisation (CHAPTER 6),(5) recycling (CHAPTER 7),(8) and use of repair (as evidenced by this study; CHAPTER 8).(9)

CHAPTER 9 Discussion

CHAPTER 9 draws upon the following:

- Rizan C, Bhutta MF. A strategy for net zero carbon surgery. British Journal of Surgery. 2021;108:737-739. doi.org/10.1093/bjs/znab130. *Invited leading article. Awarded High Altimetric Certificate. Impact factor 6.92*
- Harris H, Bhutta MF, Rizan C. A survey of UK and Irish surgeons' attitudes, behaviours and barriers to change for environmental sustainability. Annals of the Royal College of Surgeons of England. 2021;103:725-729. PMID: 34719956. *Impact factor 1.95*
- MacNeill A, Rizan C, Sherman J. Environmental impact of perioperative care. [Internet]. 2022. [cited 2022 Dec 28]. Available from: https://www.uptodate.com/contents/environmental-impact-of-perioperative-care

This final chapter summarises the key findings from this research and novel contributions to the literature. This is then used to inform a strategy for mitigating the carbon footprint of products used in surgical operations, drawing upon the evidence within this thesis alongside wider research. This is followed by considering how this research might be translated into practice and policy, limitations, areas of future research, and a final conclusion.

9.1. Summary of thesis and novel contribution to literature

CHAPTER 1 contextualised this thesis within wider issues relating to the impact of climate change on health,(1) and the paradoxical contribution that healthcare has towards global GHGs (estimated at 4.4%),(2) emphasising the responsibility that clinicians have towards current and future generations of patients and healthcare providers to transition to sustainable healthcare systems. The chapter then focused on the environmental impact of surgical operations specifically, and how this might be mitigated. CHAPTER 2 provided an overview of the methodological approaches used within this thesis.

CHAPTER 3 was the first study to systematically review studies evaluating the carbon footprint of surgical operations.(5) This review found that the carbon footprint of a single operation ranged 6 kg CO_2e - 814 kg CO_2e (the latter equivalent to driving up to 2,268 miles in an average petrol car),(31) and that the major carbon hotspots within the operating theatres were electricity use, and procurement of products (in particular those that are single-use). Subsequent research questions in this thesis focused on mitigating the carbon footprint of surgical products, chosen as the systematic review (CHAPTER 3)(5) found products were a major contributor to the carbon footprint of surgery, and because choice of products may be influenced by surgeons. Whilst sixteen studies were included within the systematic review (last review date in October 2019), this academic field is growing rapidly, as reflected by additional studies captured in a subsequent systematic review which included studies evaluating individual surgical products and anaesthetic components (excluded from the systematic review in CHAPTER 3)(78) and other more recent studies discussed within this thesis, such as those evaluating the carbon footprint of single-use versus reusable cystoscopes,(146) cardiac surgery,(141) and ophthalmology.(139)

CHAPTER 4 was the first study to evaluate the carbon footprint of products used in the five highest volume surgical operations performed in the NHS in England (aside from a limited carbon footprint of carpal tunnel decompression),(143) and was the first to include carbon footprint evaluations of each individual product. The mean average carbon footprint of products used for carpal tunnel decompression was 12.0 kg CO_2e; 11.7 kg CO_2e for inguinal hernia repair; 85.5 kg CO_2e for knee arthroplasty; 20.3 kg CO_2e for laparoscopic cholecystectomy; and 7.5 kg CO_2e for tonsillectomy. Across the five operations, just a few product types (23%) were responsible for ≥ 80% of the operation carbon footprint of products used, and this finding implies that these high carbon products should be the focus for change in practice and policy. Examples of such products with greatest carbon contribution (and with potential for mitigation) for each operation type were single-use hand drapes (carpal tunnel decompression), single-use surgical gowns (inguinal hernia repair), single-use pulsed lavage system (knee arthroplasty), single-use clip appliers (laparoscopic cholecystectomy), and single-use table drapes (tonsillectomy). Across the dataset the underpinning processes with highest carbon footprint were the production of single-use products (54%), decontamination of reusables (20%), and waste disposal of single-use products (8%). This analysis indicated that strategies to mitigate the carbon footprint of products should focus on reduction of single-use products, increasing reusables (and optimising associated sterilisation processes), and utilising low carbon waste streams, and this formed the focus of the subsequent three studies (CHAPTER 5 - CHAPTER 7).

The evaluation of laparoscopic cholecystectomy in CHAPTER 4 found that 19% of the carbon footprint of products related to three single-use products (laparoscopic clip appliers, scissors, and ports). The next study (CHAPTER 5) evaluated the environmental and financial impact of switching these to hybrid equivalents (predominantly reusable products with small single-use components), focusing on the biggest carbon hotspot process identified across operations in CHAPTER 4; production of single-use products. The environmental impact of using hybrid instruments for a laparoscopic cholecystectomy was lower than single-use equivalents across 17 midpoint environmental impacts, with mean average reductions of 60%. The carbon footprint of using hybrid versions of all three instruments was around one-quarter of single-use equivalents (1,756 g versus 7,194 g CO_2e per operation), and saved an estimated 1.13e^{-5} DALYs (disability associated life years, 74% reduction), 2.37e^{-8} species.year (loss of local species per year, 76% reduction), and US $0.6 in impact on resource depletion (78% reduction). Sensitivity analysis indicated that environmental impact of hybrid products was better than single-use equivalents even if there was a low number of instrument reuses, sterilisation with separate packaging of certain instruments, sterilisation using fossil-fuel rich energy sources, or changing the carbon intensity of product transportation. Total financial cost of using a combination of hybrid laparoscopic products was less than half that of single-use equivalents (£131 versus £282). This indicates that where it is not feasible or appropriate to use fully reusable instruments, adoption of hybrid laparoscopic instruments could play an important role in meeting carbon reduction targets for surgery, whilst saving money. This was the first published study to evaluate the environmental impact of hybrid surgical equipment.(6)

The first two original research chapters highlighted that sterilisation was an important component of the carbon footprint of products used within surgical operations, responsible for one-fifth of the carbon footprint of products used within the five most common operations (CHAPTER 4), and one-third of the carbon footprint of hybrid laparoscopic products (CHAPTER 5). CHAPTER 6 contains the first study to report the carbon footprint and financial cost of different processes for sterilisation and preparation of reusable surgical instruments, alongside how such processes can be optimised. The carbon footprint of sterilising and packaging instruments was lowest when instruments were part of sets (66-77 g CO_2e per instrument), with two to three-fold increase when instruments were individually wrapped (189 g CO_2e per instrument). Where $\leq$ 10 instruments were required intra-operatively, obtaining individually wrapped products was preferable to opening another set. The carbon footprint was significantly determined by machine loading and number of instruments per machine slot ($p<0.001$). Counterintuitively, carbon and financial costs increased with streamlining sets (assuming instruments removed were individually wrapped and used occasionally), and this was the first study to demonstrate this. High temperature incineration of waste increased carbon footprint of single-use sterile barrier system packaging by 33% - 55%, whilst recycling reduced this by 6% - 10%. Combining these strategies, the carbon footprint of reusable instrument sterilisation could be optimised by 31% - 42% through processing instruments in sets rather than individually wrapped, maximal loading of sterilisation machines, and recycling sterile barrier systems. Further reductions could be achieved through using low carbon energy sources. The evaluation of the carbon footprint of sterilisation in CHAPTER 6(7) may be used as a source of emission factors for future studies wishing to include the sterilisation process in evaluations (and was used for this purpose in CHAPTER 4, with sterilisation activity data also used in CHAPTER 5 and CHAPTER 8).

Disposal of single-use products was the third largest contributing process to the carbon footprint of products used in common operations as evaluated in CHAPTER 4, and waste was identified as an important component of the carbon footprint of both single-use laparoscopic instruments (14% related to waste; CHAPTER 5) and of the tray wrap used as a sterile barrier system (6% related to waste; CHAPTER 6). The next study (CHAPTER 7) estimated the carbon footprint of healthcare waste, estimating that the carbon footprint per t of hospital waste was lowest when it was recycled (21 kg CO_2e - 65 kg CO_2e), followed by low temperature incineration with energy from waste (172 kg CO_2e - 249 kg CO_2e).(8) When the waste was additionally decontaminated using an autoclave prior to low temperature incineration with energy from waste, the carbon footprint increased to 569 kg CO_2e. The highest carbon footprint was associated with the disposal of waste via high temperature incineration (1,074 kg CO_2e per t). NHS data show that the financial cost of waste streams mirror that of the carbon footprint. Prior to this study there was little evidence on the carbon footprint of healthcare waste (especially autoclave of infectious healthcare waste), and this was used as a source of emission factors to account for healthcare waste in CHAPTER 4 and CHAPTER 6.

The final research chapter (CHAPTER 8) evaluated how resources can be maximised further via extending reusable product lifespan through repair. The carbon footprint of reusable scissors was 70 g CO_2e per use, assuming scissors were used 40 times before replacement. This was reduced by 19% through use of offsite repair every 40 uses (57 g CO_2e per scissors use), with small additional reductions associated with onsite repair (56 g CO_2e per scissors use). Similar patterns of reduction were calculated for eighteen midpoint environmental impact categories (mean impact reduction of 30% for those repaired offsite relative to no repair) and also across three endpoint categories. Sterilisation made the biggest contribution to the carbon footprint across all baseline scenarios (76% where there was no repair, 95-97% where scissors were repaired offsite and onsite respectively), and this could be optimised using strategies outlined in CHAPTER 6. Findings were robust to alternative scenario analyses. The life cycle cost was £1.43 per use of reusable scissors, and when repaired either onsite or offsite, this decreased by 32% to £0.97 per use. Repairing surgical scissors rather than replacing them with a new pair therefore reduced both environmental impact and financial cost. The scope to repair instruments beyond scissors was also evaluated retrospectively using an eleven-year data set, finding that the most commonly repaired instruments were general surgical scissors, osteotomes, needle holders, retractors and clamps. This was the first study to evaluate the environmental and financial impact of repair in the context of healthcare products.(9)

9.2. Strategy for mitigating carbon footprint of surgical products

This section outlines a strategy for mitigating the carbon footprint of surgical products, informed by the findings of studies within this thesis and drawing upon wider research. This broadly draws upon circular economy principles, seeking to maximise the use of energy and material flows throughout the product life cycle, and to minimise the generation of waste.(87)

Reduce

Making absolute reductions in the volumes of products used will be associated with largest reductions in the environmental impact of surgical products, reducing emissions across a product's life cycle from raw material extraction and manufacture through to waste disposal. There are instances where surgical products are opened and thrown away without ever being used. This includes products opened just in case they are needed, alongside use of pre-prepared sets containing more than is required for a given procedure. Products should only be opened at the point that use is very likely, or where any delay associated with opening the product from its packaging would be clinically critical. A previous study evaluating hand operations found that an average of 11.5 products were disposed of without use, the majority of which were from a pre-prepared hand set (of which 23% was wasted).(160) A similar proportion (12 out of 40) of single-use products from a pre-prepared set used for tonsillectomy were found to be unnecessary.(90) Whilst streamlining pre-prepared sets containing single-use products likely confer environmental reductions, CHAPTER 6 found that streamlining reusable instrument sets resulted in net increased carbon and financial costs where products that were removed were occasionally used.(7) The exception would be where consolidating instrument sets enable these to be housed in a smaller mesh basket, such that more baskets can fit per decontamination machine slot (for example where instruments could be housed in a basket half the original size).

There are further opportunities to rationalise glove use where hand washing alone is sufficient such as transferring surgical patients or examining intact skin (with considerable potential to mitigate carbon footprint associated with personal protective equipment),(88) and where gloves are used inappropriately this can increase the risk of organism transmission.(215) Different surgical approaches can also confer reductions, for example five of the tonsillectomies evaluated in CHAPTER 4 were performed using steel dissection with diathermy and/ or ties for haemostasis, and five used a single-use coblation™ wand, associated with 0.93 kg CO_2e per wand. There may be clinical reasons to prefer one technique over another, but there does not appear to be reasons why a coblation™ wand cannot be manufactured as a reusable equivalent. Similarly, due to surgeon preference, one knee arthroplasty evaluated in CHAPTER 4 included use of a navigation set, generating an additional 2.25 kg CO_2e.

The principal of reduction applies beyond products used within the operating theatre to opportunities which may reduce the need for surgery at all (eliminating need for all associated surgical products). The optimum approach to reducing environmental impact of surgical care is disease prevention, reducing demand for carbon intensive operations. Once patients have entered a surgical pathway, optimal and efficient care is usually also environmentally preferable. Non-surgical options should be explored for acute conditions, and surgical pathways streamlined to eliminate non-value adding steps, and to minimise resource use. Where clinically appropriate, the latter may include telemedicine, which has been associated with lower carbon footprints due to reduced need for transportation.(216) Whilst lean models of surgical care have been shown to improve outpatient and peri-operative efficiency whilst reducing costs,(217) it is likely that they are also associated with carbon savings.

These principles are consistent with the ongoing Getting it Right First Time (GIRFT) and Choosing Wisely initiatives, which seek to minimise unexplained variations in the use of surgical interventions and to ensure that those that are used have clear evidence of benefit, with the addition of increasing the most efficient use of financial resources. The de-adoption or reduction of low value care would likely reduce the carbon footprint associated with surgical services, including reducing clinically unnecessary investigations (including blood tests and imaging).(218) The Academy of Medical Royal Colleges highlight a number of surgical procedures which should be reserved in close accordance with guidelines, such as repair of minimally symptomatic inguinal hernia, surgical intervention for chronic sinusitis, and discectomy for slipped disc.(219)

Reuse

In low- and middle-income countries resource use may be frugal out of necessity, eliminating unnecessary materials and opting for reusable products wherever possible.(220) For example, a cataract operation performed in India using predominantly reusable equipment was estimated to generate only 5% of the GHGs of the same operation performed in the UK.(79) The majority of evidence to date indicates that reusable surgical products have a lower carbon footprint when compared with single-use equivalents, with a previous systematic review finding that the carbon footprint of reusable products used within the operating theatre were lower than single-use equivalents across the majority of included studies.(78) Reusable theatre products with evidence indicating a lower carbon footprint compared with single-use equivalents include laryngoscope handles and blades,(72) laparotomy pads,(94) laryngeal mask airways,(92) surgical gowns and drapes,(93) and surgical scissors.(91) Exceptions where the impact of single-use surgical products have been estimated to have a lower carbon footprint compared with reusable equivalents include studies conducted in Australia, in which electricity is generated using predominantly coal-based non-renewable energy sources, and where such studies remodelled processes using European and US energy sources, the carbon footprint of reusables was lower.(97, 98) There are additional harms from a model reliant on single-use surgical instruments, where cost pressures mean the majority of such scissors are produced in low-resource environments such as the surgical instrument manufacturing cluster in Sialkot, Pakistan. In such settings workers suffer poor remuneration, and are exposed to risk of injury, noise-induced hearing loss, and inhalation of metal dust.(221, 222, 223)

Within the evaluation of whole operations (CHAPTER 4), a number of single-use high carbon products were identified which have reusable alternatives. For example, single-use gowns, patient drapes, and instrument table drapes were high contributors to the carbon footprint, yet a review found that reusable surgical textiles held significant reductions (200-300%) in carbon footprint,(93) and there is no evidence that reusable textiles are clinically inferior.(151) The carpal tunnel decompression operations evaluated in CHAPTER 4 also made use of a single-use hand set containing multiple products which could potentially be reusable (including a single-use bowl, kidney dish, light cover, patient drape, and table drape), alongside a sponge which was routinely disposed of without being used.

Where it is not appropriate to use fully reusable products, rather than using fully single-use products, there may be potential to use alternatives which are hybrid, with both reusable and single-use components. CHAPTER 5 associated three hybrid laparoscopic instruments with three-quarter reductions in carbon footprint when compared with single-use equivalents, alongside cost savings of around half.(6) Where hybrid products are used, the proportion that is reusable should be increased where possible. There is further potential to reduce carbon footprint of reusables through mitigating emissions associated with their use, through optimising sterilisation of instruments and laundering of linens. For example, CHAPTER 6 found that strategies for mitigating carbon footprint associated with steam sterilisation of reusable instruments include processing instruments as part of sets rather than individually wrapped, loading the sterilisation machines optimally, using low carbon renewable energy supplies, and recycling the sterile barrier system.(7)

Recycle, repair, and reprocessing

The carbon footprint of disposing of surgical products at the end of their usable life may be reduced through use of recycling or through capturing energy from waste. For example CHAPTER 7 found a 50-fold difference between high temperature incineration versus recycling.(8) The potential to recycle surgical waste has previously been estimated at 55% by weight.(94) When surgical materials are recycled into products used in other sectors (such as construction), this reduces the emissions associated with waste disposal, but the benefits associated with reducing the need to obtain virgin materials are usually assigned to the product in which recycled materials are used, in accordance with the recycled content method of carbon allocation.(20) In order for recycling to make a larger impact in the transition to net zero surgery, the recycled content of surgical products themselves would need to increase, which would offset emissions associated with product manufacture. This might start with low-risk products that do not contact non-intact mucous membranes such as aprons.

In order to extend the lifespan and potential number of uses of products in circulation further, products should be actively maintained and repaired. CHAPTER 8 found that repairing surgical scissors reduced the carbon footprint by around one-fifth, with life cycle financial savings of around one-third (compared with purchasing new reusable scissors).(9) Where 'single-use' products are necessary, it is possible to gain an additional use through reprocessing, and carbon reductions have been associated with reprocessing a range of products, compared with using single-use products once.(103, 104) The reductions associated with switching from single-use to reusable products are likely greater than switching single-use products to remanufactured single-use products, with previous LCA research finding that remanufacturing single-use electrophysiology catheters halved the carbon footprint when compared with purchasing new single-use products,(104) whilst the carbon footprint of single-use scissors was estimated at approximately 33 times higher that of reusable equivalents.(91) It is important that the principle of reduce and reuse are prioritised, and the switch to reusable alternatives should be particularly encouraged in settings where single-use equipment is commonly used including emergency department, outpatient and primary care settings.

9.3. Translating findings into practice and policy

To instigate change towards reduction and reuse of products used in the surgical operating theatre will require behaviour change from surgical teams. According to the COM-B model of behaviour change, change in practice (/Behaviour) can only occur when Capability and Opportunity are combined with Motivation.(224) The growing engagement of surgeons in sustainability(85) (motivation) therefore needs to be matched with greater education (capability), guidance, leadership and support (opportunity) in pragmatic actions to reduce environmental harm. This will require leadership from representative surgical bodies, alongside changes in infrastructure and funding, for example to ensure that sterilisation and reuse of equipment is the financially and logistically preferable option. It will also need close collaboration with supporting industries, and a more refined approach to estimating risk of infection from reuse of equipment which in many cases is based upon hypothetical rather than real-world risk.(151)

The demand for greater leadership in this area is supported by a survey which I co-authored, exploring the attitudes and behaviours of UK and Irish surgeons and surgical trainees towards environmental sustainability, and perceived barriers to change.(85) This found that the surgeons who responded to the survey were concerned about climate change and were willing to engage in efforts to transition to more sustainable practices, but would welcome greater support, guidance, and leadership.(85) Respondents reported that their behaviour towards sustainability was greater in their personal lives than the surgical workplace,(85) aligning with findings from a survey conducted by the Sustainable Development Unit.(65) The finding that the majority (82%) of respondents were willing to make changes in their clinical practice is supported by surveys of ophthalmologists in New Zealand,(225) disease control and prevention specialists in China,(226) and anaesthetists in Australia and New Zealand.(203)

The main perceived barrier to sustainability reported in the survey of UK and Irish surgeons was lack of leadership.(85) It is important that healthcare leaders spearhead this challenge, with top-down leadership both at national and local levels, within surgery and across wider healthcare services, and with appropriate governmental support. In the year 2020, NHS England became the first national health system to commit to reach carbon neutrality,(4) with endorsement from the NHS Chief Executive providing top level mandate for action. Since conducting this survey, the Royal College of Surgeons Sustainability in Surgery Strategy has been published,(227) committing to provide guidance to enable individual surgeons to embed sustainability into surgical practice. I am an academic advisor for a national report on Greener Surgery, in collaboration with the UK Health Alliance on Climate Change, and this report will include a strategy for transitioning to sustainable surgical systems.

Regional and bottom- up leadership from individual surgeons is also required, and could be fostered through the development of sustainability champions and networks, supported by platforms for dissemination of best practice. Surgeons have expertise and authority in surgical care provision, and should be ambassadors for change, encouraging, supporting and collaborating with others in the surgical team and colleagues in supporting services.

That may include staff in facilities and estates switching to renewable energy and heating, staff in sterile services increasing capacity or introducing systems for instrument repair and maintenance, and procurement teams integrating environmental sustainability into purchasing decisions. Improving disease prevention and health optimisation will require surgeons to engage with patients, and primary care and public health colleagues.

Many of the required changes outlined relate to use of single-use products, and surgeons must build relationships with industry partners, encouraging surgical product suppliers to streamline single-use sets, to develop reusable and durable alternatives, and to design products which specifically enable repair and recycling. Healthcare supply chains are globalised, and so working with international colleagues will be important in order to apply collective pressure on industry. The recycling potential of products could be increased further through encouraging manufacturers to design products which are modular (can be easily disassembled), with as few different material types as possible, with clear labelling to facilitate waste segregation and recycling. This may be prompted by policies supporting extended producer responsibility, whereby product manufacturers take on increased responsibility for products after the point of sale, including beyond the use by the primary customer.

The journey towards sustainable surgery requires the engagement of each and every surgeon. This starts with raising awareness about the interplay between health and planetary health, and education on how an individual's surgical environmental impact can be mitigated. Anaesthetic colleagues have paved the way in providing such postgraduate education in the UK, with climate change integrated within the anaesthetic core curriculum.(228) The General Medical Council has introduced sustainability into the core undergraduate curriculum,(229) and educating medical students in this area before they enter the workplace will also be important. The Roger's Diffusion of Innovation model predicts that once a critical mass has adopted a particular change in behaviour, the change will become self-sustaining and further adoption becomes inevitable.(230) National and regional bodies are well placed to promote engagement and to facilitate education enabling this.

Such change should of course be supported by evidence. The academic field of sustainable healthcare is in its infancy, signalling a need for investment from those funding research. Environmentally preferable approaches also often cost less, so capturing financial alongside carbon savings may help support the business case for change. Supporting such research will enable the surgical community to take an evidence-based approach to tackling the carbon footprint of surgery, underpinning strategies, and ensuring that action is focused on areas most likely to have largest net benefit. There are a growing number of leading surgical journals and academic conferences recognising the importance of this emerging academic field, and this should be encouraged to enable dissemination of such research to surgical audiences.

Perhaps one of the biggest challenges in moving back towards reusable equipment is concern about transmissible infection, which is often based upon a theoretical rather than proportional assessment of risk.(151) The reliance on single-use rather than reusable medical products to a large extent stems from historical concerns of infection risk. The shift towards single-use equipment arose due to emergence of variant Creutzfeld-Jakob Disease, at a time where sterilisation facilities were varied and lacked standardisation.(231) In many cases the risk of infection is hypothetical or infinitesimal, for example variant Creutzfeld-Jakob Disease was last definitively linked to surgery in the 1970s.(232) Further, sterility assurance standards are robust in the UK,(159) whilst concerns have been raised in relation to sterility of single-use products sterilised by an Italian company.(233) For most instruments and products there is no reason to think a disposable product (which is sterilised following manufacture) carries lower risk of infection than a sterilised reusable product. Where policies favour use of single-use equipment based upon infection risk, the evidence to support this claim should be requested, shifting the burden of proof.

To tackle environmental impact of surgery in a meaningful and sustainable way, action should be supported with appropriate funding and infrastructure. The development and adoption of low carbon healthcare products can be encouraged through fiscal and regulatory mechanisms. For example, the NHS roadmap for supplier alignment stipulates that by 2028 carbon footprints of individual products will be required, although the mechanism is yet to be determined. Other industries beyond healthcare have used the principles of Environmental Product Declarations as specified by ISO 14025:2006,(234) involving the development of Product Category Rules which define the assumptions and method used for a specific category of products, enabling comparison of environmental impacts between products. There are other regulatory mechanisms coming into effect such as the UK Government Social Value Model for commissioning and purchase of NHS goods and services (61) and incorporation of environmental sustainability into NICE guidance,(62) as discussed in CHAPTER 1.

When the financial cost of products are estimated across the full product life span this enables the total cost of ownership to be determined, and the majority of evidence indicates financial costs follow the carbon footprint. For example, financial savings have been demonstrated when switching from single-use to reusable laryngoscopes,(72) CHAPTER 8 demonstrated cost savings associated with repair of reusable surgical scissors,(9) and recycling companies sometimes do not charge for waste removal and processing of items including surgical products.(202) Surgical departments sometimes anecdotally underestimate the financial cost of single-use products, often due to the cost of waste disposal being centrally accounted for within the hospital, whilst the cost of reusables are often overestimated due to difficulties in accurately estimating number of uses of reusable products over their lifespan. Systems must therefore be designed which enable the capture and ringfencing of savings achieved through carbon reductions measures, allowing this money saved to be used where upfront investment is required to support other sustainability initiatives.

9.4. Limitations

Limitations specific to individual studies are outlined in respective chapters, and those associated with different methodological approaches are discussed in CHAPTER 2. There are some overarching limitations to this thesis, limiting extent to which results from studies can be directly compared. The emission factors derived for sterilisation in CHAPTER 6, and for waste in CHAPTER 7 were used to evaluate the carbon footprint of products used across five common operations (CHAPTER 4), and the methodology chosen was consistent between these studies (with the exception of using most up to date versions of emission factor databases at the time of associated publication). However, full LCA approaches were used for detailed studies of three laparoscopic products (CHAPTER 5), and repair of surgical scissors (CHAPTER 8). This limits the extent to which results from CHAPTER 5 and CHAPTER 8 can be compared to studies in other chapters, due to differences in sources of emission factors (for example use of the Ecoinvent version 3.6 rather than the DEFRA/BEIS database for energy consumption). There were also differences in system boundaries, for example, detailed LCAs of individual products in CHAPTER 5 and CHAPTER 8 included injection moulding of plastics and metal working, alongside distribution from manufacture to hospital site, whilst these were omitted from CHAPTER 4 which evaluated products at the scale of whole operations with the aim of identifying hotspot products and processes. There were also differences in the GHGs included within different emission factor databases, but the impact of this was limited through using a consistent database within a given study, and only using alternative sources where a given material or process was not available in the primary database.

Whilst CHAPTER 4 evaluated the carbon footprint of products used in five common operations and identified carbon hotspot processes, subsequent studies evaluated ways to mitigate these. Quantifying the extent to which these strategies might mitigate the carbon footprint for each of the five operations was beyond the scope of this thesis, in part due to methodological differences outlined. Secondly such analysis would be most valuable if this extended beyond strategies identified in this thesis, for example to determine whether an evidence-based low carbon alternative exists for each product used within the five operations (which might include reusables and reprocessed single-use items), alongside analysing the impact of variation in product use between cases. However, this does not detract from validity of findings of individual studies and their ability to help inform strategy for carbon mitigation, and the methods chosen were appropriate for meeting research aims.

9.5. Future research

An evidence-based approach must be used to inform change in policy and practice towards sustainable, net zero surgery. Generating robust research is particularly important due to the nuanced nature of environmental accounting and counterintuitive nature of some findings (such as those demonstrated in CHAPTER 6 in relation to increased carbon footprint associated with streamlining of reusable instrument sets). Carbon footprint and LCA evaluations will always be limited by assumptions made and system boundaries drawn, and the absolute values should be interpreted with caution, and comparison discouraged. However, these methods can be used as a tool to understand factors influencing GHG emissions and environmental impact, such that policies can be designed to help mitigate these.

There are a number of research questions arising directly from this thesis. CHAPTER 4 found a small proportion (23%) of products were responsible for the majority (80%) of the carbon footprint of products used in common operations. When seeking to mitigate carbon footprint within a given procedure it is therefore important to identify the few products that have biggest impact, and to focus mitigation strategies on these (for example through exploring opportunities for elimination or adoption of low carbon alternatives, and where alternatives do not exist, innovation should be encouraged towards this). Building upon my existing dataset, it may be possible develop a tool enabling clinicians to identify carbon hotspot products within a given surgical operation or procedure using simplified metrics based upon key determinants of the carbon footprint (which may include weight, broad material category, and number of uses). This could be used to target mitigation efforts towards carbon hotspot products, maximising impact on reducing GHG emissions.

Surprisingly, CHAPTER 6 found that the carbon footprint of a reusable rigid container (used as a sterile barrier system for reusable instrument sets) was greater than single-use wrap.(7) In this instance the two products are relatively dissimilar in dimensions and weight (despite serving a comparable function), and if a reusable wrap were to be developed with appropriate sterile barrier properties it can be hypothesised that this would have a lower environmental impact, in line with other surgical linens,(93) and formally evaluating this would be an important area for future research. Building upon CHAPTER 7, it would be helpful to evaluate the carbon footprint of disposing different types of materials commonly found within healthcare waste, incorporating direct fossil fuel emissions alongside biogenic emissions, and including landfill in the analysis (not included at the study site in this thesis).

CHAPTER 8 found that strategies for reducing carbon footprint of surgical scissors include increasing the number of uses of reusable products alongside repair. The construct of contracts with instrument suppliers may also incentivise companies to adopt these principles. For example, where surgical products are leased rather than owned by hospitals, and where these are associated with managed service contracts (also known as servitisation), this may nudge companies to design products that are durable and modular by design, and potentially increase incentive to actively maintain and repair rather than replace products where appropriate. The environmental and financial impact of these managed service contracts in the context of healthcare products is an important area of future research.

Wider research questions beyond this thesis include a lack of robust evidence to understand the carbon footprint of surgery (or indeed other clinical specialties, and surgical sub-specialties) in relation to healthcare as a whole. Understanding this would help target resources towards the most carbon intensive specialties, and where specialties hold particularly high GHG emissions, understanding the reasons for this would be helpful in designing strategies to mitigate associated emissions. Whilst this thesis focused on mitigating carbon footprint at the point that surgical care is required, the role that surgical disease prevention, minimising unwarranted variation, and de-adoption of low value care (ensuring carbon burden associated with surgery is necessary rather than avoidable) will play in meeting net zero surgery is an interesting area of future research. Consideration should also be paid to non-surgical alternatives and conservative measures, especially where an operation has limited effectiveness. For diseases with acute courses such as appendicitis, the carbon footprint of medical treatment may be lower than operating (although this has not yet been evaluated). However, whilst surgery is initially resource intensive, it may have a net lower impact on resources when considering the longer term for chronic conditions. For example, Gatenby found that the carbon footprint of surgery for gastro-oesophageal reflux disease is lower than medical treatment after nine years.(25) and more should be done to explore this in other surgical conditions.

There is much heterogeneity in the conduct and reporting of carbon footprinting within healthcare(78) and also methodological concerns arising in relation to some published studies.(148) Whilst carbon footprinting guidelines specific to healthcare do exist,(120) they are predominantly designed for industry reporting rather than academic research. In order to progress this academic field there is a need for an expert consensus statement in relation to the conduct and the reporting of healthcare carbon footprints.

9.6. Conclusion

This thesis presents foundational research in the field of sustainable surgery, including the first systematic review in the field, development of emission factors which are now being used by other researchers to account for reusable instrument sterilisation and healthcare waste, alongside estimation of product level carbon footprints for hundreds of products used in the most common operations. Research within this thesis was also the first to evaluate the carbon footprint impact of switching single-use products to hybrid equivalents, and use of repair in a healthcare context. This research indicates that strategies for mitigating carbon footprint of products used in common operations include (where appropriate), switching single-use products to reusable or hybrid equivalents, optimising sterilisation, using low carbon waste streams, and use of repair. Financial cost savings were associated with these strategies, providing further impetus for change. Given finite resources and adverse health effects of climate change, it is imperative that individual surgeons, policy makers, and all supporting industries transition to sustainable surgical systems, informed by an evidence-based approach.

References

1. Costello A, Abbas M, Allen A, Ball S, Bell S, Bellamy R, et al. Managing the health effects of climate change: Lancet and University College London institute for global health commission. Lancet. 2009;373(9676):1693-733.
2. Health Care Without Harm. Health care's climate footprint: climate-smart health care series green paper number one. [Internet]. 2019; [cited 2022 Apr 5]. Available from: https://noharm-global.org/sites/default/files/documents-files/5961/HealthCaresClimateFootprint_092319.pdf
3. Tennison I, Roschnik S, Ashby B, Boyd R, Hamilton I, Oreszczyn T, et al. Health care's response to climate change: a carbon footprint assessment of the NHS in England. Lancet Planet Health. 2021;5(2):e84-e92.
4. NHS England and NHS Improvement. Delivering a 'Net Zero' National Health Service. [Internet]. 2020; [cited 2022 Apr 5]. Available from: https://www.england.nhs.uk/greenernhs/wp-content/uploads/sites/51/2020/10/delivering-a-net-zero-national-health-service.pdf
5. Rizan C, Steinbach I, Nicholson R, Lillywhite R, Reed M, Bhutta M. The carbon footprint of surgical operations: a systematic review. Ann Surg. 2020;272(6):986-95.
6. Rizan C, Bhutta MF. Environmental impact and life cycle financial cost of hybrid (reusable/single-use) instruments versus single-use equivalents in laparoscopic cholecystectomy. Surg Endosc. 2022;36(6):4067–4078.
7. Rizan C, Lillywhite R, Reed M, Bhutta M. Minimising carbon footprint and financial costs of steam sterilization and packaging reusable surgical instruments. Br J Surg. 2022;109:200-10.
8. Rizan C, Bhutta MF, Reed M, Lillywhite R. The carbon footprint of waste streams in a UK hospital. J Clean Prod. 2021;286:125446.
9. Rizan C, Brophy T, Lillywhite R, Reed M, Bhutta M. Life cycle assessment and life cycle cost of repairing surgical scissors. Int J Life Cycle Assess. 2022;27:780–795.
10. Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, et al. Planetary boundaries: guiding human development on a changing planet. Science. 2015;347(6223):1259855.
11. Crutzen PJ. Geology of mankind. Nature. 2002;415:23.
12. International Panel on Climate Change, Matthews JBR, editor. 'Annex I: Glossary', in Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, Pirani A et al., editors. Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. [Internet]. 2018; [cited 2022 Apr 5]. Available from: https://www.ipcc.ch/sr15/chapter/glossary/
13. International Panel on Climate Change, Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S et al., editors. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. [Internet]. 2021; [cited 2022 Apr 5]. Available from: https://www.ipcc.ch/report/ar6/wg1/#FullReport
14. United Nations. Paris agreement. [Internet]. 2016; [cited 2022 April 5]. Available from: https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27

15. United Nations Climate Change. COP26 the Glasgow climate pact. [Internet]. 2021; [cited 2022 Apr 5]. Available from: https://ukcop26.org/wp-content/uploads/2021/11/COP26-Presidency-Outcomes-The-Climate-Pact.pdf
16. UK Government. Climate change act 2008 (2050 target amendment) order 2019. [Internet]. 2019; [cited 2022 Apr 5]. Available from: https://www.legislation.gov.uk/uksi/2019/1056/contents/made
17. United Nations Environment Programme. The heat is on-a world of climate promises not yet delivered-emissions gap report 2021. [Internet]. 2021; [cited 2022 Apr 5]. Available from: https://www.unep.org/resources/emissions-gap-report-2021
18. International Panel on Climate Change, Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K et al., editors. Climate change 2014: mitigation of climate change-working group III contribution to the fifth assessment report of the intergovernmental panel on climate change. [Internet]. 2021;[cited 2022 Apr 5]. Available from: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_full.pdf
19. United Nations Climate Change. Doha amendment to the Kyoto Protocol. [Internet]. 2012; [cited 2023 Jan 19]. Available from: https://unfccc.int/process/the-kyoto-protocol/the-doha-amendment
20. World Resources Institute. Greenhouse gas protocol, product life cycle accounting and reporting standard. [Internet]. 2011; [cited 2022 May 4]. Available from: https://ghgprotocol.org/product-standard
21. Department for Business Innovation and Skills. PAS 2050:2012 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. [Internet]. 2012. [cited 2022 May 4]. Available from: http://www.bsigroup.com/Standards-and-Publications/How-we-can-help-you/Professional-Standards-Service/PAS-2050
22. International Organization for Standardization. ISO 14067:2018 Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification. [Internet]. 2018; [cited 2023 Jan 17]. Available from: https://www.iso.org/standard/71206.html
23. International Organization for Standardization. ISO 14040:2006 Environmental management-life cycle assessment- principles and framework. [Internet]. 2006; [cited 2022 May 4]. Available from: https://www.iso.org/standard/37456.html
24. Drew J, Christie SD, Rainham D, Rizan C. HealthcareLCA: an open-access living database of health-care environmental impact assessments. Lancet Planet Health. 2022;6(12):E1000-E1012.
25. Gatenby PA. Modelling the carbon footprint of reflux control. Int J Surg. 2011;9(1):72-4.
26. Berner JE, Gras MDP, Troisi L, Chapman T, Vidal P. Measuring the carbon footprint of plastic surgery: a preliminary experience in a Chilean teaching hospital. J Plast Reconstr Aesthet Surg. 2017;70(12):1777-9.
27. Morris DS, Wright T, Somner JE, Connor A. The carbon footprint of cataract surgery. Eye (Lond). 2013;27(4):495-501.
28. MacNeill A, Lillywhite R, Brown C. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. Lancet Planet Health. 2017;1(9):e381-e8.
29. Greenhouse gas protocol. Required greenhouse gases in inventories. [Internet]. 2013; [cited 2023 Jan 11]. Available from: https://ghgprotocol.org/sites/default/files/standards_supporting/Required%20gases%20and%20GWP%20values_0.pdf

30. Woods DL, McAndrew T, Nevadunsky N, Hou JY, Goldberg G, Yi-Shin Kuo D, et al. Carbon footprint of robotically-assisted laparoscopy, laparoscopy and laparotomy: a comparison. Int J Med Robot. 2015;11(4):406-12.
31. Department for Environment, Food and Rural Affairs/ Department for Business, Energy & Industrial Strategy (DEFRA/BEIS). UK Government GHG conversion factors for company reporting. [Internet]. 2021; [cited 2022 Apr 5]. Available from: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021
32. Jones C, Hammond G. Inventory of carbon and energy v3.0. [Internet]. 2019; [cited 2022 May 4]. Available from: https://circularecology.com/embodied-carbon-footprint-database.html
33. Sleeswijk AW, van Oers LF, Guinée JB, Struijs J, Huijbregts MA. Normalisation in product life cycle assessment: an LCA of the global and European economic systems in the year 2000. Sci Total Environ. 2008;390(1):227-40.
34. Romanello M, McGushin A, Di Napoli C, Drummond P, Hughes N, Jamart L, et al. The 2021 report of the Lancet countdown on health and climate change: code red for a healthy future. Lancet. 2021;398(10311):1619-62.
35. Bressler RD. The mortality cost of carbon. Nat Commun. 2021;12(1):4467.
36. World Health Organisation. COP26 special report on climate change and health the health argument for climate change. [Internet]. 2021; [cited 2022 Apr 5]. Available from: https://apps.who.int/iris/handle/10665/346168
37. Asthana S, Gibson A. Averting a public health crisis in England's coastal communities: a call for public health research and policy. J Public Health (Oxf). 2022;44(3):642-650.
38. Shukla JB, Arora MS, Verma M, Misra AK, Takeuchi Y. The impact of sea level rise due to global warming on the coastal population dynamics: a modelling study. Earth Syst Environ. 2021;5:909-26.
39. Oxfam. Confronting carbon inequality- putting climate justice at the heart of the COVID-19 recovery. [Internet]. 2020; [cited 2022 Apr 5]. Available from: https://oxfamilibrary.openrepository.com/bitstream/handle/10546/621052/mb-confronting-carbon-inequality-210920-en.pdf
40. Watts N, Adger WN, Agnolucci P, Blackstock J, Byass P, Cai W, et al. Health and climate change: policy responses to protect public health. Lancet. 2015;386(10006):1861-914.
41. Healthy climate signatories. Healthy climate prescription. [Internet]. 2021; [cited 2022 Apr 5]. Available from: https://healthyclimateletter.net
42. Eckelman MJ, Sherman J. Environmental impacts of the U.S. health care system and effects on public health. PLoS One. 2016;11(6):e0157014.
43. Wu R. The carbon footprint of the Chinese health-care system: an environmentally extended input-output and structural path analysis study. Lancet Planet Health. 2019;3(10):e413-e9.
44. Malik A, Lenzen M, McAlister S, McGain F. The carbon footprint of Australian health care. Lancet Planet Health. 2018;2(1):e27-e35.
45. Varughese S, Ahmed R. Environmental and occupational considerations of anesthesia: a narrative review and update. Anesth Analg. 2021;133(4):826-35.
46. Lenzen M, Malik A, Li M, Fry J, Weisz H, Pichler PP, et al. The environmental footprint of health care: a global assessment. Lancet Planet Health. 2020;4(7):e271-e9.
47. Chung JW, Meltzer DO. Estimate of the carbon footprint of the US health care sector. JAMA. 2009;302(18):1970-2.

48. Sustainable Development Unit. Reducing the use of natural resources in health and social care. [Internet]. 2018. [cited 2022 Apr 5]. Available from: https://networks.sustainablehealthcare.org.uk/sites/default/files/resources/20180912_Health_and_Social_Care_NRF_web.pdf
49. Puckowski A, Mioduszewska K, Łukaszewicz P, Borecka M, Caban M, Maszkowska J, et al. Bioaccumulation and analytics of pharmaceutical residues in the environment: a review. J Pharm Biomed Anal. 2016;127:232-55.
50. Grand View Research. Medical plastics market size, share & trends analysis report by application (medical device packaging, medical components, orthopedic implant packaging), and segment forecasts, 2019–2025. [Internet]. 2021; [cited 2022 Apr 5]. Available from: https://www.grandviewresearch.com/industry-analysis/medical-plastics-market
51. Thompson RC, Moore CJ, vom Saal FS, Swan SH. Plastics, the environment and human health: current consensus and future trends. Philos Trans R Soc Lond B Biol Sci. 2009;364(1526):2153-66.
52. Barnes DK, Galgani F, Thompson RC, Barlaz M. Accumulation and fragmentation of plastic debris in global environments. Philos Trans R Soc Lond B Biol Sci. 2009;364(1526):1985-98.
53. United Nations. Sustainable Development Goals. [Internet]. 2015; [cited 2022 Apr 5]. Available from: https://sdgs.un.org/goals
54. Raworth K. Doughnut economics: seven ways to think like a 21st-century economist. London: Penguin Random House; 2017.
55. Tseng ML, Chang CH, Lin CR, Wu KJ, Chen Q, Xia L, et al. Future trends and guidance for the triple bottom line and sustainability: a data driven bibliometric analysis. Environ Sci Pollut Res Int. 2020;27(27):33543-67.
56. Trueba ML, Bhutta MF, Shahvisi A. Instruments of health and harm: how the procurement of healthcare goods contributes to global health inequality. J Med Ethics. 2020;47(6):423-29.
57. Mortimer F, Isherwood J, Wilkinson A, Vaux E. Sustainability in quality improvement: redefining value. Future Healthc J. 2018;5(2):88-93.
58. NHS. The NHS long term plan. [Internet]. 2019. [cited 2022 Apr 5]. Available from: https://www.longtermplan.nhs.uk/wp-content/uploads/2019/08/nhs-long-term-plan-version-1.2.pdf
59. World Health Organisation. COP26 health programme country commitments. [Internet]. 2021; [cited 2022 Apr 5]. Available from: https://www.who.int/initiatives/cop26-health-programme/country-commitments
60. Greener NHS. Suppliers. [Internet]. 2021; [cited 2022 Apr 5]. Available from: https://www.england.nhs.uk/greenernhs/get-involved/suppliers/
61. NHS England. Applying net zero and social value in the procurement of NHS goods and services. [Internet]. 2022; [cited 2022 Apr 5]. Available from: https://www.england.nhs.uk/greenernhs/wp-content/uploads/sites/51/2022/03/B1030-applying-net-zero-and-social-value-in-the-procurement-of-NHS-goods-and-services-march-2022.pdf
62. National Institute for Health and Care Excellence. Sustainability. [Internet]. 2021; [cited 2022 Apr 5]. Available from: https://www.nice.org.uk/about/who-we-are/sustainability
63. UK Health Alliance on Climate Change. Members. [Internet]. 2022; [cited 2022 Apr 5]. Available from: http://www.ukhealthalliance.org/members/
64. Greener NHS. How to produce a green plan: a three-year strategy towards net zero. [Internet]. 2021; [cited 2022 Apr 5]. Available from: https://www.england.nhs.uk/greenernhs/wp-

content/uploads/sites/51/2021/06/B0507-how-to-produce-a-green-plan-three-year-strategy-towards-net-zero-june-2021.pdf
65. Enventure Research. NHS sustainable development unit study. [Internet]. 2017; [cited 2022 April 6]. Available from: https://www.england.nhs.uk/greenernhs/wp-content/uploads/sites/51/2021/02/Sustainability-and-the-NHS-Staff-survey-2017.pdf
66. Sherman JD, Thiel C, MacNeill A, Eckelman MJ, Dubrow R, Hopf H, et al. The green print: advancement of environmental sustainability in healthcare. Resour Conserv Recycl. 2020;161:104882.
67. Connor A, Lillywhite R, Cooke MW. The carbon footprints of home and in-center maintenance hemodialysis in the United Kingdom. Hemodial Int. 2011;15(1):39-51.
68. Duane B, Borglin L, Pekarski S, Saget S, Duncan HF. Environmental sustainability in endodontics. A life cycle assessment (LCA) of a root canal treatment procedure. BMC Oral Health. 2020;20(1):348.
69. Thiel CL, Eckelman M, Guido R, Huddleston M, Landis AE, Sherman J, et al. Environmental impacts of surgical procedures: life cycle assessment of hysterectomy in the United States. Environ Sci Technol. 2015;49(3):1779-86.
70. McGain F, Burnham JP, Lau R, Aye L, Kollef MH, McAlister S. The carbon footprint of treating patients with septic shock in the intensive care unit. Crit Care Resusc. 2018;20(4):304-12.
71. Martin M, Mohnke A, Lewis GM, Dunnick NR, Keoleian G, Maturen KE. Environmental impacts of abdominal imaging: a pilot investigation. J Am Coll Radiol. 2018;15(10):1385-93.
72. Sherman JD, Raibley LA, Eckelman MJ. Life cycle assessment and costing methods for device procurement: comparing reusable and single-use disposable laryngoscopes. Anesth Analg. 2018;127(2):434-43.
73. Parvatker AG, Tunceroglu H, Sherman JD, Coish P, Anastas P, Zimmerman JB, et al. Cradle-to-gate greenhouse gas emissions for twenty anesthetic active pharmaceutical ingredients based on process scale-up and process design calculations. ACS Sustain Chem Eng. 2019;7(7):6580-91.
74. Weiser TG, Haynes AB, Molina G, Lipsitz SR, Esquivel MM, Uribe-Leitz T, et al. Estimate of the global volume of surgery in 2012: an assessment supporting improved health outcomes. Lancet. 2015;385:Suppl 2:S11.
75. COVIDSurg Collaborative. Projecting COVID-19 disruption to elective surgery. Lancet. 2022;399(10321):233-4.
76. Abbott TEF, Fowler AJ, Dobbs TD, Harrison EM, Gillies MA, Pearse RM. Frequency of surgical treatment and related hospital procedures in the UK: a national ecological study using hospital episode statistics. Br J Anaesth. 2017;119(2):249-57.
77. Lee BK, Ellenbecker MJ, Moure-Eraso R. Analyses of the recycling potential of medical plastic wastes. Waste Manag. 2002;22(5):461-70.
78. Drew J, Christie SD, Tyedmers P, Smith-Forrester J, Rainham D. Operating in a climate crisis: a state-of-the-science review of life cycle assessment within surgical and anesthetic care. Environ Health Perspect. 2021;129(7):76001.
79. Thiel CL, Schehlein E, Ravilla T, Ravindran RD, Robin AL, Saeedi OJ, et al. Cataract surgery and environmental sustainability: waste and lifecycle assessment of phacoemulsification at a private healthcare facility. J Cataract Refract Surg. 2017;43(11):1391-8.

80. McGain F, Sheridan N, Wickramarachchi K, Yates S, Chan B, McAlister S. Carbon footprint of general, regional, and combined anesthesia for total knee replacements. Anesthesiology. 2021;135(6):976-91.
81. White SM, Shelton CL, Gelb AW, Lawson C, McGain F, Muret J, et al. Principles of environmentally-sustainable anaesthesia: a global consensus statement from the World Federation of Societies of Anaesthesiologists. Anaesthesia. 2022;77(2):201-12.
82. Rizan C, Mortimer F, Stancliffe R, Bhutta MF. Plastics in healthcare: time for a re-evaluation. J R Soc Med. 2020;113(2):49-53.
83. Sustainable Development Unit. Identifying high greenhouse gas intensity procured items for the NHS in England. [Internet]. 2017; [cited 2022 Apr 13]. Available from: https://www.endsreport.com/article/1529061/nhs-sustainable-development-unit-guidance-identifying-high-greenhouse-gas-intensity-procured-items-nhs-england
84. Grand View Research. Surgical equipment market worth $24.5 billion by 2028 | CAGR: 9.8%. [Internet]. 2021; [cited 2022 Apr 13]. Available from: https://www.grandviewresearch.com/press-release/global-surgical-equipment-market
85. Harris H, Bhutta MF, Rizan C. A survey of UK and Irish surgeons' attitudes, behaviours and barriers to change for environmental sustainability. Ann R Coll Surg Engl. 2021;103(10):725-9.
86. Rizan C, Bhutta MF. Strategy for net-zero carbon surgery. Br J Surg. 2021;108(7):737-9.
87. Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ. The circular economy – a new sustainability paradigm? J Clean Prod. 2017;143:757-68.
88. Rizan C, Reed M, Bhutta MF. Environmental impact of personal protective equipment distributed for use by health and social care services in England in the first six months of the COVID-19 pandemic. J R Soc Med. 2021;114(5):250-63.
89. Webster J, Radke E, George N, Faoagali J, Harris M. Barrier properties and cost implications of a single versus a double wrap for storing sterile instrument packs. Am J Infect Control. 2005;33(6):348-52.
90. Penn E, Yasso SF, Wei JL. Reducing disposable equipment waste for tonsillectomy and adenotonsillectomy cases. Otolaryngol Head Neck Surg. 2012;147(4):615-8.
91. Ibbotson S, Dettmer T, Kara S, Herrmann C. Eco-efficiency of disposable and reusable surgical instruments- a scissors case. Int J Life Cycle Assess. 2013;18:1137-48.
92. Eckelman M, Mosher M, Gonzalez A, Sherman J. Comparative life cycle assessment of disposable and reusable laryngeal mask airways. Anesth Analg. 2012;114(5):1067-72.
93. Overcash M. A comparison of reusable and disposable perioperative textiles: sustainability state-of-the-art 2012. Anesth Analg. 2012;114(5):1055-66.
94. Kummerer K, Dettenkofer M, Scherrer M. Comparison of reusable and disposable laparotomy pads. Int J Life Cycle Assess. 1996;1(2):67-73.
95. Leiden A, Cerdas F, Noriega D, Beyerlein J, Herrmann C. Life cycle assessment of a disposable and a reusable surgery instrument set for spinal fusion surgeries. Resour Conserv Recycl. 2020;156:104704.
96. Davis NF, McGrath S, Quinlan M, Jack G, Lawrentschuk N, Bolton DM. Carbon footprint in flexible ureteroscopy: a comparative study on the environmental impact of reusable and single-use ureteroscopes. J Endourol. 2018;32(3):214-7.

97. McGain F, McAlister S, McGavin A, Story D. A life cycle assessment of reusable and single-use central venous catheter insertion kits. Anesth Analg. 2012;114(5):1073-80.
98. McGain F, Story D, Lim T, McAlister S. Financial and environmental costs of reusable and single-use anaesthetic equipment. Br J Anaesth. 2017;118(6):862-9.
99. Haddad D, Worst JG. The maintenance and repair of ophthalmic surgical instruments: training at the eye clinic. Community Eye Health. 2002;15(44):60-1.
100. Munakomi S, Shah R, Shrestha S. A pilot study comparing pattern of damage sustained among instruments from different surgical units in a tertiary care centre in Nepal - reappraising the role of instrument reprocessing in retaining their value. F1000Res. 2018;7:102.
101. Bovea MD, Ibáñez-Forés V, Pérez-Belis V. Repair vs. replacement: selection of the best end-of-life scenario for small household electric and electronic equipment based on life cycle assessment. J Environ Manage. 2020;254:109679.
102. Wursthorn S, Feifel S, Walk W, Patyk A. An environmental comparison of repair versus replacement in vehicle maintenance. Transportation Research Part D: Transport and Environment. 2010;15(6):356-61.
103. Unger S, Landis A. Assessing the environmental, human health, and economic impacts of reprocessed medical devices in a Phoenix hospital's supply chain. J Clean Prod. 2016;112:1995-2003.
104. Schulte A, Maga D, Thonemann N. Combining life cycle assessment and circularity assessment to analyze environmental impacts of the medical remanufacturing of electrophysiology catheters. Sustainability. 2021;13(2):898.
105. McGain F, Jarosz KM, Nguyen MN, Bates S, O'Shea CJ. Auditing operating room recycling: a management case report. A A Case Rep. 2015;5(3):47-50.
106. van Straten B, Dankelman J, van der Eijk A, Horeman T. A circular healthcare economy; a feasibility study to reduce surgical stainless steel waste. Sustain Prod Consum. 2021;27:169-75.
107. Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess. 2017;22(2):138-47.
108. Department for Environment, Food and Rural Affairs. Methods review to support the PAS for the calculation of the embodied greenhouse gas emissions of goods and services. [Internet]. 2008; [cited 2022 May 4]. Available from: http://randd.defra.gov.uk/Document.aspx?Document=EV02074_7071_FRP.pdf
109. Berners-Lee M, Howard DC, Moss J, Kaivanto K, Scott WA. Greenhouse gas footprinting for small businesses-the use of input-output data. Sci Total Environ. 2011;409(5):883-91.
110. Kennelly C, Berners-Lee M, Hewitt C. Hybrid life-cycle assessment for robust, best-practice carbon accounting. J Clean Prod. 2019;208:35-43.
111. World Resources Institute. Technical guidance for calculating scope 3 emissions. Greenhouse Gas Protocol. [Internet]. 2013; [cited 2022 May 4]. Available from: https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf
112. Campion N, Thiel CL, DeBlois J, Woods NC, Landis AE, Bilec MM. Life cycle assessment perspectives on delivering an infant in the US. Sci Total Environ. 2012;425:191-8.
113. Pomponi F, Lenzen M. Hybrid life cycle assessment (LCA) will likely yield more accurate results than process-based LCA. J Clean Prod. 2018;176:210-5.

114. PRé Sustainability. SimaPro v9.10 [Software]. 2020; [cited 2022 May 4]. Available from: https://simapro.com
115. Small World Consulting. Carbon factors dataset version 5.3. [Database]. 2021. Available via direct request
116. Department for Environment, Food and Rural Affairs/ Department for Business, Energy & Industrial Strategy (DEFRA/BEIS). UK Government GHG conversion factors for company reporting. [Internet]. 2019. [cited 2022 May 4]. Available from: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019
117. Small World Consulting. Carbon factors dataset version 1.5. [Database]. 2018. Available via direct request.
118. Entreprises pour l'Environnement Working Group. Protocol for the quantification of GHG emissions from waste management activities database. [Internet]. 2013. [cited 2022 Jul 19]. Available from: https://ghgprotocol.org/sites/default/files/Waste%20Sector%20GHG%20Protocol_Version%205_October%202013_1_0.pdf
119. International Organization for Standardization. ISO 14044:2006 Environmental management- life cycle assessment- requirements and guidelines. [Internet]. 2006. [cited 2022 May 4]. Available from: https://www.iso.org/standard/38498.html
120. Environmental Resources Management. Greenhouse gas accounting sector guidance for pharmaceutical products and medical devices. [Internet]. 2012. [cited 2022 May 4]. Available from: https://ghgprotocol.org/sites/default/files/Summary-Document_Pharmaceutical-Product-and-Medical-Device-GHG-Accounting_November-2012_0.pdf
121. Pier2Pier. Pier2Pier. [Internet]. 2022; [cited 2022 May 4]. Available from: http://www.pier2pier.com/Co2/
122. Google. Google maps. [Internet]. 2022; [cited 2022 May 4]. Available from: https://www.google.co.uk/maps
123. Heijungs R. On the number of Monte Carlo runs in comparative probabilistic LCA. Int J Life Cycle Assess. 2020;25:394-402.
124. NHS Digital. Estates return information collection (ERIC) for 2019/20. [Internet]. 2020; [cited 2022 Apr 6]. Available from: https://digital.nhs.uk/data-and-information/publications/statistical/estates-returns-information-collection
125. Kagoma Y, Stall N, Rubinstein E, Naudie D. People, planet and profits: the case for greening operating rooms. CMAJ. 2012;184(17):1905-11.
126. Guetter CR, Williams BJ, Slama E, Arrington A, Henry MC, Möller MG, et al. Greening the operating room. Am J Surg. 2018;216(4):683-688.
127. Kwakye G, Brat GA, Makary MA. Green surgical practices for health care. Arch Surg. 2011;146(2):131-6.
128. Moher D, Liberati A, Tetzlaff J, et al. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ. 2009;339:b2535.
129. Young JM, Solomon MJ. How to critically appraise an article. Nat Clin Pract Gastroenterol Hepatol. 2009;6(2):82-91.
130. Greenhalgh T. How to read a paper - the basics of evidence-based medicine. 5th ed. West Sussex: Wiley Blackwell; 2014.
131. Power NE, Silberstein JL, Ghoneim TP, Guillonneau B, Touijer KA. Environmental impact of minimally invasive surgery in the United States: an estimate of the carbon dioxide footprint. J Endourol. 2012;26(12):1639-44.
132. Somner JE, Stone N, Koukkoulli A, Scott KM, Field AR, Zygmunt J. Surgical scrubbing: can we clean up our carbon footprints by washing our hands? J Hosp Infect. 2008;70(3):212-5.

133. Unger SR, Hottle TA, Hobbs SR, Thiel CL, Campion N, Bilec MM, et al. Do single-use medical devices containing biopolymers reduce the environmental impacts of surgical procedures compared with their plastic equivalents? J Health Serv Res Policy. 2017;22(4):218-25.
134. Thiel CL, Woods NC, Bilec MM. Strategies to reduce greenhouse gas emissions from laparoscopic surgery. Am J Public Health. 2018;108(S2):S158-S64.
135. Ison E, Miller A. The use of LCA to introduce life-cycle thinking into decision-making for the purchase of medical devices in the NHS. J Environ Assess Policy Manag. 2000;2(4):453–76.
136. McDowell J. J&J study: an environmental, economic, and health comparison of single-use and reusable drapes and gowns. Asepsis. 1993;13:1-15.
137. Sherman J, Ryan S. Ecological responsibility in anesthesia practice. Int Anesthesiol Clin. 2010;48(3):139-51.
138. Cotton RT, Cohen AP. Eco-conservation and healthcare ethics: a call to action. Laryngoscope. 2010;120(1):4-8.
139. Ferrero A, Thouvenin R, Hoogewoud F, Marcireau I, Offret O, Louison P, et al. The carbon footprint of cataract surgery in a French university hospital. J Fr Ophtalmol. 2022;45(1):57-64.
140. Latta M, Shaw C, Gale J. The carbon footprint of cataract surgery in Wellington. N Z Med J. 2021;134(1541):13-21.
141. Grinberg D, Buzzi R, Pozzi M, Schweizer R, Capsal JF, Thinot B, et al. Eco-audit of conventional heart surgery procedures. Eur J Cardiothorac Surg. 2021;60(6):1325-31.
142. Hubert J, Gonzalez-Ciccarelli LF, Wang AW, Toledo E, Ferrufino R, Smalls K, et al. Carbon emissions during elective coronary artery bypass surgery, a single center experience. J Clin Anesth. 2022;80:110850.
143. Zhang D, Dyer GSM, Blazar P, Earp BE. The environmental impact of open versus endoscopic carpal tunnel release. J Hand Surg Am. 2022. S0363-5023(21)00791-7.
144. Talibi SS, Scott T, Hussain RA. The environmental footprint of neurosurgery operations: an assessment of waste streams and the carbon footprint. Int J Environ Res Public Health. 2022;19(10):5995.
145. Lyons R, Newell A, Ghadimi P, Papakostas N. Environmental impacts of conventional and additive manufacturing for the production of Ti-6Al-4V knee implant: a life cycle approach. Int J Adv Manuf Technol. 2021;112(3):787-801.
146. Hogan D, Rauf H, Kinnear N, Hennessey DB. The carbon footprint of single-use flexible cystoscopes compared with reusable cystoscopes. J Endourol. 2022;36(11):1460-1464.
147. Olympus. A ‘360 degree approach’ to endoscope reprocessing. [Internet]. 2015; [cited 2022 Jul 6]. Available from: https://www.clinicalservicesjournal.com/story/13791/a-360-degree-approach-to-endoscope-reprocessing
148. Rizan C, Bhutta MF. Re: The carbon footprint of single-use flexible cystoscopes compared to reusable cystoscopes. Methodological flaws led to the erroneous conclusion that single-use is "better". J Endourol. 2022;36(11):1466-1467.
149. Sørensen BL, Grüttner H. Comparative study on environmental impacts of reusable and single-use bronchoscopes. Am J Environ Prot. 2018;7(4):55-62.
150. NHS Institute for Innovation and Improvement. Improving quality and efficiency in the operating theatre. [Internet]. 2009; [cited 2022 May 26]. Available from: https://alesi-surgical.com/wp-content/uploads/2019/09/Improving-quality-and-efficiency-in-the-operating-theatre.pdf

151. Bhutta MF. Our over-reliance on single-use equipment in the operating theatre is misguided, irrational and harming our planet. Ann R Coll Surg Engl. 2021;103(10):709-12.
152. NHS Digital. Hospital admitted patient care activity, 2017-18. [Internet]. 2018; [cited 2022 May 26]. Available from: https://digital.nhs.uk/data-and-information/publications/statistical/hospital-admitted-patient-care-activity/2017-18
153. Royal College of Surgeons of England. Surgical specialties. [Internet]. 2022; [cited 2022 Jun 1]. Available from: https://www.rcseng.ac.uk/careers-in-surgery/trainees/foundation-and-core-trainees/surgical-specialties/
154. Vozzola E, Overcash M, Griffing E. Environmental considerations in the selection of isolation gowns: a life cycle assessment of reusable and disposable alternatives. Am J Infect Control. 2018;46(8):881-6.
155. Carre A. Life cycle assessment comparing laundered surgical gowns with polypropylene based disposable gowns. Melbourne: RMIT University; 2008. Available via direct request
156. European Textile Services Association. Assessment of global warming potential of two textile services. [Internet]. 2015; [cited 2022 May 26]. Available from: https://www.textile-services.eu/_common/file.cfm?id=A5A9D86A0F277C305D65E31143BB5470
157. McGain F, Moore G, Black J. Steam sterilisation's energy and water footprint. Aust Health Rev. 2016;41:26-32.
158. Koch R. The 80/20 principle - the secret to achieving more with less. 4th ed. London: Nicholas Brealey Publishing; 2022.
159. Department of Health. Health technical memorandum (HTM) 01-01 on the management and decontamination of surgical instruments (medical devices) used in acute care. [Internet]. 2013; [cited 2022 May 26]. Available from: https://www.england.nhs.uk/estates/health-technical-memoranda/
160. Bravo D, Thiel C, Bello R, Moses A, Paksima N, Melamed E. What a waste! The impact of unused surgical supplies in hand surgery and how we can improve. Hand (N Y). Epub 2022; 15589447221084011. doi.org/10.1177/15589447221084011.
161. Siu J, Hill AG, MacCormick AD. Systematic review of reusable versus disposable laparoscopic instruments: costs and safety. ANZ J Surg. 2017;87(1-2):28-33.
162. Adler S, Scherrer M, Rückauer KD, Daschner FD. Comparison of economic and environmental impacts between disposable and reusable instruments used for laparoscopic cholecystectomy. Surg Endosc. 2005;19(2):268-72.
163. Agha R, Muir G. Does laparoscopic surgery spell the end of the open surgeon? J R Soc Med. 2003;96(11):544-6.
164. iData Research. Laparoscopic devices market analysis, size, trends. [Internet]. 2020; [cited 2022 Jun 1]. Available from: https://idataresearch.com/product/laparoscopic-devices-market/
165. Comitalo JB. Laparoscopic cholecystectomy and newer techniques of gallbladder removal. JSLS. 2012;16(3):406-12.
166. NHS Supply Chain. Minimally invasive surgery FAG16308 -01.02.17 -31.01.21. [Internet]. 2017 [cited 27 Jan 2021]. Available from: https://www.supplychain.nhs.uk/product-information/contract-launch-brief/minimally-invasive-surgery/
167. NHS Digital. Hospital admitted patient care activity, 2019-20. [Internet]. 2020; [cited 2022 Jun 1]. Available from: https://digital.nhs.uk/data-and-

information/publications/statistical/hospital-admitted-patient-care-activity/2019-20
168. Boberg L, Singh J, Montgomery A, Bentzer P. Environmental impact of single-use, reusable, and mixed trocar systems used for laparoscopic cholecystectomies. PLoS One. 2022;17(7):e0271601.
169. World Health Organisation. Decontamination and reprocessing of medical devices for health-care facilities. [Internet]. 2016; [cited 2022 Jun 28]. Available from: https://www.who.int/infection-prevention/publications/decontamination/en/
170. International Standards Organisation. ISO 11607-1:2019 Packaging for terminally sterilized medical devices - part 1: requirements for materials, sterile barrier systems and packaging systems. [Internet]. 2019; [cited 2022 Jun 28]. Available from: https://www.iso.org/obp/ui/#iso:std:iso:11607:-1:dis:ed-2:v1:en
171. Farrelly JS, Clemons C, Witkins S, Hall W, Christison-Lagay ER, Ozgediz DE, et al. Surgical tray optimization as a simple means to decrease perioperative costs. J Surg Res. 2017;220:320-6.
172. Nast K, Swords KA. Decreasing operating room costs via reduction of surgical instruments. J Pediatr Urol. 2019;15(2):153.e1-.e6.
173. Crosby L, Lortie E, Rotenberg B, Sowerby L. Surgical instrument optimization to reduce instrument processing and operating room setup time. Otolaryngol Head Neck Surg. 2020;162(2):215-9.
174. Chin CJ, Sowerby LJ, John-Baptiste A, Rotenberg BW. Reducing otolaryngology surgical inefficiency via assessment of tray redundancy. Otolaryngol Head Neck Surg. 2014;43(1):46.
175. Gan Y, El-Houjeiri HM, Badahdah A, Lu Z, Cai H, Przesmitzki S, et al. Carbon footprint of global natural gas supplies to China. Nat Commun. 2020;11(1):824.
176. UK Government Department for Business, Energy and Industrial Srategy. Electricity generation costs 2020. [Internet]. 2020; [cited 2022 Jun 28]. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/911817/electricity-generation-cost-report-2020.pdf
177. Weiss A, Hollandsworth HM, Alseidi A, Scovel L, French C, Derrick EL, et al. Environmentalism in surgical practice. Curr Probl Surg. 2016;53(4):165-205.
178. Fowler AL, Kane EG, Nally D. Operation transformation. Surgeon's News. March 2020:41-4.
179. North EJ, Halden RU. Plastics and environmental health: the road ahead. Rev Environ Health. 2013;28(1):1-8.
180. Friedericy HJ, van Egmond CW, Vogtländer JG, van der Eijk AC, Jansen FW. 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. 2022;14(1):430.
181. Association of Surgical Technologists. AST Standards of practice for packaging material and preparing items for sterilization. [Internet]. 2009. [cited 2022 Jun 28]. Available from: https://www.ast.org/uploadedFiles/Main_Site/Content/About_Us/Standard_Packaging_Materials_Preparing_Items.pdf
182. Royal Cornwall Hospitals NHS Trust. Recycling unit answers the covid mask mountain problem. [Internet]. 2021; [cited 2021 Jul 16]. Available from: https://www.royalcornwall.nhs.uk/recycling-unit-answers-the-covid-mask-mountain-problem/
183. McGain F, Moore G, Black J. Hospital steam sterilizer usage: could we switch off to save electricity and water? J Health Serv Res Policy. 2016;21(3)166-71.

184. Centers for Disease Control and Prevention. Flash sterilization. [Internet]. 2008; [cited 2022 Jun 28]. Available from: https://www.cdc.gov/infectioncontrol/guidelines/disinfection/sterilization/flash.html
185. Shintani H. Ethylene oxide gas sterilization of medical devices. Biocontrol Science. 2017;22(1):1-16.
186. NHS Digital. Estates return information collection (ERIC) for 2020/2021. [Internet]. 2021; [cited 2022 Jul 19]. Available from: https://digital.nhs.uk/data-and-information/publications/statistical/estates-returns-information-collection/england-2020-21
187. Department of Health. Environment and sustainability health technical memorandum 07-01: safe management of healthcare waste. [Internet]. 2013; [cited 2022 Jul 19]. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data /file/167976/HTM_07-01Final.pdf
188. Department for Environment Food and Public Affairs. Incineration of municipal solid waste. [Internet]. 2013; [cited 2022 Jul 19]. Available from: https://www.gov.uk/government/publications/incineration-of-municipal-solid-waste
189. NHS Digital. Estates return information collection (ERIC) for 2016/17. [Internet]. 2017. [cited 2022 Jul 19]. https://digital.nhs.uk/data-and-information/publications/statistical/estates-returns-information-collection
190. Chen M, Zhou R, Du C, Meng F, Wang Y, Wu L, et al. The carbon footprints of home and in-center peritoneal dialysis in China. Int Urol Nephrol. 2019;49(2):337-43.
191. Connor A, Lillywhite R, Cooke MW. The carbon footprint of a renal service in the United Kingdom. QJM. 2010;103(12):965-75.
192. Lim AE, Perkins A, Agar JW. The carbon footprint of an Australian satellite haemodialysis unit. Aust Health Rev. 2013;37(3):369-74.
193. Duane B, Hyland J, Rowan JS, Archibald B. Taking a bite out of Scotland's dental carbon emissions in the transition to a low carbon future. Public health. 2012;126(9):770-7.
194. McPherson B, Sharip M, Grimmond T. The impact on life cycle carbon footprint of converting from disposable to reusable sharps containers in a large US hospital geographically distant from manufacturing and processing facilities. PeerJ. 2019;7:e6204.
195. UK Government. Get vehicle information from DVLA. [Internet]. 2019. [cited 2019 Dec 27]. Available from: https://www.gov.uk/get-vehicle-information-from-dvla
196. European Environment Agency. EMEP/EEA air pollution emission inventory guidebook 2019- Clinical waste incineration. [Internet]. 2019. [cited 2022 Jul 19]. Available from: https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/5-waste/5-c-1-b-iii
197. Zhao W, van der Voet E, Huppes G, Zhang Y. Comparative life cycle assessments of incineration and non-incineration treatments for medical waste. Int J Life Cycle Assess. 2009;14:114-21.
198. Golder. Waste and resources assessment tool for the environment (WRATE) database version 4. [Internet]. 2017; [cited 2022 Jul 19]. Available from: http://www.wrate.co.uk
199. UK Tradebe. UK corporate sustainability report. [Internet]. 2016. [cited 2022 Jul 19]. Available from: https://www.tradebe.co.uk/csr-reports-0

200. United States Environmental Protection Agency. Assessment of the potential costs, benefits, & other impacts of the hazardous waste combustion MACT standards: final rule. [Internet]. 1999; [cited 2022 Jul 19]. Available from: https://archive.epa.gov/epawaste/hazard/tsd/td/web/pdf/combust.pdf
201. Stall NM, Kagoma YM, Bondy JN, Naudie D. Surgical waste audit of 5 total knee arthroplasties. Can J Surg. 2013;56(2):97-102.
202. McGain F, Clark M, Williams T, Wardlaw T. Recycling plastics from the operating suite. Anaesth Intensive Care. 2008;36(6):913-4.
203. McGain F, White S, Mossenson S, Kayak E, Story D. A survey of anesthesiologists' views of operating room recycling. Anesth Analg. 2012;114(5):1049-54.
204. McGain F, Hendel SA, Story DA. An audit of potentially recyclable waste from anaesthetic practice. Anaesth Intensive Care. 2009;37(5):820-3.
205. Royal College of Physicians. Less waste, more health: a health professional's guide to reducing waste. [Internet]. 2017; [cited 2022 Apr 13]. Available from: https://www.rcplondon.ac.uk/projects/outputs/less-waste-more-health-health-professionals-guide-reducing-waste
206. Hong J, Zhan S, Yu Z, Hong J, Qi C. Life-cycle environmental and economic assessment of medical waste treatment. J Clean Prod. 2017;174:65-73.
207. Ahmad R, Liu G, Santagata R, Casazza M, Xue J, Khan K, et al. LCA of hospital solid waste treatment alternatives in a developing country: the case of District Swat, Pakistan. Sustainability. 2019;11(13):3501.
208. Beylot A, Villeneuve J. Environmental impacts of residual municipal solid waste incineration: a comparison of 110 French incinerators using a life cycle approach. Waste Manag. 2013;33(12):2781-8.
209. Dominguez ED, Rocos B. Patient safety incidents caused by poor quality surgical instruments. Cureus. 2019;11(6):e4877.
210. Medicines and Healthcare products Regulatory Agency. Managing medical devices. [Internet]. 2021. [cited 2022 Jul 27]. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/965010/Managing_medical_devices022021.pdf
211. Working Group Instrument Reprocessing. Instrument reprocessing, reprocessing of instruments to retain value. [Internet]. 2017; [cited 2022 July 27]. Available from: https://www.hse.ie/eng/about/who/qid/nationalsafetyprogrammes/decontamination/looking-after-your-instruments.pdf
212. Allied Market Research. Surgical scissors market by type (reusable surgical scissors and disposable surgical scissors), application (orthopedics, cardiology, neurology, oral and throat, gastroenterology, dermatology, and others), and end user (hospitals, ambulatory surgical centers, and others): global opportunity analysis and industry forecast, 2019–2027. [Internet]. 2020; [cited 2022 Jul 19]. Available from: https://www.alliedmarketresearch.com/surgical-scissors-market
213. Yoshikawa T, Kimura E, Akama E, Nakao H, Yorozuya T, Ishihara K. Prediction of the service life of surgical instruments from the surgical instrument management system log using radio frequency identification. BMC Health Serv Res. 2019;19(1):695.
214. Fitzgerald E, Bhutta M. Tooling up. Bull R Coll Surg Engl. 2018;100(6):269-70.
215. Lindberg M, Skytt B, Lindberg M. Continued wearing of gloves: a risk behaviour in patient care. Infect Prev Pract. 2020;2(4):100091.
216. Purohit A, Smith J, Hibble A. Does telemedicine reduce the carbon footprint of healthcare? A systematic review. Future Healthc J. 2021;8(1):e85-e91.

217. Mason SE, Nicolay CR, Darzi A. The use of lean and six sigma methodologies in surgery: a systematic review. Surg, J R C Surg E. 2015;13(2):91-100.
218. Academy of Medical Royal Colleges. Protecting resources, promoting value: a doctor's guide to cutting waste in clinical care. [Internet]. 2014; [cited 2022 Aug 11] Available from: https://www.aomrc.org.uk/wp-content/uploads/2016/05/Protecting_Resources_Promoting_Value_1114.pdf
219. Academy of Medical Royal Colleges. Evidence-based interventions engagement document. [Internet]. 2020. [cited 2022 Aug 11]. Available from: https://www.aomrc.org.uk/reports-guidance/evidence-based-interventions-engagement-document/
220. Steyn A, Cassels-Brown A, Chang DF, Faal H, Vedanthan R, Venkatesh R, et al. Frugal innovation for global surgery: leveraging lessons from low- and middle-income countries to optimise resource use and promote value-based care. Bull R Coll Surg Eng. 2020;102(5):198-200.
221. Junaid M, Hashmi MZ, Malik RN. Evaluating levels and health risk of heavy metals in exposed workers from surgical instrument manufacturing industries of Sialkot, Pakistan. Environ Sci Pollut Res Int. 2016;23(18):18010-26.
222. Bhutta MF. Fair trade for surgical instruments. BMJ. 2006;333(7562):297-9.
223. Swedwatch. Healthier procurement improvements to working conditions for surgical instrument manufacture in Pakistan report #73. [Internet]. 2015; [cited 2022 Aug 11] Available from: https://swedwatch.org/publication/healthier-procurement/
224. Michie S, van Stralen MM, West R. The behaviour change wheel: a new method for characterising and designing behaviour change interventions. Implement Sci. 2011;6:42.
225. Chandra P, Gale J, Murray N. New Zealand ophthalmologists' opinions and behaviours on climate, carbon and sustainability. Clin Exp Ophthalmol. 2020; 48(4):427-433.
226. Wei J, Hansen A, Zhang Y, Li H, Liu Q, Sun Y, et al. Perception, attitude and behavior in relation to climate change: a survey among CDC health professionals in Shanxi province, China. Environ Res. 2014;134:301-8.
227. Royal College of Surgeons of England. Sustainability in surgery. [Internet]. 2021; [cited 2022 Aug 11]. Available from: https://www.rcseng.ac.uk/about-the-rcs/about-our-mission/sustainability-in-surgery/
228. Royal College of Anaesthetists. Sustainability strategy 2018–2022. [Internet]. 2018; [cited 2022 Aug 11]. Available from: https://rcoa.ac.uk/about-college/strategy-vision/environment-sustainability/sustainability-strategy-2019-2022
229. General Medical Council. Outcomes for graduates 2018. [Internet]. 2018; [cited 2022 Aug 11]. Available from: https://www.gmc-uk.org/-/media/documents/dc11326-outcomes-for-graduates-2018_pdf-75040796.pdf
230. Rogers EM. Diffusion of innovation. 1st ed. New York: Free Press of Glencoe; 1962.
231. Coulter WA, Chew-Graham CA, Cheung SW, Burke FJ. Autoclave performance and operator knowledge of autoclave use in primary care: a survey of UK practices. J Hosp Infect. 2001;48(3):180-5.
232. Stevenson M, Uttley L, Oakley JE, Carroll C, Chick SE, Wong R. Interventions to reduce the risk of surgically transmitted Creutzfeldt-Jakob disease: a cost-effective modelling review. Health Technol Assess. 2020;24(11):1-150.
233. US Governemnt Accountability Office. Reprocessed single-use medical devices: FDA oversight has increased, and available information does not indicate that

use presents an elevated health risk. [Internet]. 2008; [cited 2022 Aug 11] Available from: https://www.gao.gov/products/gao-08-147

234. International Organization for Standardization. ISO 14025:2006 Environmental labels and declarations - Type III environmental declarations - principles and procedures. [Internet]. 2006. [cited 2022 Sep 2]. Available from: https://www.iso.org/standard/38131.html
235. Stryker. Material safety data sheet- product name: Simplex® HV cement with Gentamicin. [Internet]. 2014; [cited 2022 Jan 10]. Available from: https://www.strykermeded.com/media/2027/simplex-hv-cement-with-gentamicin.pdf
236. Stryker. Material safety data sheet- antibiotic simplex with Tobramycin. [Internet]. 2017; [cited 2022 Jan 10]. Available from: https://www.strykermeded.com/media/2792/antibiotic-simplex-p-with-tobramycin_sds_nov_2019.pdf
237. British Stainless Steel Assocaition. Selection of stainless steels for surgical instruments. [Internet]. 2022; [cited 2022 Aug 11]. Available from: https://bssa.org.uk/bssa_articles/selection-of-stainless-steels-for-surgical-instruments/

Supplementary tables

Supplementary table 1: System boundaries, data collected, impact assessment method of studies included in systematic review
For each included process/ product, the cross denotes the relevant scope (1-3). 1º= primary, 2º= secondary, ?= where datapoint was uncertain, DEFRA/ BEIS= Department for Environment, Food and Rural Affairs and Department for Business, Energy and Industrial Strategy, FAD= financial activity data, GHG= greenhouse gas, ICAO= International Civil Aviation Organization, IDEMAT= Industrial Design & Engineering MATerials, no.=number, PAD= process activity data, PEMS= Packaging Industry Research Association (PIRA) Environmental Management System Software, S1= scope 1, S2=scope 2, S3=scope 3, TRACI= Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, USLCI=United States Life Cycle Inventory, WRE= World ReCiPe Endpoint, WRM= World ReCiPe Midpoint, v=version

Study	**System boundary**				**Data collected**			**Impact assessment method**	
	Process/ product	**S1**	**S2**	**S3**	**Data source 1: data collected; data source 2: data collected**		**Data type**	**Emissions factor source**	**Impact assessment database**
Berner et al.(26)	*18 rhinoplasty, 9 bilateral breast augmentation, 11 abdominoplasty							DEFRA/BEIS 2016	
	Patient transport			X	Questionnaire (38 patients*): travel distance, mode of transport		1º PAD		
	Staff transport				Questionnaire (whole surgical team in 38 cases*): travel distance, mode of transport				
	Theatre building energy		X		Hospital data: building energy consumption				
	Recovery building energy				Hospital data: building energy consumption				
	Medical equipment energy				?: electrical consumption from each medical device involved in the surgical procedures		?1º PAD		
	Waste disposal of products			X	Waste audit (38 cases*): weight of waste products from theatre and recovery		1º PAD		
	Laundry transport				?: distance from hospital to laundry facility				
Campion et al.(112)	Electronic equipment		X		Inventory: machines, power rating, energy use	Literature: local power generation mix; Literature: assumed birth durations	1º PAD	USLCI 1.6	TRACI 2
	HVAC				Hospital data: bin model energy use				
	Lighting				Hospital data: energy use				

	Consumables production			X	Packs weighed: determine material constituents and reusability; Hospital data: assumed lifespan, number of uses, travel distance		BUWAL 250, IDEMAT 2001, USLCI v1.6, Processes	
	Reusables sterilization		X	X	Hospital data: electrical loading, travel data		USLCI v1.6	
	Disposal of single-use products			X	Hospital data: for each split of waste streams- energy in disposal, travel data		Ecoinvent 2005, Franklin USA, Processes	
Davis et al.(96)	Manufacture ureteroscope			X	Manufacturer data: weight of components of ureteroscope	2º PAD	Industry references (electronic, steel, plastic), journal article (rubber)	
	'Use' of reusables		X	X	Hospital data and sterilisation manufacturer data: Assumed lifespan, no. uses, repackaging, repair rate, sterilisation (energy used per cycle, number of scopes/ cycle)	1º PAD + 2º PAD	ICAO carbon emissions calculator + sterilisation manufacturer reference	
	Solid waste disposal			X	Manufacturer data: weight of uteroscope, sterilisation (?)	2º PAD		
Gatenby (25)	2º investigations, 2º care	X	X	X	Previous study (154 surgical, 164 medical cases): financial cost of each component of care	2º FAD	NHS Carbon Emissions Modelling 2008	
Ibbotson et al.(91)	*data source= medical company in Europe, **data source= 'the literature'							
	Raw material extraction			X	*: Material constituents, weight	1º PAD	Ecoinvent v2.2, Australian Data, SimaPro 2008	WRM, WRE
	Transport to manufacturer				*: Travel distance, mode of transport			
	Manufacturing electricity				*: Manufacturer country of origin, energy use; International Energy Agency database: local power generation mix			
	Transport to consumer				*: Distance between manufacturer and consumer, mode of travel			
	'Use' of reusables		X	X	*: Assumed lifespan, no. uses and repair rate, energy use, travel data (washing, disinfection, repair and **sterilisation)	1º PAD +2º PAD		
	Single-use and reusable product incineration/ landfill			X	*: Assumed lifespan, no. uses, air and water emissions, auxiliary consumption, energy use, travel data	1º PAD		

	Single-use and reusable product recycling				*: Assumed lifespan, no. uses, energy consumption, travel data			
Ison et al.(135)	Raw material extraction			X	Audit (all elective surgical procedures over 5 days at each hospital) + manufacturer data: weight each component of each product (including packaging) + manufacturer information on material composition	1º PAD +2º PAD	PEMS 4	PEMS 4
	Manufacturing							
	Distribution				Manufacturer data: location of manufacture, transport distribution details	2º PAD		
	'Use' of reusables		X	X	Audit + hospital data (?+ manufacturer data): lifespan, amount of water used, duration and contents of washing/drying, volume of detergent/rinse lube/ water softener used	1º PAD		
	Disposal			X	Waste disposal contractors' data (incinerator and landfill), water company data, washing chemicals manufacturer (unclear what data): ?	2º PAD		
Kummerer et al.(94)	Raw material extraction			X	Literature: data on growing, production, auxiliary material	2º PAD	Not stated	
	Manufacturing				Literature: local power generation mix; Literature and manufacturer data: energy, auxiliary materials			
	'Use' of reusables	X	X		Literature, manufacturer data, hospital data: energy use, water use, waste, pollutants (washing, sterilisation, reprocessing)			
	Single-use and reusable product waste disposal			X	Literature: energy use (landfill, incineration), emissions			
	Transport				Literature: travel data			
MacNeill et al.(28)	HVAC		X		Hospital and manufacturer data: heating system, set-points, operating parameters, air flow rates; Meteorological data: outside temperatures, combined to determine energy use	1º PAD	DEFRA/BEIS 2011	
	Lighting				Hospital data: lighting loads, power ratings, occupancy and usage patterns, theatre submetering for energy use		Local electrical utilities	
	Anaesthetic gases	X			Hospital data: annual emissions volumes		Literature	
	Consumables raw materials extraction			X	Waste audit (3 weeks): production emissions factors based on weight and material composition of waste stream		DEFRA/ BEIS 2011	
	Operative waste disposal				Waste audit (3 weeks): for each waste stream-weight, energy use in disposal, travel data			
	Linen				Linen facility data + local electrical grid intensities: energy use			

Morris et al.(27)	Building		X		Hospital data: proportion of space and time, calculate energy use	1º PAD	DEFRA/ BEIS 2011	
	Patient/ staff travel			X	Questionnaires (47 patients, staff over 2 days): travel distance, mode of transport			
	Departmental procurement	X	X	X	Hospital data: procurement activity (monetary value) for pharmaceuticals, medical equipment, IT, food and drink, stationary, water	2º FAD	National Statistics of Environmental Accounts, DEFRA 2011	
	Linen washing/ drying			X	Direct measure: weight of linen used by single patient and associated theatre staff; Unknown source: travel data to laundry site, energy used	1º PAD	DEFRA/ BEIS 2011	
	Operative waste disposal				Waste audit (1 patient): for each waste stream- weight, constituent materials, energy in disposal			
Power et al.(131)	* Extrapolated using national databases of number of operations and operation durations to give national level estimates							
	Gas insufflation direct emissions	X			*Hospital data: CO_2 procurement for volume of emissions, procedure numbers, operation duration	1º PAD	Not applicable	
	Gas insufflation procurement	X	X	X	*Hospital supplier data: annual sales (incorporate capture/ compression: gas manufacturing, power generation and supply, gas extraction)	2º FAD	Carnegie Mellon University model 2002	
				X	*Hospital data: travel distance; US Department of Transport: fuel efficiency data	1º PAD	GHG Protocol Initiative mobile guide	
	Trocar waste disposal				National US market engineering research: number of instruments, average weight	2º PAD	Time for Change Carbon Calculator for Plastic	
	Single-use robotic instruments waste disposal				National surgical supplier data: instrument catalogue unloaded waste, assumed 10 uses			
Somner et al.(132)	Heating water		X		Direct measures (25 scrubs elbow, 25 knee) + boiler manufacturer data: duration of scrub, typical temperature, tap flow rate, energy use, boiler efficiency	1º PAD + 2º PAD	Not referenced	
Thiel et al.(69)	Electronic equipment, HVAC, lighting		X		Source not stated: energy use Literature: local energy mix	?	USLCI	TRACI 2.1
	Linen			X	Hospital data + direct measure: weight, travel data, energy use (production, laundry, transport); Unknown source: linen lifespan	1º PAD +?	Ecoinvent v2	

	Production and use of reusable instruments				Waste audit (62 cases): weight, composition, travel data, energy use (raw material extraction, production, transport, sterilisation, autoclave) Type; Literature: estimated lifespan instruments	1º PAD		
	Production simple single-use products				Waste audit (62 cases): weight, composition, travel data, energy use (raw material extraction, production, transport)			
	Simple single-use products				Waste audit (62 cases): for each waste stream-weight, energy in disposal (landfill, incineration, autoclave and landfill, recycling); Literature: local energy mix and for recycling of polypropylene			
	Production complex single-use products	X	X	X	Hospital data and waste audit (62 cases): purchasing data (monetary value) for items in waste audit	2º FAD	Carnegie Mellon University model 2002	
	Use of anaesthesia (gases and IV) and gas insufflation	X		X	Patient records (62 cases): duration of surgery, volume and type of anaesthesia/ insufflation used; Interviewing staff: flow rate	1º PAD	Literature	
Thiel et al.(79)	Electronic equipment and lighting		X		Hospital data: average operation duration; Inventory of machines: power rating, power ratings to give energy used, modified for hospital diesel generators + local electrical grid	1º PAD	Ecoinvent version 3	TRACI 2.1
	Ventilation and air conditioning				Hospital data: subtract operating room electronic and equipment energy use from total electricity, modified for hospital diesel generators + local electrical grid			
	Water treatment (before and after use)		X	X	Hospital data: volume and energy used in treatment, allocated on floor area of operating room and sterilising services and no. surgeries in a year			
	Production single-use products			X	Hospital data + inventory: weight, quantities from records			
	Production reusable products				Hospital data + inventory: weight, quantities from records Purchasing data and interviews: estimated lifespan			
	Sterilization of reusables (including linen)		X		Hospital data: power rating of sterilization and laundry equipment, duration of treatment cycles to give energy use			
	Operative waste disposal			X	Waste audit (1 day-93 cases), interviews and site visits: for each waste stream-weight, energy used in disposal			
	Pharmaceuticals	X	X	X	Hospital data: purchasing data	2º FAD	Carnegie Mellon University model 2002	
	Baseline data				As per laparoscopic subset (17 patients) Thiel et al.(69)			

Thiel et al.(134)	Model anaesthetic interventions		X			Thiel et al.(69): modelled effect of using different combinations of anaesthetics	Model 1º PAD	Ecoinvent version 3, SimaPro version 3.3	TRACI 2.1
	Model surgical materials interventions				X	Thiel et al.(69): modelled potential recycling interventions			
						Thiel et al.(69): modelled potential to reuse cotton towels			
						Not stated: potential reusable gowns and laparotomy drapes	?		
						Literature: potential reprocessing single-use instruments	Model 2º PAD		
			X	X	X	Panel of 3 practicing gynaecologists: potential to lean surgical materials	Model 2º FAD	Carnegie Mellon University model 2013	
						EEIO model: maximisation of regulated medical waste			
	Model energy interventions			X		Literature: installation of theatre occupancy sensors	Model 2º PAD	Ecoinvent version 3, SimaPro version 3.3	
						Alternative energy company data: low-carbon electricity supply			
Unger et al.(133)	Raw material extraction, production, use, waste disposal	Single-use product with plastics			X	Thiel et al.(69): SUD containing plastics subset of data from waste audit (62 hysterectomies)	1º PAD	Ecoinvent version 2.2	TRACI 2.1
		Single-use product with biopolymer				Unknown source: model suitable biopolymer substitutions	Model ?	Literature, Ecoinvent version 2.2	
Woods et al.(30)	Environmental (HVAC, lighting, anaesthesia console) equipment, instruments, robotics			X		Operative records (50 of each 3 surgical approaches): operative time; Inventory + manufacturer data: energy consumption based on machine/ system specifications; US Energy Information Administration	1º PAD	National Energy Foundation calculator	
	Operative waste disposal				X	Operating room records (50 of each 3 surgical approaches) for quantities + representative materials weighed: single-use devices, sterile blue wrap, consumables (towels, dressings, catheters), number of drapes, gowns, gloves		Charleston County Report	

Supplementary table 2: Stated exclusions, assumptions, methods for calculating parameter and scenario uncertainty, and other limitations of studies included in systematic review

GHG= greenhouse gas, HVAC= heating, ventilation and air condition, TRACI= Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

Study	Stated exclusions to system boundary	Stated assumptions in data collection	1) Parameter uncertainty 2) Scenario uncertainty (results)	Other stated limitations / Other limitations, not stated
Berner et al.(26)	Revision surgeries and combined operations, laundry (aside from transport to laundry facility), indirect emissions derived from production of medical devices	• Applied the average patient travel distance across all surgeries to each specific surgery type (assuming distance does not differ between operation types)	1 & 2) Not stated	• The conversion factors were UK specific
				• No clearly stated hypothesis • Did not follow a carbon footprint guideline • Ambiguous as to the inventory boundaries- not clearly stated • Applied waste for landfill factor for all waste (does not specify whether there are other waste streams at the hospital) • Assumed all operations of a given type (e.g. rhinoplasty) used the same equipment • Unclear how building energy data is allocated to theatres/ recovery • Ambiguous elements of data sources • Limited assumptions outlined • No clear statistical plan or reporting of confidence intervals • No uncertainty modelling
Campion et al.(112)	Labour prior to delivery, post-birth care, hospital construction/ building materials, large machines, energy for hot	• Duration of births • Ratio of women having 1st birth • Steady state of environmental parameters • If consumables consisted of >1 material, total weight divided evenly by number of materials • Single-use custom pack assumed to enter waste streams and representative of hospital waste split	1) Not stated 2) Sensitivity analysis: for assumed 10-year life span reusable surgical pack (minimal impact)	• None

	water, anaesthetics, fetal heart monitor, electricity for patient beds, television, radio, gloves, masks, sutures, decontamination washer, laundry services, cleaning chemicals	• No generation of recycling, hazardous or electronic waste • Stainless steel instruments assumed life span of 10 years and to be sterilised once/ day • 10 kits sterilised during each autoclave cycle • Electrical loading of variable-draw machines (calculated at maximum)		• No clearly stated hypothesis • Number of observations per endpoint not clearly stated • For carbon footprint, no numerical data- descriptive or graphic summaries only for endpoints
Davis et al.(96)	None	• Typical use (number of uses, repairs, replacement)	1 & 2) Not stated	• Data sources indirectly from online databases • Single study centre • No clearly stated hypothesis • Did not reference a carbon footprinting guideline • Number of observations per endpoint not clearly stated • Did not state how waste is processed • Unclear which processes involved in emissions factors for materials (e.g. raw material extraction, manufacturing, transportation) • Ambiguous where repair conversion factors derived • Table 2 contains bracketed numbers without units- unclear what these refer to (e.g. for sterilisation for single-use ureteroscopes) • Proportion of material components assumed to be the same between single-use and reusable ureteroscope • No uncertainty modelling
Gatenby(25)	Visits to and from family practitioner,	• Patients in the medical treatment arm did not undergo endoscopic or physiological assessment	1 & 2) Not stated	• Financial data collected for another study (not for purpose of this study)

	further visits to 1º or 2º care (for follow up, ongoing prescriptions), travel to collect medications/ appointments	• Medication usage remain constant for patients in both arms following starting medical or surgical therapy • One in 20 medical patients will cross-over to the surgical arm • All products have same relative carbon intensity, regardless of country of manufacture • The model does not take into account differences in carbon intensity for different origins of manufacture		• No clearly stated hypothesis • Did not follow a carbon footprinting guideline • No uncertainty modelling • Did not specify the assumed lifespan of patients • Cannot determine relative contributions of different care components • Unclear what factors are incorporated into the cost of care components
Ibbotson et al.(91)	None	• Number of cycles of reusable scissors during lifetime (from previous study) • Recycling process of stainless steel based on material and energy consumption • Stainless steel within single-use and reusable scissors assumed to be the same but in reality, lower grade in single-use versions • Recycling of scissors based on Australian data- may not be applicable to Germany (case study) • Material and electricity consumption of sterilisation processes assumed from company data, expert opinion and literature • Incineration processes for plastics, cardboard and municipal solid waste assumed	1) Not stated 2) Sensitivity analysis: for modified electricity mix (variation 0.3-19%) and 100% recycling to 100% incineration (small variation)	• Where missing data, substitution from the literature and expert opinion • Electricity mix unavailable for two process cases • Databases used were not all country-specific • No clearly stated hypothesis • Ambiguity over number of observations per endpoint • Ambiguity over study site, stated 'customer location' • For carbon footprint, numerical data not available, presented as descriptive or graphic summaries only
Ison et al.(135)	Transport of raw materials from source to manufacturer, capital equipment of manufacturing and maintenance, washing/ drying machines (raw material extraction,	• Assumptions stated in 'Environmental Agency report'- not referenced and unable to find now	1 & 2) Not stated	• None stated • No clearly stated hypothesis • No carbon footprinting guideline • Ambiguity over number of observations per endpoint • Ambiguous about decontamination of reusables (states use of 'detergent') • No information on the content of data collected on disposal, only sources of the data

	manufacture and disposal)			• Ambiguous whether any decontamination included at end of life (states 'washing chemicals manufacturer') • Reusable data at one study site (where reusables no longer in used) based on 'usage' by data collector, whilst that at other site based on actual usage by regular staff • GHG data presented on logarithmic scale with no numerical data, unit is unclear, no conversion to carbon equivalents
Kummerer et al.(94)	Energy for transport within factory, chemicals for special use with minor ecological impact, drying of single-use pads, radioactive emissions and waste from nuclear power, auxiliary material, natural oil, 'questionable data and information were omitted'	• Water quality consistent (irrigation and drinking) • 100% yield of chemicals involved in manufacture	1 & 2) Not stated	• Underestimation of environmental impact of noise, lost heat, production plant, machines, complex chemicals • Some databases not specific to Germany • No clearly stated hypothesis • No uncertainty modelling • Number of observations per endpoint not clearly stated • Ambiguity over inclusion of scope one emissions: states 'pollutants' measured
MacNeill et al.(28)	Pre-operative and post-operative processes including recovery, pharmaceuticals, steam sterilisation, administrative offices, reprocessing of instruments (either	• Fuel efficiency • Waste audit representative of waste splits (no annual hospital data) • To calculate plastics production, the production emissions factors for average plastics were applied, with a 10% modifier to reflect the small non-plastic portion • Assumed that laundering of linen at one country site representative of the other two countries	1 & 2) Not stated	• Reliance on production emissions to approximate upstream emissions • Estimation of national level emissions on the basis of a very limited sample • No clearly stated hypothesis • Authors stated identification of 6 studies investigating environmental impact of surgery but no references • Authors stated primary activity data was used, but not all data was collected for the purpose of the study

	on-site or 3rd party), staff travel			• Number of observations ambiguous for some endpoints • No uncertainty modelling
Morris et al.(27)	2nd eye surgery, buildings and construction, waste from outpatient appointments, sterilisation procedures, human inputs into processes, capital cost of machinery used repeatedly, business services, immaterial emissions sources (likely to be <1% total emissions), biometric investigations, staff food and drink, scientific research, staff training	• Building energy use within operating theatres and recovery areas twice that of mean energy use for a given floor space within hospital (no reference) • All clinical waste underwent incineration • All domestic waste was sent to landfill • Each patient made three return journeys to hospital with one relative taking same mode of transport • Transport of linen to the off-site laundry service and energy requirements for the washing and drying of the laundry • Cataract services share similar carbon intensities nationally for national prediction • Highest available emissions factor for incineration has been applied to each of the constituents undergoing this form of disposal	1 & 2) Not stated	• Truncation error • Variation in activity data for the different sectors (particularly patient travel) between regions or internationally • Emissions factors available for pharmaceuticals and medical equipment not specific to the products used in cataract surgery • No clearly stated hypothesis • Number of observations per endpoint (e.g. hospital level data) not clearly stated • Ambiguity over what was meant by 'water', procurement and pharmaceuticals (including whether the latter includes anaesthetics) • No uncertainty modelling
Power et al.(131)	Elements common to traditional open surgery (operating theatre, electricity use, patient travel, paper products, CO_2 expired by the patient)	• Need for surgery considered essential • Elements under exclusions were common to surgery • CO_2 transported using a semitruck transport with set fuel efficiency and truck load • Incinerating 1 kg plastic produces 6 kg CO_2 • 10 uses of laparoscopic trocars before disposal	1 & 2) Not stated	• Inability to account for uncertainty • No clearly stated hypothesis • No clear statistical plan or reporting of confidence intervals • No uncertainty modelling • Hospital level data reflective of national carbon intensities • Relied upon correct coding for surgery and completeness of national database

				• Ambiguity over number of operations in data used to calculate average number of uses of single-use
Somner et al.(132)	Energy used to treat, store and supply the water	• Temperature at which scrubbing typically occurs • Constant tap flow rate • Boiler efficiency • Assume ≥ 2 people scrub per operation for national estimates	1) Appropriate statistical method for comparing variables, no power calculation 2) Not stated	• None • No clearly stated hypothesis • Small sample size • No reference to carbon footprinting guideline • No uncertainty modelling • No reference for emission factors used • Did not use an impact assessment database • For carbon footprint, limited numerical data, descriptive or graphic summaries only for some endpoints
Thiel et al.(69)	Postoperative length of hospital stay, postsurgical resource use, manufacturing and building materials of HVAC and machines, hot water, chemical manufacturing, cleaning products	• National projections based on assumed mix of surgical approaches • Electricity data based on duration of surgery	1) Monte Carlo Analysis and Anderson-Darling test: for variability of material used and energy consumption (large error bars) 2) Not stated	• None • No clearly stated hypothesis • Source of electricity data unclear and method for determining average duration of surgery not stated • For carbon footprint, numerical data was not available for all sub-processes, some presented as descriptive or graphic summaries only • Limited assumptions outlined • Does not state how linen lifespans were determined • Confidence intervals overlap for GHGs across all surgical modalities, limiting conclusions • Stated gas insufflation included, but unclear whether direct emissions and/ or indirect emissions were accounted for • Stated range of carbon footprint results from anaesthetics but ambiguous which

				anaesthetic modality the maximum/ minimum values relate to • Excluded postsurgical care including any inpatient care (likely to differ between alternative models of care)
Thiel et al.(79)	Patient preparation before entering the operating area, postoperative follow-ups, capital equipment (e.g. phacoemulsification machine, operating microscope, building construction)	• Water consumption allocated based on floor area of operating rooms and sterilisation rooms, and by number of surgeries performed per year • Ventilation and air conditioning allocated by total floor area of air-conditioned space • Modelled wastewater disposal on an assumed standard wastewater treatment plant, although study site has decentralised wastewater treatment site (i.e. not result representative of the study site)	1) Not stated 2) Sensitivity analysis using alternative life cycle analysis CML-IA: for use of TRACI model (no difference)	• Lack of country specific impact assessment databases • Lack of databases for pharmaceuticals • No clearly stated hypothesis • Number of observations ambiguous for some processes • For carbon footprint, numerical data not available for all sub-processes, some presented as descriptive or graphic summaries only
Thiel et al.(134)	20-minute turnover between cases form HVAC	• Duration of anaesthesia and flow rate (literature) • Anaesthetic substitutions assumed to be clinically appropriate • Recycling properly sorted • All surgical materials disposed of via regulated medical waste • Number of times a) cotton towels can be reused b) reusable surgical and laparotomy drapes can be reused c) devices can be reprocessed • Sterilisation processes conducted on-site • Hospital has sufficient space and labour for interventions • For reprocessing of single-use devices, assumed transport distance, GHGs emitted in sterilisation process • Weather conditions, occupancy, equipment, operating room size constant • Total consumption energy remains constant in each hysterectomy	1 & 2) Not stated	• Limited life cycle data specifically for healthcare • Energy savings modelled on one hospital- may not be optimal for all HVAC designs • Differences between facilities may exist and could result in different percentages of savings in carbon footprint when enacted • List of proposed interventions not exhaustive • No clearly stated hypothesis • No uncertainty modelling • Ambiguous data source for some models included • Number of observations ambiguous for data-sources used for some endpoints

Unger et al.(133)	None	• None	1) Not stated; 2) 2^3 factorial experiment: for variances of environmental impacts from different biopolymer substitutions and combinations (minimal impact)	• The biopolymer substitutions in the study were not discussed with doctors, nurses, or patients • Barriers to implementing biopolymers including financial and regulatory environment, leadership, workflow, carbon literacy and support systems
				• No clearly stated hypothesis • Ambiguous whether transport in manufacturing and waste disposal included • Stated end of life included, but ambiguous what this includes • Number of observations ambiguous for some endpoints • For carbon footprint, no numerical data, descriptive or graphical data only • No assumptions/ exclusions outlined
Woods et al.(30)	Postoperative hospital stay, capital goods, transport, manufacture and storage of equipment	• All gloves, gowns, drapes, single-use devices and associated packaging discarded at end of procedure • Double gloving used by all sterile personnel • Blue pack weight constant within group (surgical approach) • Energy to maintain temperature and power anaesthesia console constant across modalities • Percentage time overhead, operative lighting and non-surgical electrical equipment used for different modalities • Maximum energy consumption for energy- based surgical instruments represents <1% total surgical time • All robotic surgeries performed using one robotic system • Waste production was assumed to be the same among all 50 • Surgeries within a modality but to differ across surgical modalities	1) Detailed, appropriate statistical method for comparing variables, no power calculation; 2) Not stated	• Combined data from surgeons with varying levels of experience • Exclusion of data on postoperative stays, despite likely relevance (as stated and referenced in paper)
				• Study setting not specified • No clearly stated hypothesis • Uses retrospective operative records instead of prospective waste audit • Assumed all waste goes to landfill • Unclear how many GHGs taken into account • No uncertainty modelling • Assumed 1 kg of solid waste has same carbon footprint, regardless of material composition

Supplementary table 3: Key impact assessment results from studies included in systematic review
↓= decrease, ↑= increase, ~= approximated from descriptive data or graphic summaries, CO_2e= carbon dioxide equivalents, GHG= greenhouse gas

Study	Results of studies examining whole surgical processes	Results of studies identifying relative contribution of unit processes
Berner et al.(26)	• Abdominoplasty (23.68 kg CO_2e)> rhinoplasty (16.99 kg CO_2e)> bilateral breast augmentation (16.23 kg CO_2e)	• Abdominoplasty contributors CO_2e: theatre building energy (48.2%) > staff transport (18.4%) > patient transport (14.1%) > medical equipment energy (9.2%) > other (recovery building energy, waste products, laundry, each < 5%) • Rhinoplasty contributors CO_2e: theatre building energy (42.5%) > patient transport (19.7%) > staff transport (16.3%) > medical equipment energy (10.5%) > recovery building energy (6.6%) >other (waste products, laundry, each < 5%) • Bilateral breast augmentation contributors CO_2e: theatre building energy (42.5%) > patient transport (20.6%) > staff transport (16.7%) > medical equipment energy (8.2) > recovery building energy (6.9%) > other (waste products, laundry, each < 5%)
Campion et al.(112)	• Caesarean section CO_2e (100%)> vaginal delivery CO_2e (~50%)	• Contributors CO_2e caesarian section: HVAC (~55%) > machine loading (~20%) > single-use product production (~10%) > other (reusables production and sterilisation (8), lighting, waste, all ≤ 8%) • Contributors CO_2e vaginal delivery: HVAC (~50%) > machines (~25%) > reusables (~10%) > other (lighting, waste, single-use products) • Largest CO_2e contributor single-use materials in caesarean section: low density polyethylene (~50%)
Gatenby(25)	• At 20 years: medical treatment for GORD (~2,000 kg CO_2e) > surgery (~1,250 kg CO_2e) • Surgery CO_2e breaks even with medical treatment 9th post-operative year (thereafter more carbon-efficient)	
MacNeill et al.(28)	• Overall carbon footprint of surgery in Canada+ USA+ UK= 9.7 million t CO_2e/ year • Operating theatre per year: Canada (3,218,907 kg CO_2e) < USA (4,181,864 kg CO_2e) < UK (5,187,936 kg CO_2e) • Per operation: Canada 146 kg CO_2e < UK 173 kg CO_2e < USA 232 kg CO_2e	• Canada: anaesthetic gas CO_2e (63% total) > energy (17%) > supply chain and waste (20%) • USA: anaesthetic gas CO_2e (51% total) > energy (36%)> supply chain and waste (13%) • UK: energy CO_2e (84% total) > supply chain and waste (12%) > anaesthetic gas (4%) • Largest anaesthetic contributor CO_2e across countries: desflurane (not used in UK case)
Morris et al.(27)	• 1 cataract surgery: 181.8 kg CO_2e • Cataract surgery pathway at 1 hospital 405 t CO_2e per year, across England 63,000 t CO_2e per year	• Contributors CO_2e: procurement (53.8% total) > building and energy use (36.1%) > travel (10.1%) • Of procurement CO_2e: medical equipment (~60%) > pharmaceuticals (~33%) > other (paper and ink, food, laundry, Information Technology, water, waste, each <2%)

Power et al.(131)	• National USA minimally invasive surgery (CO_2e on top of traditional surgery CO_2e): 355,924 t CO_2e	• Contributors CO_2e: gas insufflation procurement (351,400 t CO_2e) > gas insufflation transportation (2,970 t CO_2e) > incineration robotic and trocar instruments (1,251 t CO_2e) > gas insufflation direct emissions (303 t CO_2e)
Thiel et al.(69)	• Hysterectomy GHG: robotic (100%) > laparoscopic (~69%) > abdominal (~37%) > vaginal (~35%) • GHG emissions from anaesthetics for 1 hysterectomy range 0.001- 505 kg CO_2e • National USA hysterectomies ~212,000 t CO_2e per year	• Anaesthetic gases contributed 1/3 GHG emissions of robotic and laparoscopic hysterectomies; 2/3 for abdominal and vaginal
Thiel et al.(79)	• 1 cataract surgery: 5.89 kg CO_2e	• Contributors CO_2e: medical equipment procurement (~73%)> building energy use (~17%) > other (water, pharmaceuticals, all < 5%), waste (net negative impact on GHG~3%) • Reusable materials for 1 cataract surgery (total 3.6 kg CO_2e): sterilisation (3.62 kg CO_2e) > production (0.04 kg CO_2e) • Single-use materials for 1 cataract surgery (total 0.93 kg CO_2e): production (0.89 kg CO_2e) > incineration/landfill (0.04 kg CO_2e)
Woods et al.(30)	• 1 endometrial staging procedure: 30.7 kg CO_2e (average across approaches) • Robotic approach (40.3 kg CO_2e) > laparoscopic approach (29.2 kg CO_2e) > laparotomy (22.7 kg CO_2e)	• Contributors CO_2e averaged across all approaches: energy (19.46 kg CO_2e) > waste (11.26 kg CO_2e)
Study (Year)	**Results of studies looking at specific consumables/ processes**	
Davis et al.(96)	• Per use: reusable ureteroscope (4.47 kg CO_2e) > single-use ureteroscope (4.43 kg CO_2e)	
Ibbotson et al.(91)	• For 4,500 uses: single-use stainless steel scissors (~10,000 kg CO_2e) > single-use plastics (~5,000 kg CO_2e) > reusable stainless steel (~300 kg CO_2e)	
Kummerer et al.(94)	• Single-use laparotomy pads GHG emissions > reusable for 5/7 GHG measured • For 1,000 uses: single-use laparotomy pads (304 kg CO_2) > reusable (163 kg CO_2)	
Somner et al.(132)	• Knee operated scrub taps saves 80 g CO_2 per surgical scrub compared with elbow operated taps	
Study (Year)	**Results of studies modelling hypothetical interventions**	
Ison et al.(135)	*Based on data at the same hospital:* • Per kg bodily fluid: single-use suction receptacle GHG effect (> ~100* GHG ? unit) > reusable suction receptacle (< ~10* GHG ? unit) *Based on data at different hospitals:* • Per kg bodily fluid: Reusable suction receptacle GHG effect (> ~100* GHG ? unit) > single-use suction receptacle (< ~100* GHG ? unit) *Unable to ascertain accurate approximation as logarithmic scale without tick marks on scale	
Somner et al.(132)	• Switching to knee operated scrub taps across UK could save 1,400 t CO_2	

Thiel et al. (69)	• Switching to propofol/ other intravenous or regional anaesthesia ↓ GHG 65-95% for abdominal and vaginal hysterectomies, 3% in laparoscopic, 28% in robotic
Thiel et al.(79)	• ↑ duration of cataract surgery→↑ GHG per case (3 min: GHG= 0.32, 40 min: GHG= 4.24 *no units*) • ↑ theatre throughput →↓ GHG per case (1 case: 79 kg CO_2e, 80 cases: 5 kg CO_2e)
Thiel et al.(134)	*Model interventions, all for laparoscopic hysterectomy as % of baseline study, results quoted here include anaesthesia • Optimising instrument tray (minimising material use and selecting reusable surgical instruments)→ 46%↓ GHG* • Switching to intravenous propofol only→ 28% ↓ GHG* • Reprocessing of single-use surgical instruments→ 9% ↓ GHG* • Switching to renewable energy on available grid system→6% ↓ GHG • Maximising recycling, minimising regulated medical waste and using reusable gowns and drapes, installing occupancy sensors→ ≤ 2% ↓ GHG per each • Combination of all above interventions→ 83% ↓ GHG* from 562 kg CO_2e to 94 kg CO_2e/ laparoscopic hysterectomy • US national emissions for hysterectomy could be reduced from 213 kilotonnes CO_2e to 141 kilotonnes CO_2e
Unger et al.(133)	• Hysterectomy medical devices containing plastics have marginally better or equivalent global warming impact than biopolymer substitutions across all surgical approaches

Supplementary table 4: Emissions factors for carbon footprint of products used for five common surgical operations
*Activities include transportation from the site of primary processing to the point of use (equating to the manufacturer of multi-component products). **Where financial spend was used, this encompassed all activities from raw material extraction to the point of sale. All other material/pharmaceutical emission factors constitute 'cradle to factory gate' emissions, including raw material extraction, transportation to primary processing site, primary processing and manufacturing through to factory gate. CO_2e= carbon dioxide equivalents, DEFRA/BEIS= Department for Environment, Food and Rural Affairs/ Department for Business, Energy & Industrial Strategy, ICE=Inventory of Carbon and Energy, v=version.

Material/ process	Emission factor	Emission factor unit	Source
Material			
Acrylonitrile Butadiene Styrene (ABS)	3.76	kg CO_2e per kg	ICE version 3(32)
Aluminium cast	6.72	kg CO_2e per kg	
Aluminium foil	7.47	kg CO_2e per kg	
Barium sulphide	1.18	kg CO_2e per kg	Ecoinvent version 3.6(114) using 'Barium sulfide {GLO}| market for barium sulfide | Cut-off, U'
Brass	4.80	kg CO_2e per kg	ICE version 3(32)
Copper	3.81	kg CO_2e per kg	
Cotton fabric	6.78	kg CO_2e per kg	
Cotton padding	1.28	kg CO_2e per kg	
Expanded polystyrene	3.29	kg CO_2e per kg	
General plastics	3.31	kg CO_2e per kg	
General polyethylene	2.54	kg CO_2e per kg	
General purpose polystyrene	3.43	kg CO_2e per kg	
Glass general	1.44	kg CO_2e per kg	
Glass reinforced plastic	8.10	kg CO_2e per kg	
High density polyethylene resin	1.93	kg CO_2e per kg	
Lithium-ion battery*	6.31	kg CO_2e per kg	DEFRA/BEIS(31)
Low density polyethylene film	2.60	kg CO_2e per kg	ICE version 3(32)
Low density polyethylene resin	2.08	kg CO_2e per kg	
Methyl methacrylate	7.18	kg CO_2e per kg	Ecoinvent version 3.6(114) using 'Methyl methacrylate {RoW}| market for methyl methacrylate | Cut-off, U'
Nickel	12.40	kg CO_2e per kg	ICE version 3(32)
Non-woven polyester*	5.56	kg CO_2e per kg	Ecoinvent version 3.6(114) using 'Non-woven polyester {GLO}| market for textile, non woven polyester| Cut-off,U'
Nylon (polyamide) 6 polymer	9.14	kg CO_2e per kg	ICE version 3(32)
Paper	1.49	kg CO_2e per kg	
Petroleum slack wax*	1.08	kg CO_2e per kg	Ecoinvent version 3.6(114)
Polycarbonate	7.62	kg CO_2e per kg	ICE version 3(32)
Polyethylene terephthalate*	4.03	kg CO_2e per kg	DEFRA/BEIS(31)
Polymethyl methacrylate	7.66	kg CO_2e per kg	Ecoinvent version 3.6(114) using 'Polymethyl

			methacrylate, beads {RoW}| production | Cut-off, U'
Polypropylene injection moulding	4.49	kg CO_2e per kg	ICE version 3(32)
Polypropylene oriented film	3.43	kg CO_2e per kg	
Polyurethane flexible foam	4.84	kg CO_2e per kg	
Polyurethane rigid foam	4.26	kg CO_2e per kg	
Polyvinylchloride general	3.10	kg CO_2e per kg	
Polyvinylchloride injection moulding	3.30	kg CO_2e per kg	
Rubber	2.85	kg CO_2e per kg	
Silicone*	3.34	kg CO_2e per kg	Ecoinvent version 3.6(114) using 'Silicone product {RoW}| market for silicone product| Cut-off,U'
Silk*	36.14	kg CO_2e per kg	Ecoinvent version 3.6(114) using 'Yarn, silk {GLO}| market for yarn, silk| Cut-off,U'
Stainless steel	6.15	kg CO_2e per kg	Small World Consulting version 5.3(115)
Titanium	20.60	kg CO_2e per kg	ICE version 3(32)
Zinc	4.18	kg CO_2e per kg	
Zirconium oxide	8.20	kg CO_2e per kg	Ecoinvent version 3.6(114) using 'Zirconium oxide {GLO}| market for | Cut-off, U'
Pharmaceuticals and cleaning chemicals			
Manufacture of basic pharmaceutical products and pharmaceutical preparations**	0.192	kg CO_2e per £	Small World Consulting version 5.3(115)
Manufacture of cleaning preparations**	0.169	kg CO_2e per £	
Adrenaline	34	kg CO_2e per kg	Parvatker et al.(73)
Bupivacaine hydrochloride	23	kg CO_2e per kg	
Carbon dioxide liquid*	0.0063	kg CO_2e per L	Ecoinvent version 3.6(114) using 'Carbon dioxide, liquid{ROW}| market for| Cut-off,U' (assumes 1 kg liquid CO_2e=150 L liquid CO_2e based upon product labelling)
Levobupivacaine	23	kg CO_2e per kg	Parvatker et al.(73)
Lidocaine	29	kg CO_2e per kg	
Ropivacaine hydrochloride	36	kg CO_2e per kg	
Instrument sterilisation and linen laundering			
Additional washing of standard sized reusable container (sterile barrier system)	0.623	kg CO_2e per reusable container	Rizan et al.(7)
Additional washing of small sized reusable container (sterile barrier system)	0.312	kg CO_2e per reusable container	
Linen laundering	0.461	kg CO_2e per kg	Supplementary information (linen laundering)
Reusable instrument sterilisation (steam sterilisation)- standard sized set	1.531	kg CO_2e per standard sized set	Rizan et al.(7)
Reusable instrument sterilisation (steam sterilisation)- small sized set	0.996	kg CO_2e per small sized set	

Reusable instrument steam sterilisation- supplementary instrument	0.145	kg CO_2e per supplementary instrument	
Waste			
Anatomical waste	1,074	kg CO_2e per t	Rizan et al.(8)
Clinical waste	1,074	kg CO_2e per t	
Domestic waste	172	kg CO_2e per t	
Infectious waste	569	kg CO_2e per t	
Non-infectious offensive waste	249	kg CO_2e per t	
Medicinal contaminated sharps waste	1,074	kg CO_2e per t	
Recycling (scrap metal, clothing, batteries)	21	kg CO_2e per t	

Supplementary table 5: Emission factors used for linen laundering

Note 2019 Department for Environment, Food and Rural Affairs (DEFRA)/ Department for Business, Energy & Industrial Strategy (BEIS) emission factors were used here and have since been updated, but using 2021 emission factors (as used in remainder of chapter) makes <1% difference to the emission factor derived here for linen laundering. CO_2e= carbon dioxide equivalents, CV=calorific value, HGV= heavy goods vehicle, t.km= one t of transported goods over one km.

Process/ product		**Emission factor**		**Emission factor unit**	**Source**
		Component	**Total**		
Natural Gas	Combustion	0.18	0.21	kg CO_2e per kWh (Gross CV)	DEFRA/BEIS(116)
	Well to tank	0.02			
HGV (diesel, average HGV), average laden		0.11	0.11	kg CO_2e per t.km	DEFRA/BEIS(116)
UK electricity (aggregated)		0.32	0.32	kg CO_2e per kWh	DEFRA/BEIS(116)
Water supply		0.34	0.34	kg CO_2e per m^3	DEFRA/BEIS(116)
Water treatment		0.71	0.71	kg CO_2e per m^3	DEFRA/BEIS(116)

Supplementary table 6: Carbon footprint of reusable instrument set used for carpal tunnel decompression

Table reports carbon footprint of minor op set used for carpal tunnel decompression (only one set used across all observed operations). The material composition of products was determined through packaging and manufacturer information where available, and alternatively through expert assessment, taking into account available emission factors. Weight reported as total for a given product (accounting for multiple products where relevant). 'Use' equates to sterilisation of instruments, determined per set. CO_2e= carbon dioxide equivalents

Category	Product	Material(s)	Weight (g)	Number of uses	Waste stream A	Carbon footprint per use (g CO_2e)		
						Production	**Use**	**Waste stream A**
Minor op set								
Sterile barrier system	Identification tag	High density polyethylene resin	11.87	46	Non-infectious offensive waste	0.50	See total	0.0642
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Metal tray (small)	Stainless steel	362.62	1,554	Scrap metal recycling	1.43	See total	0.0050
	Pin mat	Silicone	170.76	1,036	Non-infectious offensive waste	0.55		0.0410
	Tray wrap (inner, 90x90 cm)	Paper	59.5	1	Infectious waste	88.66	N/A	33.87
	Tray wrap (outer, 90x90 cm)	Polypropylene oriented film	61.02	1	Infectious waste	209.30		34.74
Instruments and set products	Adson dissecting toothed forceps	Stainless steel	20.20	1,036	Scrap metal recycling	0.12	See total	0.0004
	Bipolar diathermy forceps (small)	Stainless steel	15.26	40	Medicinal contaminated sharps waste	2.34		0.4096
		Nylon (polyamide) 6 polymer	1.70			0.39		0.0457
	Bipolar lead	Polyvinylchloride general	80.96	50	Non-infectious offensive waste	5.02		0.4031
		Copper	9.00			0.69		0.0448

	BP scalpel handle x2	Stainless steel	24.42	518	Scrap metal recycling	0.29		0.0010
	Crile wood needle holder	Stainless steel	33.30	1,036	Scrap metal recycling	0.20		0.0007
	Gillies skin hook x2	Stainless steel	14.15	1,813	Scrap metal recycling	0.05		0.0002
	Kilner cats paw retractor x2	Stainless steel	18.23	1,813	Scrap metal recycling	0.06		0.0002
	McDonald dissector	Stainless steel	23.53	1,036	Scrap metal recycling	0.14		0.0005
	Mosquito artery forceps (curved) x2	Stainless steel	18.69	2,849	Scrap metal recycling	0.04		0.0001
	Sponge holder forceps x2	Stainless steel	76.16	2,331	Scrap metal recycling	0.20		0.0007
	Stevens tenotomy scissor	Stainless steel	20.69	518	Medicinal contaminated sharps waste	0.25		0.0429
		Low density polyethylene resin	0.42			0.002		0.0009
	Suture scissors	Stainless steel	35.20	518	Scrap metal recycling	0.42		0.0014
	Towel clip x2	Stainless steel	30.65	1,554	Scrap metal recycling	0.12		0.0004
	Weitlaner retractor (3x4 teeth)	Stainless steel	62.24	1,295	Scrap metal recycling	0.30		0.0010
	Weitlaner retractor (2x3 teeth)	Stainless steel	41.56	1,295	Scrap metal recycling	0.20		0.0007
					Total minor op set=1,922.18 g CO_2e	**318.48**	**1,531.27**	**72.44**

Supplementary table 7: Carbon footprint of reusable (non-set) and single-use products used for carpal tunnel decompression
Table includes all single-use products used across all observed operations listed here and the carbon footprint per product as listed. Products used for individual operations varied, alongside number of products used. The material composition of products was determined through packaging and manufacturer information where available, and alternatively through expert assessment, taking into account available emission factors. Weight reported as total for a given product (accounting for multiple products where relevant). ‘Use’ equates to linen laundering of reusable linens. All waste of given product disposed of using consistent waste stream (A). Carbon footprint per use equates to a single use of a product in a single operation. CO_2e= carbon dioxide equivalents, ops.= operations

Product	Component	Material(s)	Weight (g), or cost where specified with (£)	Number of uses	Number of ops per use	Waste stream A	Carbon footprint per use (g CO_2e)			
							Production	Use	Waste stream A	Total (waste A)
Reusable personal protective equipment										
Reusable scrubs	Product	Cotton fabric	421.17	75	5	Clothing recycling	7.61	38.79	0.02	46.43
Non-set reusable equipment										
Reusable tourniquet pressure cuff	Product	Polyvinylchloride general	82.89	6	1	Infectious waste	42.82	N/A	7.86	50.69
		High density polyethylene resin	54.85				17.64	N/A	5.20	22.85
	Packaging	Low density polyethylene film	11.19				4.85	N/A	1.06	5.91
Single-use patient and instrument table drapes from ‘Hand pack’ set										
Patient drape (fenestrated hand drape)	Product	Polypropylene oriented film	676.08	1	1	Infectious waste	2,318.95	N/A	384.90	2,703.86
		Rubber	10.55				30.07	N/A	6.01	36.07

Table drape (instruments)	Product	Polyvinylchloride general	123.17	1	1	Infectious waste	381.83	N/A	70.12	451.95
		Nylon (polyamide) 6 polymer	61.58				562.84	N/A	35.06	597.90
‘Hand pack’ packaging (drape component)	Packaging	Low density polyethylene film	25.09	1	1	Infectious waste	65.24	N/A	14.29	79.53
		Paper	5.70				8.50	N/A	3.25	11.75
Single-use equipment from ‘Hand pack’ set										
Bowl	Product	Polypropylene injection moulding	12.58	1	1	Infectious waste	56.46	N/A	7.16	63.62
Foam cube	Product	Polyurethane flexible foam	1.71	1	1	Infectious waste	8.28	N/A	0.97	9.25
Gauze swab	Product	Cotton fabric	25.63	1	1	Infectious waste	173.77	N/A	14.59	188.36
Kidney dish	Product	Polypropylene injection moulding	29.07	1	1	Infectious waste	130.52	N/A	16.55	147.07
Light cover	Product	Low density polyethylene film	4.78	1	1	Infectious waste	12.43	N/A	2.72	15.15
Needle counter	Product	Acrylonitrile Butadiene Styrene	44.50	1	1	Medicinal contaminated sharps waste	167.32	N/A	47.80	215.12
		Polyurethane rigid foam	4.07				17.34	N/A	4.37	21.71
Surgical blade	Product	Stainless steel	0.39	1	1	Medicinal contaminated sharps waste	2.40	N/A	0.42	2.82
	Packaging	Aluminium foil	0.52				3.88	N/A	0.56	4.44
Syringe (20 ml)	Product	High density polyethylene resin	10.66	1	1	Infectious waste	20.57	N/A	6.07	26.64
‘Hand pack’ packaging (single-use equipment component)	Packaging	Low density polyethylene film	3.86	1	1	Infectious waste	10.03	N/A	2.20	12.22
		Paper	0.88				1.31	N/A	0.50	1.80

Single-use personal protective equipment										
Gloves (non-sterile, pair)	Product	Rubber	6.45	1	1	Infectious waste	18.38	N/A	3.67	22.05
Sterile gloves (pair)	Product	Rubber	27.31	1	1	Infectious waste	77.83	N/A	15.55	93.38
	Packaging	General polyethylene	5.98	1	1		15.19	N/A	3.40	18.59
		Paper	5.91				8.81	N/A	3.36	12.17
Sterile gloves (two pairs)	Product	Rubber	42.14	1	1	Infectious waste	120.10	N/A	23.99	144.09
	Packaging	Paper	11.61				17.30	N/A	6.61	23.91
		General polyethylene	5.61				14.25	N/A	3.19	17.44
Sterile gloves (two pair, latex free)	Product	General polyethylene	44.68	1	1	Infectious waste	113.49	N/A	25.44	138.92
	Packaging	Paper	11.66				17.37	N/A	6.64	24.01
		General polyethylene	5.71				14.50	N/A	3.25	17.75
Surgical face mask	Product	Polypropylene oriented film	4.36	1	1	Infectious waste	14.95	N/A	2.48	17.44
Surgical face mask with eye protection	Product	Polypropylene oriented film	6.23	1	1	Infectious waste	21.37	N/A	3.55	24.92
		Low density polyethylene film	4.04				10.50	N/A	2.30	12.80
Surgical gown (including hand towels)	Product	Polypropylene oriented film	139.00	1	1	Infectious waste	476.78	N/A	79.14	555.92
		Rubber	7.32				20.85	N/A	4.17	25.02
		Paper	13.83				20.61	N/A	7.87	28.48
	Packaging	Paper	19.30				28.76	N/A	10.99	39.74

		Low density polyethylene film	5.11				13.29	N/A	2.91	16.20
Surgical hat	Product	Polypropylene oriented film	3.54	1	4	Infectious waste	3.04	N/A	0.50	3.54
Visor	Product	Low density polyethylene resin	8.54	1	1	Infectious waste	17.76	N/A	4.86	22.63
		Low density polyethylene film	2.39				6.21	N/A	1.36	7.57
	Packaging	Low density polyethylene film	1.84				4.78	N/A	1.05	5.83
		Paper	1.43				2.13	N/A	0.81	2.94
		Nylon (polyamide) 6 polymer	0.44				4.02	N/A	0.25	4.27
Single-use equipment and medical devices										
Crepe bandage (7.5 cm wide)	Product	Cotton fabric	38.69	1	1	Infectious waste	262.32	N/A	22.03	284.34
	Packaging	Paper	7.09				10.56	N/A	4.04	14.60
		Low density polyethylene film	3.14				8.16	N/A	1.79	9.95
Elasticated fabric dressing strip	Product	Rubber	0.65	1	1	Infectious waste	1.85	N/A	0.37	2.22
Gauze (individual piece)	Product	Cotton fabric	5.06	1	1	Infectious waste	34.31	N/A	2.88	37.19
Gauze (sterile pack)	Product	Cotton fabric	25.52	1	1	Infectious waste	173.03	N/A	14.53	187.55
	Packaging	Paper	5.12				7.63	N/A	2.91	10.54
		Low density polyethylene film	1.63				4.24	N/A	0.93	5.17
Incontinence pad	Product	Low density polyethylene film	30.18	1	1	Infectious waste	78.47	N/A	17.18	95.65

Nail scrubbing brush	Product	Low density polyethylene resin	9.01	1	1	Infectious waste	18.74	N/A	5.13	23.87
		Polyurethane flexible foam	2.05				9.92	N/A	1.17	11.09
		Polypropylene injection moulding	0.91				4.09	N/A	0.52	4.60
	Packaging	Low density polyethylene film	1.31				3.41	N/A	0.75	4.15
		Paper	0.60				0.89	N/A	0.34	1.24
Needle (blue)	Product	Stainless steel	0.18	1	1	Medicinal contaminated sharps waste	1.13	N/A	0.20	1.33
		Polypropylene injection moulding	0.04				0.20	N/A	0.05	0.24
	Packaging	High density polyethylene resin	0.40			Infectious waste	0.77	N/A	0.23	1.00
		Low density polyethylene film	0.12				0.31	N/A	0.07	0.38
		Paper	0.11				0.16	N/A	0.06	0.23
Needle (green)	Product	Stainless steel	0.20	1	1	Medicinal contaminated sharps waste	1.23	N/A	0.21	1.44
		Polypropylene injection moulding	0.05				0.22	N/A	0.05	0.28
	Packaging	High density polyethylene resin	0.52			Infectious waste	1.00	N/A	0.30	1.30
		Low density polyethylene film	0.12				0.31	N/A	0.07	0.38
		Paper	0.11				0.16	N/A	0.06	0.23
Needle (red)	Product	Stainless steel	0.41	1	1	Medicinal contaminated sharps waste	2.51	N/A	0.44	2.95
		Polypropylene injection moulding	0.10				0.46	N/A	0.11	0.57
	Packaging	High density polyethylene resin	0.60			Infectious waste	1.16	N/A	0.34	1.50

		Low density polyethylene film	0.12				0.31	N/A	0.07	0.38
		Paper	0.11				0.16	N/A	0.06	0.23
Non-woven dressing	Product	Nylon (polyamide) 6 polymer	0.58	1	1	Infectious waste	5.30	N/A	0.33	5.63
	Packaging	Paper	1.22				1.82	N/A	0.69	2.51
		Low density polyethylene film	0.64				1.66	N/A	0.36	2.03
Skin marker	Product	High density polyethylene resin	6.23	1	1	Infectious waste	12.02	N/A	3.55	15.57
		Paper	0.57				0.85	N/A	0.32	1.17
	Packaging	Paper	1.82				1.36	N/A	0.52	1.87
		Low density polyethylene film	0.91				29.48	N/A	6.46	35.94
Stockinette tubular bandage	Product	Cotton fabric	11.34	1	1	Infectious waste	76.89	N/A	6.46	83.34
Surgical blade	Product	Stainless steel	0.39	1	1	Medicinal contaminated sharps waste	2.40	N/A	0.42	2.82
	Packaging	Aluminium foil	0.52			Infectious waste	3.88	N/A	0.30	4.18
Suture (monofilament, non-absorbable, 4-0)	Product	Stainless steel	0.01	1	1	Medicinal contaminated sharps waste	0.06	N/A	0.01	0.07
		Nylon (polyamide) 6 polymer	0.00				0.00	N/A	0.00	0.00
	Packaging	Paper	2.82			Infectious waste	4.20	N/A	1.61	5.81
		Low density polyethylene film	0.49				1.27	N/A	0.28	1.55
Suture (monofilament, non-absorbable 5-0)	Product	Stainless steel	0.01	1	1		0.06	N/A	0.01	0.07

		Nylon (polyamide) 6 polymer	0.00			Medicinal contaminated sharps waste	0.00	N/A	0.00	0.00
	Packaging	Paper	2.82			Infectious waste	4.20	N/A	1.61	5.81
		Low density polyethylene film	0.49				1.27	N/A	0.28	1.55
Syringe (10 ml)	Product	Polypropylene injection moulding	3.01	1	1	Infectious waste	13.51	N/A	1.71	15.23
		General polyethylene	3.01				7.65	N/A	1.71	9.36
		Rubber	0.25				0.71	N/A	0.14	0.85
	Packaging	Low density polyethylene film	0.45				1.17	N/A	0.26	1.43
		Paper	0.39				0.58	N/A	0.22	0.80
Syringe (20 ml)	Product	Polypropylene injection moulding	7.10	1	1	Infectious waste	31.90	N/A	4.04	35.94
		General polyethylene	7.10				18.04	N/A	4.04	22.09
		Rubber	0.59				1.69	N/A	0.34	2.02
	Packaging	Low density polyethylene film	1.11				2.89	N/A	0.63	3.52
		Paper	0.72				1.07	N/A	0.41	1.48
Tape (clear)	Product	Nylon (polyamide) 6 polymer	0.51	1	1	Infectious waste	4.66	N/A	0.29	4.95
Undercast padding	Product	Cotton padding	17.63	1	1	Infectious waste	22.57	N/A	10.04	32.60
	Packaging	Paper	6.89				10.27	N/A	3.92	14.19
		Low density polyethylene film	1.65				4.29	N/A	0.94	5.23

Pharmaceuticals										
Bupivacaine hydrochloride 0.5% (10 ml)	Product	Bupivacaine hydrochloride	10.00	1	1	N/A	230.00	N/A	N/A	230.00
	Packaging	Low density polyethylene film	3.71			Infectious waste	9.65	N/A	2.11	11.76
		Low density polyethylene resin	2.66				5.53	N/A	1.51	7.05
		Paper	0.55				0.82	N/A	0.31	1.13
Chlorhexidine 2% from 500 ml container (100 ml)	Product and packaging	Chlorhexidine 2%	£0.56	1	1	N/A	107.30	N/A	N/A	107.30
Hyaluronidase 1500 I.U. (10 ml)	Product and packaging	Hyaluronidase	£16.19	1	8	Infectious waste	387.75	N/A	N/A	387.75
	Packaging (weight for waste)		1.48				N/A	N/A	0.11	N/A
Levobupivacaine 5mg per 10 ml (10 ml)	Product	Levobupivacaine	10.00	1	1	N/A	230.00	N/A	N/A	230.00
	Packaging	Low density polyethylene resin	2.65			Infectious waste	5.51	N/A	1.51	7.02
		Low density polyethylene film	0.46				1.20	N/A	0.26	1.46
		Paper	0.40				0.60	N/A	0.23	0.82
Lidocaine 1% (10 ml)	Product	Lidocaine	10.00	1	1	N/A	290.00	N/A	N/A	290.00
	Packaging	Low density polyethylene resin	4.41	1	1	Infectious waste	9.17	N/A	2.51	11.68
Lidocaine 1% with adrenaline 1:200,000 (20 ml)	Product	Lidocaine	20.00	1	1	N/A	580.00	N/A	N/A	580.00
	Packaging	Low density polyethylene film	33.22			Medicinal contaminated sharps waste	86.37	N/A	35.68	122.05
Sodium Chloride 0.9% from 1 litre bottle (100 ml)	Product and packaging	Sodium chloride	£0.40	1	1	N/A	75.87	N/A	N/A	75.87

Cleaning products, waste											
Clear bin bag (linen laundering)	Product	Low density polyethylene film	13.91	1	5	Domestic waste	7.23	N/A	0.48	7.71
		Nylon (polyamide) 6 polymer	2.58				4.72	N/A	0.09	4.80
Disinfectant sachet	Product and packaging	Disinfectant	£0.70	1	5	Infectious waste	26.82	N/A	N/A	26.82
	Packaging (weight for waste)		2.58				N/A	N/A	0.66	N/A
Disinfectant wipe	Product	Non-woven polyester	2.30	1	1	Infectious waste	12.79	N/A	1.31	14.10
Orange waste bag (infectious waste) with cable tie from theatre	Product	Polypropylene oriented film	70.61	1	1	Infectious waste	242.19	N/A	40.20	282.39
		Nylon (polyamide) 6 polymer	2.58				23.58	N/A	1.47	25.05
Orange waste bag (infectious waste) with cable tie from scrub room	Product	Polypropylene oriented film	70.61	1	5	Infectious waste	48.44	N/A	8.04	56.48
		Nylon (polyamide) 6 polymer	2.58				4.72	N/A	0.29	5.01
Mop head	Product	Nylon (polyamide) 6 polymer	70.36	1	5	Infectious waste	128.62	N/A	8.01	136.63
		High density polyethylene resin	30.16				11.64	N/A	3.43	15.08
Red bag (linen laundering) with cable tie	Product	Polypropylene oriented film	29.22	1	5	Domestic waste	20.04	N/A	1.00	21.05
		Nylon (polyamide) 6 polymer	2.58				4.72	N/A	0.09	4.80

Supplementary table 8: Carbon footprint of reusable instrument sets used for inguinal hernia repair
Table includes all reusable instrument sets and individually wrapped instruments across all observed operations, and the carbon footprint per set. Sets and individually wrapped instruments used for individual operations varied. The material composition of products was determined through packaging and manufacturer information where available, and alternatively through expert assessment, taking into account available emission factors. Weight reported as total for a given product (accounting for multiple products where relevant). Some products listed as 'bottom tray'/'top tray' where not individually counted by theatre staff. 'Use' equates to sterilisation of instruments, determined per set. All waste of given product disposed of using consistent waste stream (A). CO_2e= carbon dioxide equivalents

Category	**Product**	**Material(s)**	**Weight (g)**	**Number of uses**	**Waste stream A**	**Carbon footprint per use (g CO_2e)**		
						Production	**Use**	**Waste stream A**
General basic set (A)								
Sterile barrier system	Identification tag	High density polyethylene resin	12.13	46	Non-infectious offensive waste	0.51	See total	0.0656
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Metal tray (medium)	Stainless steel	1147.39	1,554	Scrap metal recycling	4.54	See total	0.0157
	Tray lining (60x60 cm)	Paper	21.11	1	Infectious waste	31.45	N/A	12.02
	Tray wrap (inner, 150x180 cm)	Polypropylene oriented film	154.12	1	Infectious waste	528.63		87.74
	Tray wrap (outer, 150x180 cm)	Polypropylene oriented film	156.5	1	Infectious waste	536.80		89.10
Instruments and set products	Allis tissue forceps x2	Stainless steel	62.30	4,476	Scrap metal recycling	0.09	See total	0.0003
	Babcock forceps x2	Stainless steel	47.18	4,476	Scrap metal recycling	0.06		0.0002
	Baby Mixter forceps	Stainless steel	25.60	4,476	Scrap metal recycling	0.04		0.0001
	BP scalpel handle (no. 3) x2	Stainless steel	51.56	895	Scrap metal recycling	0.35		0.0012

	BP scalpel handle (no. 4)	Stainless steel	27.78	895	Scrap metal recycling	0.19		0.0007
	Crile baby needle holder	Stainless steel	36.64	1,791	Scrap metal recycling	0.13		0.0004
	Czerny retractor x2	Stainless steel	103.32	5,372	Scrap metal recycling	0.12		0.0004
	Debakey plan dissecting forceps x2	Stainless steel	50.08	1,343	Scrap metal recycling	0.23		0.0008
	Diathermy lead	Polyvinylchloride general	86.52	50	Non-infectious offensive waste	5.36		0.4307
		Copper	9.61			0.73		0.0478
	Diathermy quiver	Polypropylene injection moulding	95.15	1,343	Non-infectious offensive waste	0.32		0.0176
	Dunhill artery forceps x5	Stainless steel	111.00	4,476	Scrap metal recycling	0.15		0.0005
	Gallipot x2	Polypropylene injection moulding	8.06	1	Non-infectious offensive waste	36.19	N/A	2.0064
	Gilles toothed dissecting forceps x2	Stainless steel	46.74	1,074	Scrap metal recycling	0.27	See total	0.0009
	Hernia ring	Stainless steel	37.62	2,523	Scrap metal recycling	0.09		0.0003
	Kidney dish (20 cm)	Polypropylene injection moulding	50.22	895	Non-infectious offensive waste	0.25		0.0140
	Lahey cholecystectomy forceps	Stainless steel	45.99	2,523	Scrap metal recycling	0.11		0.0004
	Lanes tissue forceps x2	Stainless steel	93.16	4,476	Scrap metal recycling	0.13		0.0004
	Langenbeck medium retractor x2	Stainless steel	159.40	6,267	Scrap metal recycling	0.16		0.0005
	Langenbeck small retractor x2	Stainless steel	119.12	6,267	Scrap metal recycling	0.12		0.0004
	Mayo curved scissor	Stainless steel	70.08	895	Scrap metal recycling	0.48		0.0017
	Mayo Hegar needle holder	Stainless steel	38.65	1,791	Scrap metal recycling	0.13		0.0005

	Mayo straight scissor	Stainless steel	64.64	1,343	Scrap metal recycling	0.30		0.0010
	McIndoe curved scissor	Stainless steel	35.61	895	Scrap metal recycling	0.24		0.0008
	McIndoe plain diathermy forceps	Stainless steel	38.30	40	Medicinal contaminated sharps waste	5.88		1.0283
		Nylon (polyamide) 6 polymer	4.26			0.97		0.1143
	Morris retractor	Stainless steel	102.06	5,372	Scrap metal recycling	0.12		0.0004
	Mosquito fine artery forceps x5	Stainless steel	102.80	2,686	Scrap metal recycling	0.24		0.0008
	Paper (90x90 cm)	Paper	49.00	1	Infectious waste	73.01	N/A	27.8963
	Pulp tray (no.3)	Paper	12.13	1	Infectious waste	18.07		6.9058
	Spencer Wells curved artery forceps x2	Stainless steel	109.86	4,476	Scrap metal recycling	0.15	See total	0.0005
	Sponge holder forceps x4	Stainless steel	294.92	4,029	Scrap metal recycling	0.45		0.0016
	Towel clip x5	Stainless steel	162.15	895	Scrap metal recycling	1.11		0.0039
	Travers self-retaining retractor	Stainless steel	121.73	1,970	Scrap metal recycling	0.38		0.0013
					Total general basic set (A)= 3,017.22 g CO_2e	**1,255.77**	**1,531.27**	**230.18**
				General basic set (B)				
Sterile barrier system	Basket	Stainless steel	1,170.57	116	Scrap metal recycling	62.01	See total	0.2149
	Container	Aluminium cast	2,996.54	1,000	Scrap metal recycling	20.14		0.0638
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211

	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89		1.0134
Instruments and set products	Allis tissue forceps x2	Stainless steel	56.92	4,476	Scrap metal recycling	0.08	See total	0.0003
	Babcock tissue forceps x2	Stainless steel	48.50	4,476	Scrap metal recycling	0.07		0.0002
	Bag plain closure (H)	Paper	13.69	1	Infectious waste	20.40	N/A	7.7939
	Bipolar diathermy	Stainless steel	31.98	40	Medicinal contaminated sharps waste	4.91	See total	0.8588
		High density polyethylene resin	31.98			1.54		0.8588
	Bonney toothed dissecting forceps	Stainless steel	61.07	4,029	Scrap metal recycling	0.09		0.0003
	BP scalpel handle (no. 3) x2	Stainless steel	49.40	895	Scrap metal recycling	0.34		0.0012
	BP scalpel handle (no. 4) x2	Stainless steel	57.44	895	Scrap metal recycling	0.39		0.0014
	Bulldog clip	Stainless steel	49.77	1,343	Scrap metal recycling	0.23		0.0008
	Czerny retractor x2	Stainless steel	123.94	5,372	Scrap metal recycling	0.14		0.0005
	Debakey dissecting forceps	Stainless steel	21.42	1,343	Scrap metal recycling	0.10		0.0003
	Diathermy lead	Polyvinylchloride general	86.52	50	Non-infectious offensive waste	5.36		0.4307
		Copper	9.61			0.73		0.0478
	Diathermy quiver	Polypropylene injection moulding	96.13	1,343	Non-infectious offensive waste	0.32		0.0178
	Gallipot x3	Polypropylene injection moulding	14.10	1	Infectious waste	63.31	N/A	8.0273

	Gillies toothed dissecting forceps	Stainless steel	24.31	1,074	Scrap metal recycling	0.14	See total	0.0005
	Halstead mosquito curved artery forceps x6	Stainless steel	122.76	2,686	Scrap metal recycling	0.28		0.0010
	Kidney dish (25 cm) x4	Polypropylene injection moulding	395.52	895	Non-infectious offensive waste	1.98		0.1100
	Lanes tissue forceps x2	Stainless steel	84.32	4,476	Scrap metal recycling	0.12		0.0004
	Langenbeck retractor (medium) x2	Stainless steel	105.10	6,267	Scrap metal recycling	0.10		0.0004
	Mayo curved scissors	Stainless steel	70.12	895	Scrap metal recycling	0.48		0.0017
	Mayo Hegar needle holder x2	Stainless steel	58.24	1,791	Scrap metal recycling	0.20		0.0007
	Mayo straight scissors	Stainless steel	44.34	1,343	Scrap metal recycling	0.20		0.0007
	McIndoe dissecting forceps	Stainless steel	20.69	2,238	Scrap metal recycling	0.06		0.0002
	McIndoe plain diathermy forceps	Stainless steel	32.49	40	Medicinal contaminated sharps waste	4.99		0.8725
		Nylon (polyamide) 6 polymer	3.61			0.82		0.0969
	McIndoe scissors	Stainless steel	34.01	895	Scrap metal recycling	0.23		0.0008
	Plain dissecting forceps (5")	Stainless steel	23.09	40	Scrap metal recycling	3.55		0.0123
	Plain dissecting forceps (7")	Stainless steel	37.01	895	Scrap metal recycling	0.25		0.0009
	Rampley sponge holder forceps x4	Stainless steel	256.56	1,343	Scrap metal recycling	1.17		0.0041
	Schnidt artery forceps x6	Stainless steel	238.56	4,029	Scrap metal recycling	0.36		0.0013
	Spencer Wells curved artery forceps x4	Stainless steel	209.52	3,581	Scrap metal recycling	0.36		0.0012
	Spencer Wells straight artery forceps x6	Stainless steel	146.46	4,476	Scrap metal recycling	0.20		0.0007

	Stitch scissor	Stainless steel	32.74	4,476	Scrap metal recycling	0.04		0.0002
	Towel clip x6	Stainless steel	211.86	1,343	Scrap metal recycling	0.97		0.0034
	Travers self-retaining retractor	Stainless steel	107.66	895	Scrap metal recycling	0.74		0.0026
	Treves toothed dissecting forceps x6	Stainless steel	141.12	1,970	Scrap metal recycling	0.44		0.0015
Total general basic set (B)= 2,395.86 g CO_2e						**216.62**	**2,153.96**	**25.27**
Roberts artery forceps								
Sterile barrier system	Flexible pouch	General polyethylene	11.14	1	Infectious waste	28.30	N/A	6.3421
		Paper	8.06			12.01		4.5887
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
Instruments and set products	Roberts artery forceps	Stainless steel	42.46	4,476	Scrap metal recycling	0.06		0.0002
Total Roberts artery forceps= 197.07 g CO_2e						**40.71**	**145.38**	**10.98**
Collingwood Stewart hernia forceps								
Sterile barrier system	Flexible pouch	General polyethylene	11.14	1	Infectious waste	28.30	N/A	6.3421
		Paper	8.06			12.01		4.5887
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
Instruments and set products	Collingwood Stewart hernia forceps	Stainless steel	38.57	2,523	Scrap metal recycling	0.09		0.0003
Total Collingwood Stewart hernia forceps= 197.10 g CO_2e						**40.74**	**145.38**	**10.98**

Supplementary table 9: Carbon footprint of reusable (non-set) and single-use products used for inguinal hernia repair

Table includes all single-use products used across all observed operations listed here and the carbon footprint per product as listed. Products used for individual operations varied, alongside number of products used. The material composition of products was determined through packaging and manufacturer information where available, and alternatively through expert assessment, taking into account available emission factors. Weight reported as total for a given product (accounting for multiple products where relevant). 'Use' equates to linen laundering of reusable linens. Carbon footprint per use equates to a single use of a product in a single operation. CO_2e= carbon dioxide equivalents, ops.= operations

Product	Component	Material(s)	Weight (g), or cost where specified with (£)	Number of uses	Number of ops per use	Waste stream A	Waste stream B	Carbon footprint per use (g CO_2e)					
								Production	Use	Waste stream A	Waste stream B	Total (waste A)	Total (waste B)
Reusable patient drapes													
High fluid drape	Product	Polyethylene terephthalate	1876.3	75	1	Clothing recycling	N/A	100.88	864.09	0.53	N/A	965.51	N/A
	Packaging	Paper	51.53	1		Infectious waste		76.78	N/A	29.34	N/A	106.12	N/A
		Nylon (polyamide) 6 polymer	2.76					25.23	N/A	1.57	N/A	26.80	N/A
Huck towel	Product	Cotton fabric	120.55	75	1	Clothing recycling	N/A	10.90	55.52	0.03	N/A	66.45	N/A
	Packaging	Paper	20.63	1		Infectious waste		30.74	N/A	11.74	N/A	42.48	N/A
		Low density polyethylene film	4.6					11.96	N/A	2.62	N/A	14.58	N/A
Low fluid drape	Product	Polyethylene terephthalate	1171.14	75	1	Clothing recycling	N/A	62.97	539.35	0.33	N/A	602.64	N/A
	Packaging	Paper	71.04	1		Domestic waste		105.85	N/A	12.20	N/A	118.05	N/A

		Nylon (polyamide) 6 polymer	2.56					23.40	N/A	0.44	N/A	23.84	N/A
Reusable personal protective equipment													
Reusable surgical gown (including hand towels)	Product	Polyethylene terephthalate	303.70	75	1	Clothing recycling	N/A	16.33	139.86	0.09	N/A	156.28	N/A
		Rubber	15.98					0.61	7.36	0.0045	N/A	7.97	N/A
		Paper	13.41	1		Domestic waste	Clinical waste	19.98	N/A	2.30	14.40	22.28	34.39
	Packaging	Paper	19.90					29.65	N/A	3.42	21.38	33.07	51.03
		General polyethylene	6.42					29.65	N/A	3.42	21.38	33.07	51.03
Reusable surgical hat	Product	Cotton fabric	26.58	75	4	Clothing recycling	N/A	0.60	3.06	0.0019	N/A	3.66	N/A
Reusable scrubs	Product	Cotton fabric	421.17	75	4	Clothing recycling	N/A	9.52	48.49	0.0299	N/A	58.04	N/A
Non-set reusable equipment													
Diathermy pad lead	Product	Polyvinylchloride general	121.57	50	1	Non-infectious offensive waste	N/A	7.54	N/A	0.61	N/A	8.14	N/A
		Copper	13.51					1.03	N/A	0.07	N/A	1.10	N/A
Shaver base	Product	High density polyethylene resin	38.15	1,300	1	Infectious waste	Clinical waste	0.06	N/A	0.02	0.03	0.07	0.09
		Aluminium cast	35.43					0.18	N/A	0.02	0.03	0.20	0.21
		Lithium-ion battery	35.43			Batteries recycling	N/A	0.17	N/A	0.0006	N/A	0.17	N/A
Single-use personal protective equipment													

Gloves (non-sterile, pair)	Product	Rubber	6.45	1	1	Infectious waste	Clinical waste	18.38	N/A	3.67	6.93	22.05	25.31
Sterile gloves (pair)	Product	Rubber	27.31	1	1	Infectious waste	Clinical waste	77.83	N/A	15.55	29.33	93.38	107.17
	Packaging	General polyethylene	5.98			Domestic waste		15.19	N/A	1.03	6.42	16.22	21.61
		Paper	5.91					8.81	N/A	1.02	6.35	9.82	15.15
Sterile gloves (two pairs)	Product	Rubber	42.14	1	1	Infectious waste	N/A	120.10	N/A	23.99	N/A	144.09	N/A
	Packaging	Paper	11.61			Domestic waste		17.30	N/A	1.99	N/A	19.29	N/A
		General polyethylene	5.61					14.25	N/A	0.96	N/A	15.21	N/A
Sterile gloves (one pair, latex free)	Product	General polyethylene	24.66	1	1	Infectious waste	Clinical waste	62.64	N/A	14.04	26.49	76.68	89.12
	Packaging	Paper	6.01			Domestic waste		8.95	N/A	1.03	6.46	9.99	15.41
		General polyethylene	5.83					14.81	N/A	1.00	6.26	15.81	21.07
Sterile under-gloves (pair)	Product	Rubber	18.54	1	1	Infectious waste	Clinical waste	52.84	N/A	10.56	19.91	63.39	72.75
	Packaging	General polyethylene	5.64			Domestic waste		14.33	N/A	0.97	6.06	15.29	20.38
		Paper	5.85					8.72	N/A	1.00	6.28	9.72	15.00
Surgical face mask	Product	Polypropylene oriented film	4.36	1	1	Infectious waste	Clinical waste	14.95	N/A	2.48	4.68	17.44	19.64
Surgical face mask with eye protection	Product	Polypropylene oriented film	6.23	1	1	Infectious waste	Clinical waste	21.37	N/A	3.55	6.69	24.92	28.06
		Low density polyethylene film	4.04					10.50	N/A	2.30	4.34	12.80	14.84
Surgical gown	Product	Polypropylene oriented film	139.004	1	1	Infectious waste	Clinical waste	476.78	N/A	79.14	149.31	555.92	626.09

(including hand towels)		Rubber	7.316					20.85	N/A	4.17	7.86	25.02	28.71
		Paper	13.83			Domestic waste		20.61	N/A	2.38	14.86	22.98	35.46
	Packaging	Paper	25.34					37.76	N/A	4.35	27.22	42.11	64.98
		Low density polyethylene film	5.11					13.29	N/A	0.88	5.49	14.16	18.77
Surgical hat	Product	Polypropylene oriented film	3.54	1	4	Infectious waste	Clinical waste	3.04	N/A	0.50	0.95	3.54	3.99
Single-use patient drape and instrument table drapes													
Patient drape (incise drape, with iodine)	Product	Low density polyethylene film	11.65	1	1	Infectious waste	N/A	30.29	N/A	6.63	N/A	36.92	N/A
		Iodine	£0.02					0.00	N/A	0.74	N/A	0.74	N/A
	Packaging	Paper	26.085					38.87	N/A	14.85	N/A	53.72	N/A
		General polyethylene	7.945					20.18	N/A	4.52	N/A	24.70	N/A
Table drape (instrum-ents)	Product	Polyvinylchloride general	122.17	1	1	Infectious waste	N/A	378.73	N/A	69.55	N/A	448.28	N/A
		Polypropylene oriented film	61.09					209.54	N/A	34.78	N/A	244.32	N/A
	Packaging	Paper	12.64					18.83	N/A	7.20	N/A	26.03	N/A
		Polypropylene oriented film	9.05					31.04	N/A	5.15	N/A	36.19	N/A
		Low density polyethylene film	6.49					16.87	N/A	3.69	N/A	20.57	N/A
Single-use equipment and medical devices													
Absorbent towel pack	Product	Paper	28.47	1	1	Infectious waste	N/A	42.42	N/A	16.21	N/A	58.63	N/A

	Packaging	Paper	5.00					7.45	N/A	2.85	N/A	10.30	N/A
		Low density polyethylene film	2.16					5.62	N/A	1.23	N/A	6.85	N/A
Diathermy pad	Product	Aluminium foil	5.49	1	1	Infectious waste	Clinical waste	41.01	N/A	3.13	5.90	44.14	46.91
		General polyethylene	5.49					13.94	N/A	3.13	5.90	17.07	19.84
	Packaging	Polyethylene terephthalate	1.84					7.42	N/A	1.05	1.98	8.47	9.40
Diathermy tip	Product	Stainless steel	1.58	1	1	Medicinal contamina-ted sharps waste	N/A	9.72	N/A	1.70	N/A	11.42	N/A
		High density polyethylene resin	0.53					1.02	N/A	0.57	N/A	1.58	N/A
	Packaging	Low density polyethylene film	0.90			Infectious waste		2.34	N/A	0.51	N/A	2.85	N/A
		Paper	0.59					0.88	N/A	0.34	N/A	1.21	N/A
Gauze (sterile pack, 10x7.5 cm)	Product	Cotton fabric	19.66	1	1	Infectious waste	Clinical waste	133.29	N/A	11.19	21.12	144.49	154.41
	Packaging	Paper	4.73				Domestic waste	7.05	N/A	2.69	0.81	9.74	7.86
		Low density polyethylene film	1.54					4.00	N/A	0.88	0.26	4.88	4.27
Gauze (sterile pack, 30x30 cm)	Product	Cotton fabric	91.90	1	1	Infectious waste	N/A	623.08	N/A	52.32	N/A	675.40	N/A
	Packaging	Paper	12.67					18.88	N/A	7.21	N/A	26.09	N/A
		Low density polyethylene film	3.72					9.67	N/A	2.12	N/A	11.79	N/A
Gauze (sterile pack, 10x10 cm)	Product	Cotton fabric	25.52	1	1	Infectious waste	Clinical waste	173.03	N/A	14.53	27.41	187.55	200.44
	Packaging	Paper	5.12				Domestic waste	7.63	N/A	2.91	0.88	10.54	8.51
		Low density polyethylene film	1.63					4.24	N/A	0.93	0.28	5.17	4.52

Incontin-ence pad	Product	Cotton padding	15.09	1	1	Infectious waste	Clinical waste	19.32	N/A	8.59	16.21	27.91	35.52
		Low density polyethylene film	15.09					39.23	N/A	8.59	16.21	47.82	55.44
Kidney dish	Product	Paper	18.98	1	1	Clinical waste	N/A	28.28	N/A	20.39	N/A	48.67	N/A
	Packaging	Low density polyethylene film	5.86			Domestic waste		15.24	N/A	1.01	N/A	16.24	N/A
		Paper	4.89					7.29	N/A	0.84	N/A	8.13	N/A
Light handle	Product	Low density polyethylene film	4.78	1	1	Infectious waste	Clinical waste	12.43	N/A	2.72	5.13	15.15	17.56
	Packaging	Low density polyethylene film	3.38				Domestic waste	8.79	N/A	1.92	0.58	10.71	9.37
		Paper	1.93					2.88	N/A	1.10	0.33	3.97	3.21
Mesh	Product	Polypropylene oriented film	1.06	1	1	N/A	N/A	3.64	N/A	N/A	N/A	3.64	3.64
	Packaging	Paper	84.66			Infectious waste	Clinical waste	126.14	N/A	48.20	90.94	174.34	217.08
		Low density polyethylene film	7.17					18.64	N/A	4.08	7.70	22.72	26.34
		Polypropylene oriented film	7.15					24.52	N/A	4.07	7.68	28.60	32.20
Monopolar diathermy with smoke evacuation system	Product	Low density polyethylene resin	78.58	1	1	Infectious waste	Clinical waste	163.45	N/A	44.74	84.41	208.18	247.85
		Polyvinylchloride general	54.07					167.62	N/A	30.78	58.08	198.40	225.70
		High density polyethylene resin	39.62					76.47	N/A	22.56	42.56	99.02	119.02
		Stainless steel	5.36			Medicinal contamina-ted sharps waste	N/A	32.91	N/A	5.75	N/A	38.67	N/A
		Copper	3.79			Infectious waste	Clinical waste	14.44	N/A	2.16	4.07	16.60	18.51

		Acrylonitrile Butadiene Styrene	1.86					6.99	N/A	1.06	2.00	8.05	8.99
	Packaging	Low density polyethylene film	11.33					29.46	N/A	6.45	12.17	35.91	41.63
		Polypropylene oriented film	8.47					29.05	N/A	4.82	9.10	33.87	38.15
		Paper	1.34					2.00	N/A	0.76	1.44	2.76	3.44
Nail scrubbing brush	Product	Low density polyethylene resin	9.01	1	1	Domestic waste	Clinical waste	18.74	N/A	1.55	9.68	20.29	28.42
		Polyurethane flexible foam	2.05					9.92	N/A	0.35	2.20	10.27	12.12
		Polypropylene injection moulding	0.91					4.09	N/A	0.16	0.98	4.24	5.06
	Packaging	Low density polyethylene film	1.31					3.41	N/A	0.23	1.41	3.63	4.81
		Paper	0.6					0.89	N/A	0.10	0.64	1.00	1.54
Needle (green)	Product	Stainless steel	0.20	1	1	Medicinal contaminated sharps waste	N/A	1.23	N/A	0.21	N/A	1.44	N/A
		Polypropylene injection moulding	0.05					0.22	N/A	0.05	N/A	0.28	N/A
	Packaging	High density polyethylene resin	0.52			Infectious waste	Domestic waste	1.00	N/A	0.30	0.09	1.30	1.09
		Low density polyethylene film	0.12					0.31	N/A	0.07	0.02	0.38	0.33
		Paper	0.11					0.16	N/A	0.06	0.02	0.23	0.18
Needle counter	Product	Acrylonitrile Butadiene Styrene	44.50	1	1	Medicinal contaminated sharps waste	N/A	167.32	N/A	47.80	N/A	215.12	N/A
		Polyurethane rigid foam	4.00					17.04	N/A	4.30	N/A	21.34	N/A
	Packaging	Low density polyethylene film	4.38			Infectious waste	Domestic waste	11.39	N/A	2.49	0.75	13.88	12.14
		Polypropylene oriented film	1.15					3.94	N/A	0.65	0.20	4.60	4.14

Nonwoven dressing (10x20 cm)	Product	Cotton padding	2.21	1	1	Infectious waste	Clinical waste	2.83	N/A	1.26	2.38	4.09	5.21
		Low density polyethylene film	0.12					0.30	N/A	0.07	0.13	0.37	0.43
	Packaging	Paper	4.17			Domestic waste	N/A	6.21	N/A	0.72	N/A	6.93	N/A
		Polypropylene oriented film	2.04					7.00	N/A	0.35	N/A	7.35	N/A
		Low density polyethylene film	1.71					4.45	N/A	0.29	N/A	4.74	N/A
Nonwoven dressing (10x30 cm)	Product	Cotton padding	10.67	1	1	Clinical waste	N/A	13.66	N/A	11.46	N/A	25.12	N/A
		Low density polyethylene film	0.56					1.46	N/A	0.60	N/A	2.06	N/A
	Packaging	Paper	3.22			Domestic waste		4.80	N/A	0.55	N/A	5.35	N/A
		Polypropylene oriented film	2.9					9.95	N/A	0.50	N/A	10.45	N/A
		Low density polyethylene film	2.53					6.58	N/A	0.43	N/A	7.01	N/A
Pre-operative adhesive glove	Product	Low density polyethylene film	2.60	1	1	Infectious waste	Clinical waste	6.76	N/A	1.48	2.79	8.24	9.55
	Packaging	Paper	1.73					2.58	N/A	0.98	1.86	3.56	4.44
Reinforced skin closure strip	Product	General polyethylene	0.66	1	1	Clinical waste	N/A	1.68	N/A	0.71	N/A	2.39	N/A
	Packaging	Paper	1.49					2.22	N/A	1.60	N/A	3.82	N/A
		Low density polyethylene film	0.74					1.92	N/A	0.79	N/A	2.72	N/A
Shaver head	Product	Stainless steel	2.9	1	1	Medicinal contamina-ted sharps waste	N/A	17.82	N/A	3.11	N/A	20.94	N/A
		Acrylonitrile Butadiene Styrene	2.76					10.36	N/A	2.96	N/A	13.32	N/A
		Low density polyethylene resin	2.76					5.73	N/A	2.96	N/A	8.69	N/A

	Packaging	Polyethylene terephthalate	0.77			Infectious waste	Clinical waste	3.10	N/A	0.44	0.83	3.54	3.93
		Paper	0.23					0.34	N/A	0.13	0.25	0.47	0.59
Specimen pot (40 ml 4% formalde-hyde)	Product	4% Formaldehyde	£0.20	1	1	Clinical waste	N/A	42.97	N/A	N/A	N/A	42.97	N/A
	(Product weight-for waste)		40.00					0.00	N/A	42.97	N/A	42.97	N/A
	Product	Polypropylene injection moulding	6.53					29.32	N/A	7.01	N/A	36.33	N/A
	Product	High density polyethylene resin	5.19					10.02	N/A	5.57	N/A	15.59	N/A
Surgical blade (10)	Product	Stainless steel	0.61	1	1	Medicinal contamina-ted sharps waste	N/A	3.75	N/A	0.66	N/A	4.40	N/A
	Packaging	Aluminium foil	0.46			Infectious waste	Domestic waste	3.44	N/A	0.26	0.08	3.70	3.52
Surgical suspensory bandage	Product	Cotton fabric	23.30	1	1	Domestic waste	N/A	157.97	N/A	4.00	N/A	161.98	N/A
		Stainless steel	2.92					17.94	N/A	0.50	N/A	18.45	N/A
	Packaging	Low density polyethylene film	3.55			Clinical waste		9.23	N/A	3.81	N/A	13.04	N/A
		Paper	3.02					4.50	N/A	3.24	N/A	7.74	N/A
Suture (braided, absorbable, 0)	Product	Stainless steel	0.26	1	1	Medicinal contamina-ted sharps waste	N/A	1.60	N/A	0.28	N/A	1.88	N/A
		Nylon (polyamide) 6 polymer	0.09					0.82	N/A	0.10	N/A	0.92	N/A
	Packaging	Aluminium foil	1.22			Infectious waste	Domestic waste	9.11	N/A	0.69	0.21	9.81	9.32
		Paper	0.91					1.36	N/A	0.52	0.16	1.87	1.51

		Polypropylene oriented film	0.52					1.78	N/A	0.30	0.09	2.08	1.87
		Low density polyethylene film	0.50					1.30	N/A	0.28	0.09	1.58	1.39
Suture (braided, absorbable, 2-0)	Product	Stainless steel	0.26	1	1	Medicinal contaminated sharps waste	N/A	1.60	N/A	0.28	N/A	1.88	N/A
		Nylon (polyamide) 6 polymer	0.09					0.82	N/A	0.10	N/A	0.92	N/A
	Packaging	Aluminium foil	1.22			Infectious waste	Domestic waste	9.11	N/A	0.69	0.21	9.81	9.32
		Paper	0.91					1.36	N/A	0.52	0.16	1.87	1.51
		Polypropylene oriented film	0.52					1.78	N/A	0.30	0.09	2.08	1.87
		Low density polyethylene film	0.50					1.30	N/A	0.28	0.09	1.58	1.39
Suture (mono-filament, absorbable, 3-0)	Product	Stainless steel	0.26	1	1	Medicinal contaminated sharps waste	N/A	1.60	N/A	0.28	N/A	1.88	N/A
		Nylon (polyamide) 6 polymer	0.09					0.82	N/A	0.10	N/A	0.92	N/A
	Packaging	Aluminium foil	1.22			Infectious waste	Domestic waste	9.11	N/A	0.69	0.21	9.81	9.32
		Paper	0.91					1.36	N/A	0.52	0.16	1.87	1.51
		Polypropylene oriented film	0.52					1.78	N/A	0.30	0.09	2.08	1.87
		Low density polyethylene film	0.50					1.30	N/A	0.28	0.09	1.58	1.39
Suture (mono-filament, non-absorbable, 1)	Product	Stainless steel	0.26	1	1	Medicinal contaminated sharps waste	N/A	1.60	N/A	0.28	N/A	1.88	N/A
		Nylon (polyamide) 6 polymer	0.09					0.82	N/A	0.10	N/A	0.92	N/A
	Packaging	Aluminium foil	1.22			Infectious waste	Domestic waste	9.11	N/A	0.69	0.21	9.81	9.32
		Paper	0.91					1.36	N/A	0.52	0.16	1.87	1.51

		Polypropylene oriented film	0.52					1.78	N/A	0.30	0.09	2.08	1.87
		Low density polyethylene film	0.50					1.30	N/A	0.28	0.09	1.58	1.39
Suture (mono-filament, non-absorbable, 2-0)	Product	Stainless steel	0.26	1	1	Medicinal contamina-ted sharps waste	N/A	1.60	N/A	0.28	N/A	1.88	N/A
		Nylon (polyamide) 6 polymer	0.09					0.82	N/A	0.10	N/A	0.92	N/A
	Packaging	Aluminium foil	1.22			Infectious waste	Domestic waste	9.11	N/A	0.69	0.21	9.81	9.32
		Paper	0.91					1.36	N/A	0.52	0.16	1.87	1.51
		Polypropylene oriented film	0.52					1.78	N/A	0.30	0.09	2.08	1.87
		Low density polyethylene film	0.5					1.30	N/A	0.28	0.09	1.58	1.39
Syringe (20 ml)	Product	Polypropylene injection moulding	7.10	1	1	Infectious waste	Clinical waste	31.90	N/A	4.04	7.63	35.94	39.53
		General polyethylene	7.10					18.04	N/A	4.04	7.63	22.09	25.67
	Product	Rubber	0.59					1.69	N/A	0.34	0.64	2.02	2.32
		Low density polyethylene film	1.11					2.89	N/A	0.63	0.19	3.52	3.08
		Paper	0.72					1.07	N/A	0.41	0.12	1.48	1.20
Pharmaceuticals													
Chlorhexid-ine 1% from 500 ml container (100 ml)	Product and packaging	Chlorhexidine 2%	£0.56	1	1	N/A	N/A	107.30	N/A	N/A	N/A	107.30	N/A
	Product	Levobupivacaine	10	1	1	N/A	N/A	230.00	N/A	N/A	N/A	230.00	N/A

Levobupiv-acaine 5mg per 10 ml (10 ml)													
	Packaging	Low density polyethylene resin	2.65	1	1	Infectious waste	Clinical waste	5.51	N/A	1.51	2.85	7.02	8.36
		Low density polyethylene film	0.46	1	1			1.20	N/A	0.26	0.49	1.46	1.69
		Paper	0.40	1	1			0.60	N/A	0.23	0.43	0.82	1.03
Povidone iodine 10% from 500 ml container (60 ml)	Product and packaging	Povidone iodine	£0.96	1	1	N/A	N/A	183.24	N/A	N/A	N/A	183.24	183.24
Sodium Chloride 0.9% from 1 litre bottle (50 ml)	Product and packaging	Sodium chloride	£0.20	1	1	N/A	N/A	37.94	N/A	N/A	N/A	37.94	37.94
Topical skin adhesive (0.8 g)	Product	Topical skin adhesive (0.8 g)	£20.47	1	1	N/A	N/A	3,922.02	N/A	N/A	N/A	3,922.02	N/A
	(Packaging - weight for waste)		4.38	1	1	Infectious waste		0.00	N/A	2.49	N/A	2.49	N/A
Cleaning products, waste													
Black waste bag (domestic waste) with cable tie	Product	Polypropylene oriented film	22.37	1	1	Domestic waste	N/A	76.73	N/A	3.84	N/A	80.57	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	0.44	N/A	24.02	N/A
Chlorine tablet	Product and packaging	Chlorine tablet	£0.04	1	1	N/A	N/A	7.01	N/A	0.00	N/A	7.01	N/A
	Product	Low density polyethylene film	12.48	1	1	Clinical waste	N/A	32.45	N/A	13.41	N/A	45.85	N/A

Clear bin bag (for swab count)		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	2.77	N/A	26.35	N/A
Clear bin bag (recycling) with cable tie	Product	Low density polyethylene film	15.01	1	1	Domestic waste	N/A	39.03	N/A	2.58	N/A	41.60	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	0.44	N/A	24.02	N/A
Disinfectant sachet	Product	Disinfectant	£0.70	1	4	Infectious waste	N/A	33.53	N/A	N/A	N/A	33.53	N/A
	(Packaging - weight for waste)		5.81					N/A	N/A	0.83	N/A	0.83	N/A
Disinfectant wipe	Product	Non-woven polyester	3.34	1	1	Infectious waste	Clinical waste	18.57	N/A	1.90	3.59	20.47	22.16
Green bag (linen laundering) with cable tie	Product	Low density polyethylene film	16.47	1	4	Domestic waste	N/A	10.71	N/A	0.71	N/A	11.41	N/A
		Nylon (polyamide) 6 polymer	2.58					5.90	N/A	0.11	N/A	6.01	N/A
Mop head	Product	Nylon (polyamide) 6 polymer	70.36	1	4	Infectious waste	Clinical waste	160.77	N/A	10.01	18.89	170.79	179.67
		High density polyethylene resin	30.16					14.55	N/A	4.29	8.10	18.84	22.65
Orange waste bag (infectious waste, large) with cable tie	Product	Polypropylene oriented film	70.61	1	1	Infectious waste	N/A	242.19	N/A	40.20	N/A	282.39	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	1.47	N/A	25.05	N/A
Orange waste bag (infectious waste,	Product	Polypropylene oriented film	27.75	1	1	Infectious waste	N/A	95.18	N/A	15.80	N/A	110.98	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	1.47	N/A	25.05	N/A

small) with cable tie													
Red bag (linen laundering) with cable tie	Product	Polypropylene oriented film	29.22	1	4	Domestic waste	N/A	25.06	N/A	1.25	N/A	26.31	N/A
		Nylon (polyamide) 6 polymer	2.58					5.90	N/A	0.11	N/A	6.01	N/A
Yellow waste bag (clinical waste) with cable tie	Product	Polypropylene oriented film	28.15	1	1	Clinical waste	N/A	96.55	N/A	30.24	N/A	126.79	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	2.77	N/A	26.35	N/A

Supplementary table 10: Carbon footprint of reusable instrument sets used for knee arthroplasty
Table includes all reusable instrument sets and individually wrapped instruments across all observed operations, and the carbon footprint per set. Sets and individually wrapped instruments used for individual operations varied. The material composition of products was determined through packaging and manufacturer information where available, and alternatively through expert assessment, taking into account available emission factors. Weight reported as total for a given product (accounting for multiple products where relevant). Some products listed as 'bottom tray'/'top tray' where not individually identified by theatre or sterile services staff and so were clustered. 'Use' equates to sterilisation of instruments, determined per set. All waste of given product disposed of using consistent waste stream (A). CO_2e= carbon dioxide equivalents

Category	Product	Material(s)	Weight (g)	Number of uses	Waste stream A	Carbon footprint per use (g CO_2e)		
						Production	Use	Waste stream A
Basic major orthopaedic set								
Sterile barrier system	Basket	Stainless steel	955.83	116	Scrap metal recycling	50.63	See total	0.1755
	Container	Aluminium cast	3213.76	1000	Scrap metal recycling	21.60		0.0684
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Pin mat	Silicone	51.04	888	Non-infectious offensive waste	0.19	See total	0.0143
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89	N/A	1.0134
Instruments and set products	Bone hook	Stainless steel	65.96	2441	Scrap metal recycling	0.17	See total	0.0006
	Bone nibbler x2	Stainless steel	488.51	888	Scrap metal recycling	3.38		0.0117

	Bonney toothed dissecting forceps	Stainless steel	47.40	1775	Scrap metal recycling	0.16		0.0006
	BP scalpel handle (no. 3) x2	Stainless steel	51.86	666	Scrap metal recycling	0.48		0.0017
	BP scalpel handle (no. 3L)	Stainless steel	44.23	666	Scrap metal recycling	0.41		0.0014
	Bristow elevator	Stainless steel	108.95	888	Scrap metal recycling	0.75		0.0026
	Capener gouge (large)	Stainless steel	122.61	666	Medicinal contaminated sharps waste	1.13		0.1979
		Acrylonitrile Butadiene Styrene	30.65			0.17		0.0495
	Capener gouge (small)	Stainless steel	121.84	666	Medicinal contaminated sharps waste	1.12		0.1966
		Acrylonitrile Butadiene Styrene	30.46			0.17		0.0492
	Cement gun	Stainless steel	454.15	888	Non-infectious offensive waste	3.14		0.1274
		Glass reinforced plastic	454.15			4.14		0.1274
	Curette	Stainless steel	85.12	976	Medicinal contaminated sharps waste	0.54		0.0936
		Glass reinforced plastic	85.12			0.71		0.0937
	Curette (double ended)	Stainless steel	46.98	888	Scrap metal recycling	0.33		0.0011
	Galabin ligature carrier	Stainless steel	27.52	1775	Scrap metal recycling	0.10		0.0003
	Gillies toothed dissecting forceps	Stainless steel	30.10	1775	Scrap metal recycling	0.10		0.0004
	Heath mallet	Stainless steel	929.94	1553	Scrap metal recycling	3.68		0.0127
		Rubber	232.49			0.43		0.0032
	Hohmann lever bone x2	Stainless steel	199.16	1109	Scrap metal recycling	1.10		0.0038

	Kocher artery forceps (7") x4	Stainless steel	191.16	1775	Scrap metal recycling	0.66		0.0023
	Langenbeck retractor (large) x2	Stainless steel	233.20	1997	Scrap metal recycling	0.72		0.0025
	Langenbeck retractor (medium) x2	Stainless steel	163.82	1997	Scrap metal recycling	0.50		0.0017
	Mayo needle holder x 2	Stainless steel	99.64	1775	Scrap metal recycling	0.34		0.0012
	Mayo scissors (curved, 6")	Stainless steel	63.35	1109	Scrap metal recycling	0.35		0.0012
	Mayo scissors (straight, 6")	Stainless steel	48.60	976	Scrap metal recycling	0.31		0.0011
	McDonald dissector	Stainless steel	23.88	1775	Scrap metal recycling	0.08		0.0003
	McGoey punch	Stainless steel	270.51	888	Scrap metal recycling	1.87		0.0065
	McIndoe scissor	Stainless steel	42.39	1109	Scrap metal recycling	0.23		0.0008
	Norfolk and Norwich retractor x2	Stainless steel	384.70	1109	Scrap metal recycling	2.13		0.0074
	Osteotome (25 mm)	Stainless steel	127.17	1109	Scrap metal recycling	0.70		0.0024
	Osteotome (8 mm)	Stainless steel	134.27	1109	Scrap metal recycling	0.74		0.0026
	Pin for instruments	Stainless steel	12.74	2663	Scrap metal recycling	0.03		0.0001
	Quiver	Polypropylene injection moulding	96.17	888	Scrap metal recycling	0.49		0.0023
	Scalpel handle (no. 4) x2	Stainless steel	58.72	666	Scrap metal recycling	0.54		0.0019
	Scalpel handle (no. 4L)	Stainless steel	57.62	666	Scrap metal recycling	0.53		0.0018
	Spencer Wells artery forceps (curved, 7") x2	Stainless steel	102.12	1775	Scrap metal recycling	0.35		0.0012
	Spencer Wells artery forceps (straight, 5") x2	Stainless steel	62.94	1775	Scrap metal recycling	0.22		0.0008

	Sponge holder x3	Stainless steel	232.29	1997	Scrap metal recycling	0.71		0.0025
	Stitch scissor	Stainless steel	31.24	1331	Scrap metal recycling	0.14		0.0005
	Towel clip x3	Stainless steel	88.11	1109	Scrap metal recycling	0.49		0.0017
	Trethowan bone lever x2	Stainless steel	81.48	1109	Scrap metal recycling	0.45		0.0016
	Treves dissecting forceps	Stainless steel	29.11	1775	Scrap metal recycling	0.10		0.0003
	Universal orange scissor	Stainless steel	45.69	444	Medicinal contaminated sharps waste	0.63		0.1106
		Glass reinforced plastic	45.69			0.83		0.1106
Total basic major orthopaedic set=2,288.88 g CO_2e						**127.58**	**2,153.96**	**7.34**
Miscellaneous knee system set								
Sterile barrier system	Container	Aluminium cast	3,099.44	1000	Scrap metal recycling	20.83	See total	0.0660
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89		1.0134
	Tray	Stainless steel	2,278.39	1000	Non-infectious offensive waste	14.00	See total	0.5672
		Acrylonitrile Butadiene Styrene	119.92		Non-infectious offensive waste	0.45		0.0299
Instruments and set products	Drill bit/ pins x4	Stainless steel	10.59	688	Scrap metal recycling	0.09		0.0003
		Stainless steel	1,102.82	688		9.85		0.3991

	Instruments (bottom tray, 12 products)				Non-infectious offensive waste			
		High density polyethylene resin	275.71			0.77		0.0998
	Instruments (top tray, 13 products)	Stainless steel	1,320.89	688	Non-infectious offensive waste	11.80		0.4780
		High density polyethylene resin	330.22			0.93		0.1195
	Nails (short, headed) x4	Stainless steel	7.14	688	Scrap metal recycling	0.06		0.0002
	Pins (long, headless) x4	Stainless steel	14.24	688	Scrap metal recycling	0.13		0.0004
Total miscellaneous set=2,239.23 g CO_2e						**77.67**	**2,153.96**	**7.60**
Femoral and tibial preparation set (size 3-6)								
Sterile barrier system	Container	Aluminium cast	3,099.44	1000	Scrap metal recycling	20.83	See total	0.0660
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89		1.0134
	Tray	Stainless steel	2,996.19	1000	Non-infectious offensive waste	18.41	See total	0.7458
		Acrylonitrile Butadiene Styrene	157.69			0.59		0.0393
Instruments and set products	Instruments (bottom tray, 13 products)	Stainless steel	3,679.06	2040	Non-infectious offensive waste	11.08		0.4489
		High density polyethylene resin	164.47			0.16		0.0201
	Instruments (top tray, 17 products)	Stainless steel	1,480.21	2040	Scrap metal recycling	4.46		0.0155

Total femoral and tibial preparation set (size 3-6) = 2,235.42 g CO_2e						**74.28**	**2,153.96**	**7.18**
Cruciate retaining femoral and tibial trialing set (size 3-6)								
Sterile barrier system	Container	Aluminium cast	3,099.44	1000	Scrap metal recycling	20.83	See total	0.0660
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89		1.0134
	Tray	Stainless steel	2,457.99	1000	Non-infectious offensive waste	15.10	See total	0.6119
		Acrylonitrile Butadiene Styrene	129.37	1000		0.49		0.0322
Instruments and set products	Instruments (bottom tray, 12 products)	Stainless steel	370.56	1126	Scrap metal recycling	2.02		0.0070
	Instruments (top tray, 16 products)	Stainless steel	1,988.55	1126	Scrap metal recycling	10.86		0.0376
		Nylon (polyamide) 6 polymer	61.40		Non-infectious offensive waste	0.50		0.0136
Total cruciate retaining femoral and tibial trialing set (size 3-6) = 2,229.12 g CO_2e						**68.55**	**2,153.96**	**6.61**
Posterior stabilised femoral and tibial trialing set (size 3-6)								
Sterile barrier system	Container	Aluminium cast	3,099.44	1000	Scrap metal recycling	20.83	See total	0.0660
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444

	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89		1.0134
	Tray	Stainless steel	2,643.49	1000	Non-infectious offensive waste	16.24	See total	0.6580
		Acrylonitrile Butadiene Styrene	139.13			0.52		0.0346
Instruments and set products	Instruments (bottom tray, 16 products)	Acrylonitrile Butadiene Styrene	407.84	610	Non-infectious offensive waste	2.51		0.1664
	Instruments (top tray, 16 products)	Stainless steel	2,874.83	610	Scrap metal recycling	28.96		0.1004
		Nylon (polyamide) 6 polymer	69.35		Non-infectious offensive waste	1.04		0.0283
Total posterior stabilised femoral and tibial trialing set (size 3-6) = 2,249.72 g CO_2e						**88.86**	**2,153.96**	**6.89**
Cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8)								
Sterile barrier system	Container	Aluminium cast	3,099.44	1,000	Scrap metal recycling	20.83	See total	0.0660
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89		1.0134
	Tray	Stainless steel	2,667.63	1,000	Non-infectious offensive waste	16.39	See total	0.6641
		Acrylonitrile Butadiene Styrene	140.40			0.53		0.0349
	Instruments (bottom tray, 18 products)	Stainless steel	1685.78	174	Scrap metal recycling	59.54		0.2063

Instruments and set products		Nylon (polyamide) 6 polymer	235.31		Non-infectious offensive waste	12.36		0.3366
	Instruments (top tray, 19 products)	Stainless steel	1812.36	174	Scrap metal recycling	64.01		0.2218
		Nylon (polyamide) 6 polymer	220.42		Non-infectious offensive waste	11.58		0.3153
Total cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8) = 2,365.63 g CO_2e						**203.98**	**2,153.96**	**7.69**
Patella preparation and trialing set								
Sterile barrier system	Container	Aluminium cast	3,099.44	1,000	Scrap metal recycling	20.83	See total	0.0660
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89		1.0134
	Tray	Stainless steel	2944.47	1,000	Non-infectious offensive waste	18.09	See total	0.7330
		Acrylonitrile Butadiene Styrene	154.97			0.58		0.0386
Instruments and set products	Instruments (bottom tray, 13 products)	Stainless steel	49.20	500	Scrap metal recycling	0.60		0.0021
	Instruments (top tray, 5 products)	Stainless steel	1300.49	500	Scrap metal recycling	15.98		0.0554
		Brass	407.50			3.91		0.0174
Total patella preparation and trialing set= 2,239.47 g CO_2e						**78.76**	**2,153.96**	**6.75**
Orthopaedic surgical drill set								

Sterile barrier system	Container	Aluminium cast	3,099.44	1,000	Scrap metal recycling	20.83	See total	0.0660
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89		1.0134
	Tray	Stainless steel	1322.95	1,000	Non-infectious offensive waste	8.13	See total	0.3293
Instruments and set products	Instruments (13 products)	Stainless steel	3498.15	473	Scrap metal recycling	45.45		0.0282
		Acrylonitrile Butadiene Styrene	320.20		Non-infectious offensive waste	2.55		0.1685
Total orthopaedic surgical drill set= 2,255.92 g CO_2e						**95.70**	**2,153.96**	**626**
Knee navigation set								
Sterile barrier system	Container	Aluminium cast	3,099.44	1,000	Scrap metal recycling	20.83	See total	0.0660
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Pin mat	Silicone	110.25	888	Non-infectious offensive waste	0.41	See total	0.0309
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89	N/A	1.0134
	Tray	Stainless steel	3089.65	1000	Scrap metal recycling	18.99	See total	0.0658
		Stainless steel	901.24	248		22.38		0.9064

Instruments and set products	Instruments (13 products)	High density polyethylene resin	56.33		Non-infectious offensive waste	0.44		0.0567
		Acrylonitrile Butadiene Styrene	168.98			2.57		0.1700
Total knee navigation set= 2,245.46 g CO_2e						**84.36**	**2,153.96**	**7.14**
Diathermy extras								
Sterile barrier system	Flexible pouch	General polyethylene	15.42	1	Infectious waste	39.17	N/A	8.7788
		Paper	10.46			15.59		5.9550
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tray	Paper	20.41	1	Scrap metal recycling	30.41	See total	0.4346
Instruments and set products	Bipolar diathermy forceps	Stainless steel	31.98	40	Medicinal contaminated sharps waste	4.91		0.8588
		High density polyethylene resin	31.98			1.54		0.8588
	Diathermy lead	Polyvinylchloride general	74.62	50	Non-infectious offensive waste	4.63		0.3715
		Copper	8.29			0.63		0.0413
	Monopolar diathermy	Stainless steel	28.91	40	Medicinal contaminated sharps waste	4.44		0.7763
		High Density Polyethylene Resin	28.91			1.39		0.7763
Total diathermy extras= 277.33 g CO_2e						**110.28**	**145.38**	**21.66**
Bipolar diathermy								

Sterile barrier system	Flexible pouch	General polyethylene	15.42	1	Infectious waste	39.17	N/A	8.7788
		Paper	10.46			15.59		5.9550
Instruments and set products	Bipolar diathermy forceps	Stainless steel	31.98	40	Medicinal contaminated sharps waste	4.91	See total	0.8588
		High density polyethylene resin	31.98			1.54		0.8588
					Bipolar diathermy = 223.04 g CO_2e	**61.21**	**145.38**	**16.45**
				Diathermy lead				
Sterile barrier system	Flexible pouch	General polyethylene	15.42	1	Infectious waste	39.17	N/A	8.7788
		Paper	10.46			15.59		5.9550
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
Instruments and set products	Diathermy lead	Polyvinylchloride general	74.62	50	Non-infectious offensive waste	4.63		0.3715
		Copper	8.29			0.63		0.0413
					Total diathermy lead= 220.93 g CO_2e	**60.35**	**145.38**	**15.19**
				Blunt Hohman bone elevator				
Sterile barrier system	Flexible pouch	General polyethylene	11.14	1	Infectious waste	28.30	N/A	6.3421
		Paper	8.06			12.01		4.5887
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444

Instruments and set products	Blunt Hohman bone elevator	Stainless steel	131.44	375	Scrap metal recycling	2.15		0.0075
Total blunt Hohman bone elevator= 199.17 g CO_2e						**42.80**	**145.38**	**10.98**
Lanes tissue forceps								
Sterile barrier system	Flexible pouch	General polyethylene	11.14	1	Infectious waste	28.30	N/A	6.3421
		Paper	8.06			12.01		4.5887
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
Instruments and set products	Lanes tissue forceps	Stainless steel	81.28	300	Scrap metal recycling	1.66		0.0058
Total Lanes tissue forceps= 198.68 g CO_2e						**42.31**	**145.38**	**10.98**
Light cover								
Sterile barrier system	Flexible pouch	General polyethylene	11.14	1	Infectious waste	28.30	N/A	6.3421
		Paper	8.06			12.01		4.5887
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
Instruments and set products	Light cover	High density polyethylene resin	183.71	393	Non-infectious offensive waste	0.90		0.2661
Total light cover= 198.18 g CO_2e						**41.55**	**145.38**	**11.24**
Light handle								

Sterile barrier system	Flexible pouch	General polyethylene	11.14	1	Infectious waste	28.30	N/A	6.3421
		Paper	8.06			12.01		4.5887
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
Instruments and set products	Light handle	High density polyethylene resin	87.05	188	Non-infectious offensive waste	0.89		0.2636
Total light handle= 198.17 g CO_2e						**41.54**	**145.38**	**11.24**
Non-toothed lamina spreader (large)								
Sterile barrier system	Flexible pouch	General polyethylene	15.42	1	Infectious waste	39.17	N/A	8.7788
		Paper	10.46			15.59		5.9550
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
Instruments and set products	Non-toothed lamina spreader (large)	Stainless steel	430.38	308	Scrap metal recycling	8.59		0.0298
Total non-toothed lamina spreader (large)= 223.88 g CO_2e						**63.68**	**145.38**	**14.81**
Non-toothed lamina spreader (small)								
Sterile barrier system	Flexible pouch	General polyethylene	11.14	1	Infectious waste	28.30	N/A	6.3421
		Paper	8.06			12.01		4.5887
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444

Instruments and set products	Non-toothed lamina spreader (small)	Stainless steel	130.42	225	Scrap metal recycling	3.56		0.0123
Total non-toothed lamina spreader (small)= 200.58 g CO_2e						**44.21**	**145.38**	**10.99**
Semb bone holding forceps (small)								
Sterile barrier system	Flexible pouch	General polyethylene	8.3	1	Infectious waste	21.08	N/A	4.7253
		Paper	5.21			7.76		2.9661
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
Instruments and set products	Semb bone holding forceps	Stainless steel	159.08	186	Scrap metal recycling	5.25		0.0182
Total Semb bone holding forceps = 187.57 g CO_2e						**34.44**	**145.38**	**7.75**

Supplementary table 11: Carbon footprint of reusable (non-set) and single-use products used for knee arthroplasty
Table includes all single-use products used across all observed operations listed here and the carbon footprint per product as listed. Products used for individual operations varied, alongside number of products used. The material composition of products was determined through packaging and manufacturer information where available, and alternatively through expert assessment, taking into account available emission factors. Weight reported as total for a given product (accounting for multiple products where relevant). 'Use' equates to linen laundering of reusable linens. Carbon footprint per use equates to a single use of a product in a single operation. CO_2e= carbon dioxide equivalents, ops.= operations

Product	Component	Material(s)	Weight (g), or cost where specified with (£)	Number of uses	Number of ops per use	Waste stream A	Waste stream B	Carbon footprint per use (g CO_2e)					
								Production	Use	Waste stream A	Waste stream B	Total (waste A)	Total (waste B)
Reusable personal protective equipment													
Reusable scrubs	Product	Cotton fabric	421.17	75	3	Clothing recycling	N/A	12.69	64.65	0.04	N/A	77.39	N/A
Non-set reusable equipment													
Shaver base	Product	High density polyethylene resin	38.15	1300	1	Infectious waste	N/A	0.06	N/A	0.02	N/A	0.07	N/A
		Aluminium cast	35.43					0.18	N/A	0.02	N/A	0.20	N/A
		Lithium-ion battery	35.43			Batteries recycling		0.17	N/A	0.00	N/A	0.17	N/A
Single-use personal protective equipment from 'Knee pack' set													
Gown	Product	Polypropylene oriented film	260.60	1	1	Infectious waste	N/A	893.87	N/A	148.37	N/A	1,042.24	N/A
		Rubber	13.72					39.09	N/A	7.81	N/A	46.90	N/A

Knee pack packaging (equipment component)	Packaging	Paper	14.33	1	1	Infectious waste	N/A	21.35	N/A	8.16	N/A	29.51	N/A
		Polyethylene terephthalate	5.20					20.96	N/A	2.96	N/A	23.92	N/A
		Polypropylene oriented film	0.55					1.87	N/A	0.31	N/A	2.19	N/A
Single-use patient and instrument table drapes from 'Knee pack' set													
Patient drape (240x150 cm)	Product	Polypropylene oriented film	284.23	1	1	Infectious waste	N/A	974.91	N/A	161.82	N/A	1,136.72	N/A
		Paper	12.95					19.30	N/A	7.37	N/A	26.67	N/A
Patient drape (90 x75 cm)	Product	Polypropylene oriented film	54.79	1	1	Infectious waste	N/A	187.93	N/A	31.19	N/A	219.12	N/A
		Paper	4.63					6.90	N/A	2.64	N/A	9.53	N/A
Patient drape (extremity, 230x325 cm)	Product	Polypropylene oriented film	396.77	1	1	Infectious waste	N/A	1,360.92	N/A	225.89	N/A	1,586.81	N/A
		Rubber	14.33					40.84	N/A	8.16	N/A	49.00	N/A
Patient drape (impervious, split, 152x177 cm)	Product	Polyvinylchloride general	175.56	1	1	Infectious waste	N/A	544.24	N/A	99.95	N/A	644.18	N/A
Patient drape (Mayo cover, 75x144 cm) x2	Product	Polyvinylchloride general	90.01	1	1	Infectious waste	N/A	279.03	N/A	51.24	N/A	330.27	N/A
		Nylon (polyamide) 6 polymer	19.90					500.78	N/A	11.33	N/A	512.11	N/A
Patient drape (pouch fluid collection, 40x35 cm)	Product	Low density polyethylene film	26.10	1	1	Infectious waste	N/A	1,031.60	N/A	225.89	N/A	1,257.49	N/A
	Packaging	Paper	26.10					21.35	N/A	8.16	N/A	29.51	N/A
Patient drape (stockinette,	Product	Polyvinylchloride general	66.93	1	1	Infectious waste	N/A	279.03	N/A	51.24	N/A	330.27	N/A

impervious, 30x120 cm)		Nylon (polyamide) 6 polymer	72.06					238.55	N/A	14.86	N/A	253.41	N/A
Table drape (140x90 cm)	Product	Polyvinylchloride general	119.47	1	1	Infectious waste	N/A	207.48	N/A	38.10	N/A	245.59	N/A
		Nylon (polyamide) 6 polymer	59.73					1,091.93	N/A	68.01	N/A	1,159.94	N/A
Table drape (fan folded, 140x190 cm)	Product	Polyvinylchloride general	121.79	1	1	Infectious waste	N/A	377.54	N/A	69.33	N/A	446.87	N/A
		Nylon (polyamide) 6 polymer	60.89					556.53	N/A	34.67	N/A	591.20	N/A
Knee pack packaging (equipment component)	Packaging	Paper	88.32	1	1	Infectious waste	N/A	131.59	N/A	50.28	N/A	181.87	N/A
		Polyethylene terephthalate	32.04					129.20	N/A	18.24	N/A	147.45	N/A
		Polypropylene oriented film	3.37					11.55	N/A	1.92	N/A	13.47	N/A
Single-use equipment from 'Knee pack' set													
Bowl (250 ml) x2	Product	Polypropylene injection moulding	13.24	1	1	Infectious waste	N/A	59.45	N/A	7.54	N/A	66.99	N/A
Bowl (500 ml)	Product	Polypropylene injection moulding	18.13	1	1	Infectious waste	N/A	81.40	N/A	10.32	N/A	91.73	N/A
Cast padding bandage x2	Product	Cotton padding	47.56	1	1	Infectious waste	N/A	60.88	N/A	27.08	N/A	87.95	N/A
	Packaging	Paper	48.56					72.35	N/A	27.65	N/A	100.00	N/A
Crepe bandage x2	Product	Cotton fabric	74.84	1	1	Infectious waste	N/A	507.42	N/A	42.61	N/A	550.02	N/A
Diathermy bag	Product	Low density polyethylene film	18.47	1	1	Infectious waste	N/A	48.02	N/A	10.52	N/A	58.54	N/A
	Packaging	Paper	1.92					2.86	N/A	1.09	N/A	3.95	N/A
Diathermy tip cleaner	Product	Polyurethane flexible foam	1.65	1	1	Infectious waste	N/A	7.97	N/A	0.94	N/A	8.91	N/A

		Nylon (polyamide) 6 polymer	0.18					1.65	N/A	0.10	N/A	1.75	N/A
	Packaging	Paper	0.15					0.22	N/A	0.09	N/A	0.31	N/A
Kidney dish x3	Product	Polypropylene oriented film	28.71	1	1	Infectious waste	N/A	98.48	N/A	16.34	N/A	114.82	N/A
Light cover	Product	Low density polyethylene film	4.46	1	1	Infectious waste	N/A	11.60	N/A	2.54	N/A	14.14	N/A
Monopolar diathermy	Product	High density polyethylene resin	24.15	1	1	Medicinal contaminated sharps waste	N/A	46.60	N/A	25.94	N/A	72.54	N/A
		Polyvinylchloride general	34.31			Infectious waste		106.36	N/A	19.53	N/A	125.89	N/A
		Stainless steel	3.39			Medicinal contaminated sharps waste		20.83	N/A	3.64	N/A	24.47	N/A
		Copper	3.81			Infectious waste		14.52	N/A	2.17	N/A	16.69	N/A
	Packaging	Paper	0.27					0.40	N/A	0.15	N/A	0.56	N/A
Needle counter	Product	Acrylonitrile Butadiene Styrene	44.50	1	1	Infectious waste	N/A	167.32	N/A	25.33	N/A	192.65	N/A
		Polyurethane flexible foam	4.00					19.36	N/A	2.28	N/A	21.64	N/A
Skin marker pen	Product	High density polyethylene resin	8.45	1	1	Infectious waste	N/A	16.31	N/A	4.81	N/A	21.12	N/A
		Paper	0.45					0.67	N/A	0.26	N/A	0.93	N/A
Suction tubing	Product	Polyvinylchloride general	116.66	1	1	Infectious waste	N/A	361.65	N/A	66.42	N/A	428.06	N/A
		High density polyethylene resin	3.43					6.62	N/A	1.95	N/A	8.57	N/A
Surgical blade (10) x3	Product	Stainless steel	0.61	1	1	Medicinal contaminated sharps waste	N/A	3.75	N/A	0.66	N/A	4.40	N/A

	Packaging	Aluminium foil	0.46			Infectious waste		3.44	N/A	0.26	N/A	3.70	N/A
Swab gauze (10x7.5 cm) x5	Product	Cotton fabric	4.42	1	1	Infectious waste	N/A	29.97	N/A	2.52	N/A	32.48	N/A
Swab gauze (30x30 cm) x10	Product	Cotton fabric	18.39	1	1	Infectious waste	N/A	124.68	N/A	10.47	N/A	135.15	N/A
Towel dressing (2 in pack)	Product	Paper	21.18	1	1	Infectious waste	N/A	31.56	N/A	12.06	N/A	43.62	N/A
Tray (small)	Product	Polypropylene injection moulding	116.43	1	1	Infectious waste	N/A	522.77	N/A	66.29	N/A	589.06	N/A
Yankauer sucker	Product	Polyvinylchloride injection moulding	16.98	1	1	Infectious waste	N/A	56.03	N/A	9.67	N/A	65.70	N/A
Knee pack packaging (equipment component)	Packaging	Paper	37.38	1	1	Infectious waste	N/A	55.69	N/A	21.28	N/A	76.97	N/A
		Polyethylene terephthalate	13.56					54.68	N/A	7.72	N/A	62.40	N/A
		Polypropylene oriented film	1.43					4.89	N/A	0.81	N/A	5.70	N/A
Single-use personal protective equipment													
Gloves (non-sterile, pair)	Product	Rubber	6.45	1	1	Infectious waste	N/A	18.38	N/A	3.67	N/A	22.05	N/A
Orthopaedic hood	Product	Polypropylene oriented film	61.68	1	1	Infectious waste	N/A	211.56	N/A	35.12	N/A	246.68	N/A
		Low density polyethylene film	33.69					87.59	N/A	19.18	N/A	106.77	N/A
		Stainless steel	33.69					207.03	N/A	19.18	N/A	226.21	N/A
	Packaging	Low density polyethylene film	18.02				Non-infectious offensive waste	46.85	N/A	10.26	4.49	57.11	51.34
		Polypropylene oriented film	9.42					32.31	N/A	5.36	2.34	37.67	34.66

Sterile gloves (pair)	Product	Rubber	27.31	1	1	Infectious waste	N/A	77.83	N/A	15.55	N/A	93.38	N/A
	Packaging	General polyethylene	5.98				Non-infectious offensive waste	15.19	N/A	3.40	1.49	18.59	16.68
		Paper	5.91					8.81	N/A	3.36	1.47	12.17	10.28
Sterile gloves (two pairs)	Product	Rubber	42.14	1	1	Infectious waste	N/A	120.10	N/A	23.99	N/A	144.09	N/A
	Packaging	Paper	11.61				Non-infectious offensive waste	17.30	N/A	6.61	2.89	23.91	20.19
		General polyethylene	5.61					14.25	N/A	3.19	1.40	17.44	15.65
Sterile gloves (two pair, latex free)	Product	General polyethylene	44.68	1	1	Infectious waste	N/A	113.49	N/A	25.44	N/A	138.92	N/A
	Packaging	Paper	11.66				Non-infectious offensive waste	17.37	N/A	6.64	2.90	24.01	20.28
		General polyethylene	5.71					14.50	N/A	3.25	1.42	17.75	15.92
Surgical face mask	Product	Polypropylene oriented film	4.36	1	1	Infectious waste	N/A	14.95	N/A	2.48	N/A	17.44	N/A
Surgical face mask with eye protection	Product	Polypropylene oriented film	6.23	1	1	Infectious waste	N/A	21.37	N/A	3.55	N/A	24.92	N/A
		Low density polyethylene film	4.04					10.50	N/A	2.30	N/A	12.80	N/A
Surgical gown (including hand towels)	Product	Polypropylene oriented film	139.00	1	1	Infectious waste	N/A	476.78	N/A	79.14	N/A	555.92	N/A
		Rubber	7.32					20.85	N/A	4.17	N/A	25.02	N/A
		Paper	13.83					20.61	N/A	7.87	N/A	28.48	N/A
	Packaging	Low density polyethylene film	5.11	1	1		Non-infectious offensive waste	13.29	N/A	2.91	1.27	16.20	14.56
		Paper	25.34					37.76	N/A	14.43	6.31	52.18	44.06
Surgical hat	Product	Polypropylene oriented film	3.54	1	1	Infectious waste	N/A	12.14	N/A	2.02	N/A	14.16	N/A

Sweat bands for hood x3	Product	Polyurethane flexible foam	3.29	1	1	Infectious waste	N/A	15.92	N/A	1.87	N/A	17.80	N/A
		Polyethylene terephthalate	0.37					1.49	N/A	0.21	N/A	1.70	N/A
Single-use patient and instrument table drapes													
Patient drape (adhesive split sheet)	Product	Polypropylene oriented film	231.80	1	1	Infectious waste	N/A	795.07	N/A	131.97	N/A	927.04	N/A
	Packaging	Paper	8.13					12.11	N/A	4.63	N/A	16.74	N/A
		Low density polyethylene film	6.48					16.85	N/A	3.69	N/A	20.54	N/A
		Polypropylene oriented film	6.46					22.16	N/A	3.68	N/A	25.84	N/A
Patient drape (clear U drape)	Product	Low density polyethylene film	115.94	1	1	Infectious waste	N/A	301.44	N/A	66.01	N/A	367.45	N/A
	Packaging	Low density polyethylene film	18.15					47.19	N/A	10.33	N/A	57.52	N/A
		Paper	7.67					11.43	N/A	4.37	N/A	15.79	N/A
Patient drape (incise drape)	Product	Low density polyethylene film	36.52	1	1	Infectious waste	N/A	94.95	N/A	20.79	N/A	115.74	N/A
	Packaging	Paper	71.62					106.71	N/A	40.77	N/A	147.49	N/A
		General polyethylene	8.69					22.07	N/A	4.95	N/A	27.02	N/A
Patient drape (incise drape, with iodine)	Product	Low density polyethylene film	23.30	1	1	Infectious waste	N/A	60.58	N/A	13.27	N/A	73.85	N/A
		Iodine	£0.04					7.91	N/A	1.47	N/A	9.38	N/A
	Packaging	Paper	52.17					77.73	N/A	29.70	N/A	107.43	N/A
		General polyethylene	15.89					40.36	N/A	9.05	N/A	49.41	N/A

Table drape (instruments)	Product	Polyvinylchloride general	375.06	1	1	Infectious waste	N/A	1162.69	N/A	213.53	N/A	1376.21	N/A
	Packaging	Paper	12.67					18.88	N/A	7.21	N/A	26.09	N/A
		Nylon (polyamide) 6 polymer	8.56					78.24	N/A	4.87	N/A	83.11	N/A
		Low density polyethylene film	6.02					15.65	N/A	3.43	N/A	19.08	N/A
Single-use equipment and medical devices													
Adhesive operative towel	Product	Nylon (polyamide) 6 polymer	20.41	1	1	Infectious waste	N/A	186.55	N/A	11.62	N/A	198.17	N/A
		Polyvinylchloride general	20.41					63.27	N/A	11.62	N/A	74.89	N/A
	Packaging	Low density polyethylene film	9.25					24.05	N/A	5.27	N/A	29.32	N/A
		Paper	3.36					5.01	N/A	1.91	N/A	6.92	N/A
Batteries for knee navigation set (x3)	Product	Lithium-ion battery	9.81	1	1	Batteries recycling	N/A	61.88	N/A	0.21	N/A	62.09	N/A
		Aluminium cast	1.09					7.32	N/A	0.02	N/A	7.35	N/A
	Packaging	Low density polyethylene film	4.19			Infectious waste		10.89	N/A	2.39	N/A	13.28	N/A
		Polypropylene oriented film	3.16					10.84	N/A	1.80	N/A	12.64	N/A
Border dressing (10x30 cm)	Product	Cotton padding	10.67	1	1	Infectious waste	N/A	13.66	N/A	6.07	N/A	19.73	N/A
		Low density polyethylene film	0.56					1.46	N/A	0.32	N/A	1.78	N/A
	Packaging	Paper	3.22					4.80	N/A	1.83	N/A	6.63	N/A
		Polypropylene oriented film	2.90					9.95	N/A	1.65	N/A	11.60	N/A

		Low density polyethylene film	2.53					6.58	N/A	1.44	N/A	8.02	N/A
Border dressing (6x8 cm)	Product	Cotton padding	1.68	1	1	Infectious waste	N/A	2.15	N/A	0.96	N/A	3.11	N/A
		Low density polyethylene film	0.09					0.23	N/A	0.05	N/A	0.28	N/A
	Packaging	Paper	1.07					1.59	N/A	0.61	N/A	2.20	N/A
		Low density polyethylene film	0.86					2.24	N/A	0.49	N/A	2.73	N/A
		Polypropylene oriented film	0.73					2.50	N/A	0.42	N/A	2.92	N/A
Catheter tip syringe	Product	High density polyethylene resin	28.03	1	1	Infectious waste	N/A	54.10	N/A	15.96	N/A	70.06	N/A
	Packaging	Low density polyethylene film	2.16					5.62	N/A	1.23	N/A	6.85	N/A
		Paper	1.07					1.59	N/A	0.61	N/A	2.20	N/A
Cement mixing and delivery system	Product	High density polyethylene resin	214.15	1	1	Infectious waste	N/A	413.31	N/A	121.92	N/A	535.23	N/A
		Polyvinylchloride injection moulding	37.04					122.23	N/A	21.09	N/A	143.32	N/A
		Low density polyethylene resin	24.73					51.44	N/A	14.08	N/A	65.52	N/A
		Glass reinforced plastic	13.10					106.11	N/A	7.46	N/A	113.57	N/A
	Packaging	General purpose polystyrene	98.78					338.82	N/A	56.24	N/A	395.05	N/A
		Polypropylene oriented film	11.82					40.54	N/A	6.73	N/A	47.27	N/A
		Low density polyethylene film	4.74					12.32	N/A	2.70	N/A	15.02	N/A
Cement mixing bowl	Product	Glass reinforced plastic	164.54	1	1	Infectious waste	N/A	1,332.77	N/A	93.67	N/A	1,426.45	N/A
		Polyvinylchloride general	36.69					113.74	N/A	20.89	N/A	134.63	N/A

		High density polyethylene resin	26.19					50.55	N/A	14.91	N/A	65.46	N/A
	Packaging	General purpose polystyrene	81.14					278.31	N/A	46.19	N/A	324.50	N/A
		Low density polyethylene film	18.26					47.48	N/A	10.40	N/A	57.87	N/A
		Polypropylene oriented film	6.76					23.19	N/A	3.85	N/A	27.04	N/A
Crepe bandage (15 cm wide)	Product	Cotton fabric	77.55	1	1	Infectious waste	N/A	525.79	N/A	44.15	N/A	569.94	N/A
	Packaging	Paper	5.66					8.43	N/A	3.22	N/A	11.66	N/A
		Polypropylene oriented film	3.57					12.25	N/A	2.03	N/A	14.28	N/A
		Low density polyethylene film	3.19					8.29	N/A	1.82	N/A	10.11	N/A
Cruciate retaining femoral implant	Product	Titanium	251.99	1	1	N/A	N/A	5,190.99	N/A	0.00	N/A	5,190.99	N/A
	Packaging	Paper	101.71			Domestic waste		151.55	N/A	17.47	N/A	169.02	N/A
		Polyethylene terephthalate	30.83			Infectious waste		124.32	N/A	17.55	N/A	141.87	N/A
		Polypropylene oriented film	2.50					8.58	N/A	1.42	N/A	10.00	N/A
		Low density polyethylene resin	2.41					5.01	N/A	1.37	N/A	6.38	N/A
Diathermy bag	Product	Low density polyethylene film	18.47	1	1	Infectious waste	N/A	48.02	N/A	10.52	N/A	58.54	N/A
	Packaging	Low density polyethylene film	4.03					10.48	N/A	2.29	N/A	12.77	N/A
		Paper	1.92					2.86	N/A	1.09	N/A	3.95	N/A
Diathermy tip	Product	Stainless steel	1.58	1	1	Medicinal contaminated sharps waste	N/A	9.72	N/A	1.70	N/A	11.42	N/A
		High density polyethylene resin	0.53					1.02	N/A	0.57	N/A	1.58	N/A

	Packaging	Low density polyethylene film	0.90			Infectious waste		2.34	N/A	0.51	N/A	2.85	N/A
		Paper	0.59					0.88	N/A	0.34	N/A	1.21	N/A
Diathermy tip cleaner	Product	Aluminium foil	5.49	1	1	Infectious waste	N/A	41.01	N/A	3.13	N/A	44.14	N/A
		General polyethylene	5.49					13.94	N/A	3.13	N/A	17.07	N/A
	Packaging	Polyethylene terephthalate	1.84					7.42	N/A	1.05	N/A	8.47	N/A
Elasticated fabric dressing strip	Product	Rubber	0.65	1	1	Infectious waste	N/A	1.85	N/A	0.37	N/A	2.22	N/A
Gauze (individual piece)	Product	Cotton fabric	5.06	1	1	Infectious waste	N/A	34.31	N/A	2.88	N/A	37.19	N/A
Gauze (sterile pack)	Product	Cotton fabric	25.52	1	1	Infectious waste	N/A	173.03	N/A	14.53	N/A	187.55	N/A
	Packaging	Paper	5.12					7.63	N/A	2.91	N/A	10.54	N/A
		Low density polyethylene resin	1.28					2.66	N/A	0.73	N/A	3.39	N/A
High-vacuum wound drainage	Product	General plastics	124.43	1	1	Infectious waste	N/A	411.86	N/A	70.84	N/A	482.70	N/A
		Polyvinylchloride general	35.26					109.31	N/A	20.07	N/A	129.38	N/A
		Stainless steel	13.87					85.23	N/A	7.90	N/A	93.13	N/A
		High density polyethylene resin	5.14					9.92	N/A	2.93	N/A	12.85	N/A
	Packaging	Low density polyethylene film	7.14					18.56	N/A	4.06	N/A	22.63	N/A
		Paper	2.35					3.50	N/A	1.34	N/A	4.84	N/A
Incontinence pad	Product	Low density polyethylene film	40.01	1	1	Infectious waste	N/A	104.03	N/A	22.78	N/A	126.80	N/A

		Cotton padding	40.01					51.21	N/A	22.78	N/A	73.99	N/A
Intravenous infusion giving set	Product	High density polyethylene resin	13.60	1	1	Infectious waste	N/A	26.25	N/A	7.74	N/A	33.99	N/A
		Low density polyethylene resin	27.49					57.18	N/A	15.65	N/A	72.83	N/A
	Packaging	Low density polyethylene film	2.16					5.62	N/A	1.23	N/A	6.85	N/A
		Paper	1.53					2.28	N/A	0.87	N/A	3.15	N/A
Marker pen and ruler	Product	High density polyethylene resin	6.27	1	1	Infectious waste	N/A	12.10	N/A	3.57	N/A	15.67	N/A
		Paper	0.59					0.88	N/A	0.34	N/A	1.21	N/A
	Packaging	Paper	1.85					2.76	N/A	1.05	N/A	3.81	N/A
		Low density polyethylene film	0.95					2.47	N/A	0.54	N/A	3.01	N/A
Monopolar diathermy	Product	Polyvinylchloride general	34.31	1	1	Medicinal contaminated sharps waste	N/A	46.60	N/A	25.94	N/A	72.54	N/A
		High density polyethylene resin	24.15					11.82	N/A	4.09	N/A	15.91	N/A
		Copper	3.81					14.52	N/A	4.09	N/A	18.62	N/A
		Stainless steel	3.39					20.83	N/A	3.64	N/A	24.47	N/A
	Packaging	Low density polyethylene film	3.61			Infectious waste		5.38	N/A	2.06	N/A	7.43	N/A
		Paper	3.27					6.80	N/A	1.86	N/A	8.66	N/A
Nail scrubbing brush	Product	Low density polyethylene resin	9.01	1	1	Infectious waste	N/A	18.74	N/A	5.13	N/A	23.87	N/A
		Polyurethane flexible foam	2.05					9.92	N/A	1.17	N/A	11.09	N/A
		Polypropylene injection moulding	0.91					4.09	N/A	0.52	N/A	4.60	N/A

	Packaging	Low density polyethylene film	1.31					3.41	N/A	0.75	N/A	4.15	N/A
		Paper	0.60					0.89	N/A	0.34	N/A	1.24	N/A
Needle (green)	Product Packaging	Stainless steel	0.20	1	1	Medicinal contaminated sharps waste	N/A	1.23	N/A	0.21	N/A	1.44	N/A
		Polypropylene injection moulding	0.05					0.22	N/A	0.05	N/A	0.28	N/A
		High density polyethylene resin	0.52			Infectious waste		1.00	N/A	0.30	N/A	1.30	N/A
		Low density polyethylene film	0.12					0.31	N/A	0.07	N/A	0.38	N/A
		Paper	0.11					0.16	N/A	0.06	N/A	0.23	N/A
Needle (red)	Product	Stainless steel	0.41	1	1	Medicinal contaminated sharps waste	N/A	2.51	N/A	0.44	N/A	2.95	N/A
		Polypropylene injection moulding	0.10					0.46	N/A	0.11	N/A	0.57	N/A
	Packaging	High density polyethylene resin	0.60			Infectious waste		1.16	N/A	0.34	N/A	1.50	N/A
		Low density polyethylene film	0.12					0.31	N/A	0.07	N/A	0.38	N/A
		Paper	0.11					0.16	N/A	0.06	N/A	0.23	N/A
Needle (white)	Product	Stainless steel	0.29	1	1	Medicinal contaminated sharps waste	N/A	1.77	N/A	0.31	N/A	2.08	N/A
		Polypropylene injection moulding	0.07					0.32	N/A	0.08	N/A	0.40	N/A
	Packaging	High density polyethylene resin	0.60			Infectious waste		1.16	N/A	0.34	N/A	1.50	N/A
		Low density polyethylene film	0.15					0.39	N/A	0.09	N/A	0.48	N/A
		Paper	0.10					0.15	N/A	0.06	N/A	0.21	N/A
Posterior stabilised	Product	Titanium	412.32	1	1	N/A	N/A	8,493.79	N/A	0.00	N/A	8,493.79	N/A

femoral implant	Packaging	Paper	101.71			Domestic waste		151.55	N/A	17.47	N/A	169.02	N/A
		Polyethylene terephthalate	30.83			Infectious waste		124.32	N/A	17.55	N/A	141.87	N/A
		Polypropylene oriented film	2.50					8.58	N/A	1.42	N/A	10.00	N/A
		Low density polyethylene resin	2.41					5.01	N/A	1.37	N/A	6.38	N/A
Pre-operative adhesive glove	Product	Low density polyethylene film	2.60	1	1	Infectious waste	N/A	6.76	N/A	1.48	N/A	8.24	N/A
	Packaging	Paper	1.73					2.58	N/A	0.98	N/A	3.56	N/A
Primary tibial baseplate implant	Product	Titanium	129.59	1	1	N/A	N/A	2,669.55	N/A	0.00	N/A	2,669.55	N/A
	Packaging	Paper	101.71			Domestic waste		151.55	N/A	17.47	N/A	169.02	N/A
		Polyethylene terephthalate	30.83			Infectious waste		124.32	N/A	17.55	N/A	141.87	N/A
		Polypropylene oriented film	2.50					8.58	N/A	1.42	N/A	10.00	N/A
		Low density polyethylene resin	2.41					5.01	N/A	1.37	N/A	6.38	N/A
Pulsed lavage system	Product	Acrylonitrile Butadiene Styrene	302.68	1	1	Infectious waste		1,138.08	N/A	172.32	N/A	1,310.40	N/A
		Polyvinylchloride general	282.35					875.28	N/A	160.74	N/A	1,036.02	N/A
		Lithium-ion battery	124.77			Batteries recycling		787.05	N/A	2.66	N/A	789.71	N/A
		Copper	5.76			Infectious waste		21.95	N/A	3.28	N/A	25.23	N/A
	Packaging	Polyethylene terephthalate	116.06					468.00	N/A	66.07	N/A	534.07	N/A
		Polypropylene oriented film	7.80					26.75	N/A	4.44	N/A	31.19	N/A

Saw blade	Product	Stainless steel	23.82	1	1	Medicinal contaminated sharps waste	N/A	146.37	N/A	25.59	N/A	171.96	N/A
	Packaging	Low density polyethylene film	1.81			Infectious waste		4.71	N/A	1.03	N/A	5.74	N/A
		General polyethylene	1.81					4.60	N/A	1.03	N/A	5.63	N/A
		Polypropylene oriented film	0.80					2.74	N/A	0.46	N/A	3.20	N/A
Self- adherent bandage	Product	Polyurethane flexible foam	57.58	1	1	Infectious waste	N/A	278.69	N/A	32.78	N/A	311.47	N/A
	Packaging	Paper	11.09					16.52	N/A	6.31	N/A	22.84	N/A
		Low density polyethylene film	2.49					6.47	N/A	1.42	N/A	7.89	N/A
Shaver head	Product	Stainless steel	2.90	1	1	Medicinal contaminated sharps waste	N/A	17.82	N/A	3.11	N/A	20.94	N/A
		Acrylonitrile Butadiene Styrene	2.76					10.36	N/A	2.96	N/A	13.32	N/A
		Low density polyethylene resin	2.76					5.73	N/A	2.96	N/A	8.69	N/A
	Packaging	Polyethylene terephthalate	0.77			Infectious waste		3.10	N/A	0.44	N/A	3.54	N/A
		Paper	0.23					0.34	N/A	0.13	N/A	0.47	N/A
Skin stapler	Product	Acrylonitrile Butadiene Styrene	51.50	1	1	Medicinal contaminated sharps waste	N/A	193.63	N/A	55.32	N/A	248.95	N/A
		Aluminium cast	4.58					30.76	N/A	4.92	N/A	35.68	N/A
		Stainless steel	1.14					7.03	N/A	1.23	N/A	8.26	N/A
	Packaging	Polyethylene terephthalate	15.00			Infectious waste	N/A	60.49	N/A	8.54	N/A	69.03	N/A
		Polypropylene oriented film	1.55					5.32	N/A	0.88	N/A	6.20	N/A

Sticky label	Product	Paper	0.40	1	1	Infectious waste	N/A	0.60	N/A	0.23	N/A	0.82	N/A
		Paper	0.25					0.37	N/A	0.14	N/A	0.51	N/A
Suction receptacle	Product	Low density polyethylene resin	72.62	1	1	Infectious waste	N/A	151.04	N/A	41.34	N/A	192.38	N/A
Suction tip	Product	High density polyethylene resin	18.68	1	1	Infectious waste	N/A	36.05	N/A	10.63	N/A	46.69	N/A
	Packaging	Paper	2.19					3.26	N/A	1.25	N/A	4.51	N/A
		Low density polyethylene film	2.17					5.64	N/A	1.24	N/A	6.88	N/A
Suction tubing	Product	Polyvinylchloride injection moulding	121.21	1	1	Infectious waste	N/A	399.99	N/A	69.01	N/A	469.00	N/A
	Packaging	Low density polyethylene film	5.40					14.04	N/A	3.07	N/A	17.11	N/A
		Paper	3.31					4.93	N/A	1.88	N/A	6.82	N/A
Surgical blade (10)	Product	Stainless steel	0.61	1	1	Medicinal contaminated sharps waste	N/A	3.75	N/A	0.66	N/A	4.40	N/A
	Packaging	Aluminium foil	0.46			Infectious waste		3.44	N/A	0.26	N/A	3.70	N/A
Suture (braided, absorbable, 2-0)	Product	Stainless steel	0.25	1	1	Medicinal contaminated sharps waste	N/A	1.54	N/A	0.27	N/A	1.80	N/A
		Nylon (polyamide) 6 polymer	0.23					2.10	N/A	0.25	N/A	2.35	N/A
	Packaging	High density polyethylene resin	3.19			Infectious waste		6.16	N/A	1.82	N/A	7.98	N/A
		Aluminium foil	1.25					9.34	N/A	0.71	N/A	10.05	N/A
		Low density polyethylene resin	0.47					0.98	N/A	0.27	N/A	1.25	N/A
		Polypropylene oriented film	0.60					2.06	N/A	0.34	N/A	2.40	N/A
	Product	Stainless steel	0.03	1	1		N/A	0.18	N/A	0.03	N/A	0.22	N/A

Suture (monofilament, absorbable, 3-0, 643)						Medicinal contaminated sharps waste							
		Nylon (polyamide) 6 polymer	0.05					0.46	N/A	0.05	N/A	0.51	N/A
	Packaging	Aluminium foil	1.33			Infectious waste		9.94	N/A	0.76	N/A	10.69	N/A
		Paper	0.88					1.31	N/A	0.50	N/A	1.81	N/A
		Low density polyethylene resin	0.50					1.04	N/A	0.28	N/A	1.32	N/A
		Polypropylene oriented film	0.61					2.09	N/A	0.35	N/A	2.44	N/A
Suture (monofilament, absorbable 3-0, 696)	Product	Stainless steel	0.03	1	1	Medicinal contaminated sharps waste	N/A	0.18	N/A	0.03	N/A	0.22	N/A
		Nylon (polyamide) 6 polymer	0.05					0.46	N/A	0.05	N/A	0.51	N/A
	Packaging	Aluminium foil	1.33			Infectious waste		9.94	N/A	0.76	N/A	10.69	N/A
		Paper	0.88					1.31	N/A	0.50	N/A	1.81	N/A
		Low density polyethylene resin	0.50					1.04	N/A	0.28	N/A	1.32	N/A
		Polypropylene oriented film	0.61					2.09	N/A	0.35	N/A	2.44	N/A
Suture (braided, absorbable 1-0, 803)	Product	Stainless steel	0.25	1	1	Medicinal contaminated sharps waste	N/A	1.54	N/A	0.27	N/A	1.80	N/A
		Nylon (polyamide) 6 polymer	0.23					2.10	N/A	0.25	N/A	2.35	N/A
	Packaging	High density polyethylene resin	3.19			Infectious waste		6.16	N/A	1.82	N/A	7.98	N/A
		Aluminium foil	1.25					9.34	N/A	0.71	N/A	10.05	N/A
		Low density polyethylene resin	0.47					0.98	N/A	0.27	N/A	1.25	N/A
		Polypropylene oriented film	0.60					2.06	N/A	0.34	N/A	2.40	N/A
	Product	stainless steel	0.25	1	1		N/A	1.54	N/A	0.27	N/A	1.80	N/A

Suture (braided, absorbable 1-0, 932)						Medicinal contaminated sharps waste							
		Nylon (polyamide) 6 polymer	0.02					0.21	N/A	0.02	N/A	0.23	N/A
	Packaging	High density polyethylene resin	3.19			Infectious waste		6.16	N/A	1.82	N/A	7.98	N/A
		Aluminium foil	1.25					9.34	N/A	0.71	N/A	10.05	N/A
		Low density polyethylene resin	0.47					0.98	N/A	0.27	N/A	1.25	N/A
		Polypropylene oriented film	0.60					2.06	N/A	0.34	N/A	2.40	N/A
Swab tray (large)	Product	Polyethylene terephthalate	58.32	1	1	Infectious waste	N/A	235.17	N/A	33.20	N/A	268.37	N/A
Swab tray (small)	Product	Polyethylene terephthalate	27.90	1	1	Infectious waste	N/A	112.50	N/A	15.88	N/A	128.39	N/A
Symmetric patella implant	Product	Titanium	10.70	1	1	N/A	N/A	220.42	N/A	0.00	N/A	220.42	N/A
	Packaging	Paper	71.41			Domestic waste		106.40	N/A	12.27	N/A	118.67	N/A
		General plastics	33.35			Infectious waste		110.39	N/A	18.99	N/A	129.38	N/A
		Aluminium foil	4.87					36.38	N/A	2.77	N/A	39.15	N/A
		Low density polyethylene resin	1.84					3.83	N/A	1.05	N/A	4.87	N/A
Syringe (20 ml)	Product	Polypropylene injection moulding	7.10	1	1	Infectious waste	N/A	31.90	N/A	4.04	N/A	35.94	N/A
		General polyethylene	7.10					18.04	N/A	4.04	N/A	22.09	N/A
		Rubber	0.59					1.69	N/A	0.34	N/A	2.02	N/A
	Packaging	Low density polyethylene film	1.11					2.89	N/A	0.63	N/A	3.52	N/A
		Paper	0.72					1.07	N/A	0.41	N/A	1.48	N/A

Syringe (50 ml)	Product	Polypropylene injection moulding	15.06	1	1	Infectious waste	N/A	67.63	N/A	8.58	N/A	76.21	N/A
		General polyethylene	15.06					38.26	N/A	8.58	N/A	46.83	N/A
		Rubber	1.26					3.58	N/A	0.71	N/A	4.29	N/A
	Packaging	Low density polyethylene film	2.35					6.11	N/A	1.34	N/A	7.45	N/A
		Paper	1.04					1.55	N/A	0.59	N/A	2.14	N/A
Tibial bearing insert cruciate retaining implant	Product	Titanium	36.33	1	1	N/A	N/A	748.40	N/A	0.00	N/A	748.40	N/A
	Packaging	Paper	91.30			Domestic waste		136.04	N/A	15.68	N/A	151.72	N/A
		General plastics	21.23			Infectious waste		70.27	N/A	12.09	N/A	82.36	N/A
		Aluminium foil	3.22					24.05	N/A	1.83	N/A	25.89	N/A
		Low density polyethylene resin	2.13					4.43	N/A	1.21	N/A	5.64	N/A
Tibial bearing insert posterior stabilised implant	Product	Titanium	40.97	1	1	N/A	N/A	843.98	N/A	0.00	N/A	843.98	N/A
	Packaging	Paper	91.30			Domestic waste		136.04	N/A	15.68	N/A	151.72	N/A
		General plastics	21.23			Infectious waste		70.27	N/A	12.09	N/A	82.36	N/A
		Aluminium foil	3.22					24.05	N/A	1.83	N/A	25.89	N/A
		Low density polyethylene resin	2.13					4.43	N/A	1.21	N/A	5.64	N/A
Tourniquet pressure cuff (leg)	Product	Polyvinylchloride general	165.14	1	1	Infectious waste	N/A	511.92	N/A	94.01	N/A	605.93	N/A
		High density polyethylene resin	136.95					264.30	N/A	77.96	N/A	342.27	N/A
	Packaging	Low density polyethylene film	10.19					26.49	N/A	5.80	N/A	32.30	N/A

Transparent film adhesive dressing	Product	Low density polyethylene film	0.62	1	1	Infectious waste	N/A	1.61	N/A	0.35	N/A	1.96	N/A
	Packaging	Paper	4.11					6.12	N/A	2.34	N/A	8.46	N/A
		Low density polyethylene film	1.45					3.77	N/A	0.83	N/A	4.60	N/A
Tubular support bandage	Product	Cotton fabric	29.22	1	1	Infectious waste	N/A	198.11	N/A	16.64	N/A	214.75	N/A
Wound closure strips	Product	General polyethylene	0.66	1	1	Infectious waste	N/A	1.68	N/A	0.38	N/A	2.05	N/A
	Packaging	Paper	1.49					2.22	N/A	0.85	N/A	3.07	N/A
		Low density polyethylene film	0.74					1.92	N/A	0.42	N/A	2.35	N/A
Pharmaceuticals													
Adrenaline 1mg in 1ml (1ml)	Product	Adrenaline	1.00	1	1	N/A	N/A	34.00	N/A	N/A	N/A	34.00	N/A
	Packaging	Glass	1.00			Medicinal contaminated sharps waste		1.38	N/A	1.07	N/A	2.45	N/A
Bone cement mix (with gentamicin)	Product and packaging	Bone cement (with gentamicin)	£68.28	1	1	N/A	N/A	13,082.34	N/A	N/A	N/A	13,082.34	N/A
	(Glass packaging-weight for waste)		11.61			Medicinal contaminated sharps waste		N/A	N/A	12.47	N/A	12.47	N/A
	(Non-glass packaging-weight for waste)		189.65			Infectious waste		N/A	N/A	107.97	N/A	107.97	N/A

Bone cement mix (with tobramycin)	Product and packaging	Bone cement (with tobramycin)	£68.60	1	1	N/A	N/A	13,143.65	N/A	N/A	N/A	13,143.65	N/A
	(Glass packaging- weight for waste)		9.30			Medicinal contaminated sharps waste		N/A	N/A	9.99	N/A	9.99	N/A
	(Non-glass packaging- weight for waste)		104.75			Infectious waste		N/A	N/A	59.64	N/A	59.64	N/A
Chlorhexidine 2% from 500 ml bottle (150 ml)	Product	Chlorhexidine 2%	£0.84	1	1	N/A	N/A	160.94	N/A	N/A	N/A	160.94	N/A
Chlorhexidine gluconate in 70% denatured ethanol with 4ml red stain solution from 200 ml bottle (150 ml)	Product	Chlorhexidine gluconate in 70% denatured ethanol with 4ml red stain solution	£5.13	1	1	N/A	N/A	982.90	N/A	N/A	N/A	982.90	N/A
Iodinated povidone 10% w/w alcoholic tincture from 500 ml bottle (50 ml)	Product	Iodinated povidone 10% w/w alcoholic tincture	£0.48	1	1	N/A	N/A	92.16	N/A	N/A	N/A	92.16	N/A
Ketorolac tromethamine 30mg in 1ml (1ml)	Product	Ketorolac tromethamine 30mg in 1ml	£1.36	1	1	N/A	N/A	260.57	N/A	N/A	N/A	260.57	N/A
	(Packaging - weight for waste)		1.48			Medicinal contaminated sharps waste		N/A	N/A	1.59	N/A	1.59	N/A

Levobupivacaine 2.5mg per ml (10 ml)	Product	Levobupivacaine	10.00	1	1	N/A	N/A	230.00	N/A	N/A	N/A	230.00	N/A
	Packaging	Low density polyethylene resin	2.65			Infectious waste		5.51	N/A	1.51	N/A	7.02	N/A
		Low density polyethylene film	0.46					1.20	N/A	0.26	N/A	1.46	N/A
		Paper	0.40					0.60	N/A	0.23	N/A	0.82	N/A
Ropivacaine 75mg in 10 ml (10 ml)	Product	Ropivacaine hydrochloride	10.00	1	1	Infectious waste	N/A	360.00	N/A	5.69	N/A	365.69	N/A
	Packaging	Polyethylene terephthalate	2.56					10.32	N/A	1.46	N/A	11.78	N/A
		Polypropylene injection moulding	2.41					10.82	N/A	1.37	N/A	12.19	N/A
Sodium chloride 0.9% (100 ml)	Product	Sodium chloride 0.9%	£0.59	1	1	N/A	N/A	113.04	N/A	N/A	N/A	113.04	N/A
	(Packaging - weight for waste)		5.16			Infectious waste		N/A	N/A	2.94	N/A	2.94	N/A
Sodium chloride 0.9% for irrigation (3 L bag)	Product	Sodium chloride 0.9%	£4.52	1	1	N/A	N/A	866.02	N/A	N/A	N/A	866.02	N/A
	(Packaging - weight for waste)		91.13			Infectious waste		N/A	N/A	51.88	N/A	51.88	N/A
Topical skin adhesive (0.8 g)	Product	Topical skin adhesive (0.8 g)	£20.47	1	1	N/A	N/A	3,922.02	N/A	N/A	N/A	3,922.02	N/A
	(Packaging - weight for waste)		4.38			Infectious waste		N/A	N/A	2.49	N/A	2.49	N/A
Cleaning products, waste													
Anatomical waste bin	Product	Paper	81.22	1	1	Anatomical waste	N/A	121.02	N/A	87.24	N/A	208.26	N/A
	Product	Low density polyethylene film	13.91	1	3	Domestic waste	N/A	12.06	N/A	0.80	N/A	12.85	N/A

Clear bin bag (linen laundering)		Nylon (polyamide) 6 polymer	2.58					7.86	N/A	0.15	N/A	8.01	N/A
Clear waste bag (recycling) with cable tie	Product	Low density polyethylene film	15.01	1	1	Domestic waste	N/A	39.03	N/A	2.58	N/A	41.60	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	0.44	N/A	24.02	N/A
Disinfectant sachet	Product	Disinfectant	£0.70	1	1	N/A	N/A	134.12	N/A	N/A	N/A	134.12	N/A
	(Packaging - weight for waste)		5.81			Infectious waste		N/A	N/A	3.31	N/A	3.31	N/A
Disinfectant wipe	Product	Non-woven polyester	2.30	1	1	Infectious waste	N/A	12.79	N/A	1.31	N/A	14.10	N/A
Orange waste bag (infectious waste) with cable tie from theatre	Product	Polypropylene oriented film	70.61	1	1	Infectious waste	N/A	242.19	N/A	40.20	N/A	282.39	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	1.47	N/A	25.05	N/A
Orange waste bag (infectious waste) with cable tie from scrub room	Product	Polypropylene oriented film	70.61	1	3	Infectious waste	N/A	80.73	N/A	13.40	N/A	94.13	N/A
		Nylon (polyamide) 6 polymer	2.58					7.86	N/A	0.49	N/A	8.35	N/A
Mop head	Product	Nylon (polyamide) 6 polymer	70.36	1	3	Infectious waste	N/A	214.36	N/A	13.35	N/A	227.72	N/A
		High density polyethylene resin	30.16					19.40	N/A	5.72	N/A	25.13	N/A
Red bag (linen laundering) with cable tie	Product	Polypropylene oriented film	29.22	1	3	Domestic waste	N/A	33.41	N/A	1.67	N/A	35.08	N/A
		Nylon (polyamide) 6 polymer	2.58					7.86	N/A	0.15	N/A	8.01	N/A
Yellow/ black waste bag	Product	Polypropylene oriented film	24.93	1	3	Non-infectious	N/A	28.50	N/A	2.07	N/A	30.57	N/A

(non-infectious offensive waste) with cable tie from scrub room		Nylon (polyamide) 6 polymer	2.58			offensive waste		7.86	N/A	0.21	N/A	8.07	N/A

Supplementary table 12: Carbon footprint of reusable instrument sets used for laparoscopic cholecystectomy
Table includes all reusable instrument sets and individually wrapped instruments across all observed operations, and the carbon footprint per set. Sets and individually wrapped instruments used for individual operations varied. The material composition of products was determined through packaging and manufacturer information where available, and alternatively through expert assessment, taking into account available emission factors. Weight reported as total for a given product (accounting for multiple products where relevant). Some products listed as 'bottom tray'/'top tray' where not individually counted by theatre staff. 'Use' equates to sterilisation of instruments, determined per set. All waste of given product disposed of using consistent waste stream (A). CO_2e= carbon dioxide equivalents

Category	Product	Material(s)	Weight (g)	Number of uses	Waste stream A	Carbon footprint per use ($g\ CO_2e$)		
						Production	Use	Waste stream A
General basic set								
Sterile barrier system	Basket	Stainless steel	1170.57	116	Scrap metal recycling	62.01	See total	0.2149
	Container	Aluminium cast	2996.54	1,000	Scrap metal recycling	20.14		0.0638
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89		1.0134
Instruments and set products	Allis tissue forceps x2	Stainless steel	56.92	4,476	Scrap metal recycling	0.08	See total	0.0003
	Babcock tissue forceps x2	Stainless steel	48.50	4,476	Scrap metal recycling	0.07		0.0002
	Bag plain closure (H)	Paper	13.69	1	Infectious waste	20.40	N/A	7.7939
	Bipolar diathermy	Stainless steel	31.98	40		4.91	See total	0.8588

		High density polyethylene resin	31.98		Medicinal contaminated sharps waste	1.54		0.8588
	Bonney toothed dissecting forceps	Stainless steel	61.07	4,029	Scrap metal recycling	0.09		0.0003
	BP scalpel handle (no. 3) x2	Stainless steel	49.40	895	Scrap metal recycling	0.34		0.0012
	BP scalpel handle (no. 4) x2	Stainless steel	57.44	895	Scrap metal recycling	0.39		0.0014
	Bulldog clip	Stainless steel	49.77	1,343	Scrap metal recycling	0.23		0.0008
	Czerny retractor x2	Stainless steel	123.94	5,372	Scrap metal recycling	0.14		0.0005
	Debakey dissecting forceps	Stainless steel	21.42	1,343	Scrap metal recycling	0.10		0.0003
	Diathermy lead	Polyvinylchloride general	86.52	50	Non-infectious offensive waste	5.36		0.4307
		Copper	9.61			0.73		0.0478
	Diathermy quiver	Polypropylene injection moulding	96.13	1,343	Non-infectious offensive waste	0.32		0.0178
	Gallipot x3	Polypropylene injection moulding	14.10	1	Infectious waste	63.31	N/A	8.0273
	Gillies toothed dissecting forceps	Stainless steel	24.31	1,074	Scrap metal recycling	0.14	See total	0.0005
	Halstead mosquito curved artery forceps x6	Stainless steel	122.76	2,686	Scrap metal recycling	0.28		0.0010
	Kidney dish (25 cm) x4	Polypropylene injection moulding	395.52	895	Non-infectious offensive waste	1.98		0.1100
	Lanes tissue forceps x2	Stainless steel	84.32	4,476	Scrap metal recycling	0.12		0.0004
	Langenbeck retractor (medium) x2	Stainless steel	105.10	6,267	Scrap metal recycling	0.10		0.0004
	Mayo curved scissors	Stainless steel	70.12	895	Scrap metal recycling	0.48		0.0017

	Mayo Hegar needle holder x2	Stainless steel	58.24	1,791	Scrap metal recycling	0.20		0.0007
	Mayo straight scissors	Stainless steel	44.34	1,343	Scrap metal recycling	0.20		0.0007
	McIndoe dissecting forceps	Stainless steel	20.69	2,238	Scrap metal recycling	0.06		0.0002
	McIndoe plain diathermy forceps	Stainless steel	32.49	40	Medicinal contaminated sharps waste	4.99		0.8725
		Nylon (polyamide) 6 polymer	3.61			0.82		0.0969
	McIndoe scissors	Stainless steel	34.01	895	Scrap metal recycling	0.23		0.0008
	Plain dissecting forceps (5")	Stainless steel	23.09	40	Scrap metal recycling	3.55		0.0123
	Plain dissecting forceps (7")	Stainless steel	37.01	895	Scrap metal recycling	0.25		0.0009
	Rampley sponge holder forceps x4	Stainless steel	256.56	1,343	Scrap metal recycling	1.17		0.0041
	Schnidt artery forceps x6	Stainless steel	238.56	4,029	Scrap metal recycling	0.36		0.0013
	Spencer Wells curved artery forceps x4	Stainless steel	209.52	3,581	Scrap metal recycling	0.36		0.0012
	Spencer Wells straight artery forceps x6	Stainless steel	146.46	4,476	Scrap metal recycling	0.20		0.0007
	Stitch scissor	Stainless steel	32.74	4,476	Scrap metal recycling	0.04		0.0002
	Towel clip x6	Stainless steel	211.86	1,343	Scrap metal recycling	0.97		0.0034
	Travers self-retaining retractor	Stainless steel	107.66	895	Scrap metal recycling	0.74		0.0026
	Treves toothed dissecting forceps x6	Stainless steel	141.12	1,970	Scrap metal recycling	0.44		0.0015
Total general basic set (B)= 2,395.86 g CO_2e						**216.62**	**2,153.96**	**25.27**
General laparoscopic set								

Sterile barrier system	Container base (deep)	Aluminium cast	2,629.88	116	Scrap metal recycling	17.67	See total	0.0560
	Container lid (deep)	General plastic	1,659.99	1,000	Non-infectious offensive waste	5.49		0.4132
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	12.13	46	Non-infectious offensive waste	0.51	See total	0.0656
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Laparoscopic instrument rack	Stainless steel	937.84	500	Scrap metal recycling	11.53	See total	0.0399
		Rubber	165.50			0.94		0.0070
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89	N/A	1.0134
Instruments and set products	Desjardin forceps	Stainless steel	33.64	2028.40	Scrap metal recycling	0.10	See total	0.0004
	Diathermy hook	stainless steel	30.64	500.00	Scrap metal recycling	0.38		0.0013
	Diathermy lead	Polyvinylchloride general	94.88	50.00	Non-infectious offensive waste	5.88		0.4724
		Copper	10.54			0.80		0.0525
	Johann grasping forceps	Polypropylene injection moulding	58.51	500.00	Medicinal contaminated sharps waste	0.53		0.1257
		Stainless steel	26.26			0.32		0.0564
	Kelly crocodile grasping forceps x2	Polypropylene injection moulding	117.48	500.00	Medicinal contaminated sharps waste	1.05		0.2524
		Stainless steel	58.74			0.72		0.1262
	Kocher artery forceps x2	Stainless steel	93.42	2353.50	Scrap metal recycling	0.24		0.0008

	Lahey right angle dissecting forceps	Polypropylene injection moulding	52.34	500.00	Medicinal contaminated sharps waste	0.47		0.1124
		Stainless steel	26.17			0.32		0.0562
	Langenbeck retractor (small) x2	Stainless steel	132.86	3549.70	Scrap metal recycling	0.23		0.0008
	Littlewoods tissue forceps x2	Stainless steel	80.96	2353.50	Scrap metal recycling	0.21		0.0007
	Manhes grasping forceps	Polypropylene injection moulding	59.37	500.00	Medicinal contaminated sharps waste	0.53		0.1275
		Stainless steel	29.69			0.36		0.0638
	Maryland dissecting forceps	Polypropylene injection moulding	52.06	500.00	Medicinal contaminated sharps waste	0.47		0.1118
		Stainless steel	26.03			0.32		0.0559
	Pietlyn dissecting forceps	Polypropylene injection moulding	57.89	500.00	Medicinal contaminated sharps waste	0.52		0.1244
		Stainless steel	28.94			0.36		0.0622
	Raptor toothed grasping forceps	Polypropylene injection moulding	77.99	500.00	Medicinal contaminated sharps waste	0.70		0.1675
		Stainless steel	39.00			0.48		0.0838
Total general laparoscopic set= 2,231.95 g CO_2e						**69.56**	**2,153.96**	**8.43**
Laparoscope set								
Sterile barrier system	Identification tag	High density polyethylene resin	13.72	46	Non-infectious offensive waste	0.58	See total	0.0742
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tray wrap (outer, 100x100 cm)	Paper	110.88	1	Infectious waste	165.21		63.13

	Tray wrap (inner, 100x100 cm)	Polypropylene oriented film	111.10	1	Infectious waste	381.07		63.25
	Wire cage with lid	Stainless steel	892.10	500	Scrap metal recycling	10.96	See total	0.0380
Instruments and set products	Light lead	Polypropylene injection moulding	208.38	400	Non-infectious offensive waste	2.34		0.1297
		Stainless steel	104.19			1.60		0.0648
		Glass general	104.19			0.38		0.0648
	Hopkins laparoscope (10 mm, 0 degree)	Stainless steel	151.15	500	Non-infectious offensive waste	1.86		0.0753
		Polypropylene injection moulding	26.67			0.24		0.0133
		Glass general	8.89			0.03		0.0044
					Total laparoscope set = 1,778.07 g CO_2e	**571.49**	**1,076.89**	**129.60**
Diathermy lead								
Sterile barrier system	Flexible pouch	General polyethylene	11.14	1	Infectious waste	28.30	N/A	6.3421
		Paper	8.06			12.01		4.5887
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
Instruments and set products	Diathermy lead	Polyvinylchloride general	94.88	50	Non-infectious offensive waste	5.88		0.4724
		Copper	10.54			0.80		0.0525
					Total diathermy lead= 204.22 g CO_2e	**47.34**	**145.38**	**11.50**
Laparoscopic grasping forceps								

Sterile barrier system	Flexible pouch	General polyethylene	15.42	1	Infectious waste	39.17	N/A	8.7788
		Paper	10.46			15.59		5.9550
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
Instruments and set products	Laparoscopic grasping forceps	Polypropylene injection moulding	59.37	500	Medicinal contaminated sharps waste	0.53		0.1275
		Stainless steel	29.69			0.36		0.0638
Total laparoscopic grasping forceps = 216.35 g CO_2e						**55.99**	**145.38**	**14.97**
Quiver and clip								
Sterile barrier system	Flexible pouch	General polyethylene	11.14	1	Infectious waste	28.30	N/A	6.3421
		Paper	8.06			12.01		4.5887
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
Instruments and set products	Quiver	Polypropylene injection moulding	279.75	1,342.89	Non-infectious offensive waste	0.94		0.0519
	Clip	Stainless steel	18.97	1,342.89	Scrap metal recycling	0.09		0.0003
Quiver and clip= 198.08 g CO_2e						**41.67**	**145.38**	**11.03**

Supplementary table 13: Carbon footprint of reusable (non-set) and single-use products used for laparoscopic cholecystectomy
Table includes all single-use products used across all observed operations listed here and the carbon footprint per product as listed. Products used for individual operations varied, alongside number of products used. The material composition of products was determined through packaging and manufacturer information where available, and alternatively through expert assessment, taking into account available emission factors. Weight reported as total for a given product (accounting for multiple products where relevant). 'Use' equates to linen laundering of reusable linens. Carbon footprint per use equates to a single use of a product in a single operation. CO_2e= carbon dioxide equivalents, ops.= operations

Product	Component	Material(s)	Weight (g), or cost where specified with (£), or volume where specified	Number of uses	Number of ops per use	Waste stream A	Waste stream B	Carbon footprint per use (g CO_2e)					
								Production	Use	Waste stream A	Waste stream B	Total (waste A)	Total (waste B)
Reusable patient drapes													
High fluid drape	Product	Polyethylene terephthalate	1876.3	75	1	Clothing recycling	N/A	100.88	864.09	0.53	N/A	965.51	N/A
	Packaging	Paper	51.53	1		Infectious waste	Domestic waste	76.78	N/A	29.34	8.85	106.12	85.63
		Nylon (polyamide) 6 polymer	2.76					25.23	N/A	1.57	0.47	26.80	25.70
Huck towel	Product	Cotton fabric	120.55	75	1	Clothing recycling	N/A	10.90	55.52	0.03	N/A	66.45	N/A
	Packaging	Paper	20.63	1		Infectious waste	Domestic waste	30.74	N/A	11.74	3.54	42.48	34.28
		Low density polyethylene film	4.6					11.96	N/A	2.62	0.79	14.58	12.75

Reusable personal protective equipment													
Reusable surgical gown (including hand towels)	Product	Polyethylene terephthalate	303.70	75	1	Clothing recycling	N/A	16.33	139.86	0.09	N/A	156.28	N/A
		Rubber	15.98					0.61	7.36	0.0045	N/A	7.97	N/A
		Paper	13.41	1		Domestic waste		19.98	N/A	2.30	N/A	22.28	N/A
	Packaging	Paper	19.90					29.65	N/A	3.42	N/A	33.07	N/A
		General polyethylene	6.42					29.65	N/A	3.42	N/A	33.07	N/A
Reusable surgical gown (including hand towels) double pack	Product	Polyethylene terephthalate	555.48	75	1	Clothing recycling	N/A	29.87	255.82	0.16	N/A	285.84	N/A
		Rubber	29.24					1.11	13.46	0.01	N/A	14.58	N/A
		Paper	24.57	1		Domestic waste		36.61	N/A	4.22	N/A	40.83	N/A
	Packaging	Paper	24.31					36.22	N/A	4.18	N/A	40.40	N/A
		General polyethylene	8.81					22.38	N/A	1.51	N/A	23.89	N/A
Reusable surgical hat	Product	Cotton fabric	26.58	75	4	Clothing recycling	N/A	0.60	3.06	0.0019	N/A	3.66	N/A
Reusable scrubs	Product	Cotton fabric	421.17	75	4	Clothing recycling	N/A	9.52	48.49	0.0299	N/A	58.04	N/A
Non-set reusable equipment													
Diathermy pad lead	Product	Polyvinyl-chloride general	121.57	50	1	Non-infectious offensive waste	N/A	7.54	N/A	0.61	N/A	8.14	N/A
		Copper	13.51					1.03	N/A	0.07	N/A	1.10	N/A

Single-use personal protective equipment													
Gloves (non-sterile, pair)	Product	Rubber	6.45	1	1	Infectious waste	Non-infectious offensive waste	18.38	N/A	3.67	1.61	22.05	19.99
Sterile gloves (pair)	Product	Rubber	27.31	1	1	Infectious waste	Non-infectious offensive waste	77.83	N/A	15.55	6.80	93.38	84.63
	Packaging	General polyethylene	5.98			Domestic waste	N/A	15.19	N/A	1.03	N/A	16.22	N/A
		Paper	5.91					8.81	N/A	1.02	N/A	9.82	N/A
Sterile gloves (two pairs)	Product	Rubber	42.14	1	1	Infectious waste	Non-infectious offensive waste	120.10	N/A	23.99	10.49	144.09	130.59
	Packaging	Paper	11.61			Domestic waste	N/A	17.30	N/A	1.99	N/A	19.29	N/A
		General polyethylene	5.61					14.25	N/A	0.96	N/A	15.21	N/A
Sterile gloves (one pair, latex free)	Product	General polyethylene	24.66	1	1	Infectious waste	Non-infectious offensive waste	62.64	N/A	14.04	6.14	76.68	68.78
	Packaging	Paper	6.01			Domestic waste	N/A	8.95	N/A	1.03	N/A	9.99	N/A
		General polyethylene	5.83					14.81	N/A	1.00	N/A	15.81	N/A
Surgical face mask	Product	Polypropylene oriented film	4.36	1	1	Infectious waste	Non-infectious offensive waste	14.95	N/A	2.48	1.09	17.44	16.04

Surgical face mask with eye protection	Product	Polypropylene oriented film	6.23	1	1	Infectious waste	Non-infectious offensive waste	21.37	N/A	3.55	1.55	24.92	22.92
		Low density polyethylene film	4.04					10.50	N/A	2.30	1.01	12.80	11.51
Surgical gown (including hand towels)	Product	Polypropylene oriented film	139.004	1	1	Infectious waste	Non-infectious offensive waste	476.78	N/A	79.14	34.60	555.92	511.39
		Rubber	7.316					20.85	N/A	4.17	1.82	25.02	22.67
		Paper	13.83			Domestic waste	N/A	20.61	N/A	2.38	N/A	22.98	N/A
	Packaging	Paper	25.34					37.76	N/A	4.35	N/A	42.11	N/A
		Low density polyethylene film	5.11					13.29	N/A	0.88	N/A	14.16	N/A
Surgical hat	Product	Polypropylene oriented film	3.54	1	4	Infectious waste	Non-infectious offensive waste	3.04	N/A	0.50	0.22	3.54	3.26
Single-use instrument table drapes													
Table drape (instruments)	Product	Polyvinyl-chloride general	122.17	1	1	Infectious waste	Non-infectious offensive waste	378.73	N/A	69.55	30.41	448.28	409.14
		Polypropylene oriented film	61.09					209.54	N/A	34.78	15.21	244.32	224.75
	Packaging	Paper	12.64				Domestic waste	18.83	N/A	7.20	2.17	26.03	21.00
		Polypropylene oriented film	9.05					31.04	N/A	5.15	1.55	36.19	32.60
		Low density polyethylene film	6.49					16.87	N/A	3.69	1.11	20.57	17.99

Single-use equipment and medical devices													
Absorbent towel pack	Product	Paper	28.47	1	1	Infectious waste	N/A	42.42	N/A	16.21	N/A	58.63	N/A
	Packaging	Paper	5					7.45	N/A	2.85	N/A	10.30	N/A
		Low density polyethylene film	2.16					5.62	N/A	1.23	N/A	6.85	N/A
Anti-fog endoscopic demister	Product	Anti-fog	£3.5	1	1	N/A	N/A	670.59	N/A	N/A	N/A	670.59	670.59
	(Product only weight-for waste)		5.47			Infectious waste	Non-infectious offensive waste	N/A	N/A	3.11	1.36	3.11	1.36
	(Packaging weight-for waste)		15.2				Domestic waste	N/A	N/A	8.65	2.61	8.65	2.61
Diathermy pad	Product	Aluminium foil	5.49	1	1	Infectious waste	Non-infectious offensive waste	41.01	N/A	3.13	1.37	44.14	42.38
		General polyethylene	5.49					13.94	N/A	3.13	1.37	17.07	15.31
	Packaging	Polyethylene terephthalate	1.84				Domestic waste	7.42	N/A	1.05	0.32	8.47	7.74
Endoscopic clip applier	Product	Stainless steel	64.13	1	1	Medicinal contaminated sharps waste	N/A	394.08	N/A	68.88	N/A	462.96	N/A
		Polypropylene injection moulding	24.91					111.85	N/A	26.76	N/A	138.60	N/A
		Polycarbonate	19.83					151.10	N/A	21.30	N/A	172.40	N/A
		Polyvinyl-chloride general	6.71					20.80	N/A	7.21	N/A	28.01	N/A

		Nylon (polyamide) 6 polymer	0.4					3.66	N/A	0.43	N/A	4.09	N/A
		Titanium	0.08					1.65	N/A	0.09	N/A	1.73	N/A
	Packaging	Paper	178.64			Infectious waste	Domestic waste	266.17	N/A	101.70	30.69	367.88	296.86
		Polyethylene terephthalate	97.18					391.87	N/A	55.33	16.69	447.19	408.56
		High density polyethylene resin	9.39					18.12	N/A	5.35	1.61	23.47	19.74
Gauze (sterile pack)	Product	Cotton fabric	19.66	1	1	Infectious waste	Non-infectious offensive waste	133.29	N/A	11.19	4.89	144.49	138.19
	Packaging	Paper	4.73				Domestic waste	7.05	N/A	2.69	0.81	9.74	7.86
		Low density polyethylene film	1.54					4.00	N/A	0.88	0.26	4.88	4.27
Incontinence pad	Product	Cotton padding	15.09	1	1	Infectious waste	Non-infectious offensive waste	19.32	N/A	8.59	3.76	27.91	23.07
		Low density polyethylene film	15.09					39.23	N/A	8.59	3.76	47.82	42.99
Insufflating tubing	Product	Polyvinyl-chloride general	124.23	1	1	Infectious waste	Non-infectious offensive waste	385.11	N/A	70.73	30.92	455.84	416.04
		Polypropylene injection moulding	20.86					93.66	N/A	11.88	5.19	105.54	98.85
	Packaging	Low density polyethylene film	9.94				Domestic waste	25.84	N/A	5.66	1.71	31.50	27.55

		Paper	6.72					10.01	N/A	3.83	1.15	13.84	11.17
		Polyvinyl-chloride general	5.60					17.36	N/A	3.19	0.96	20.55	18.32
Laparoscope cover	Product	Low density polyethylene film	19.55	1	1	Infectious waste	Non-infectious offensive waste	50.83	N/A	11.13	4.87	61.96	55.70
		Polyvinyl-chloride general	18.69					57.94	N/A	10.64	4.65	68.58	62.59
		Paper	2.06					3.07	N/A	1.17	0.51	4.24	3.58
	Packaging	Paper	2.62				Domestic waste	3.90	N/A	1.49	0.45	5.40	4.35
		Low density polyethylene film	1.97					5.12	N/A	1.12	0.34	6.24	5.46
Laparoscopic scissors	Product	Stainless steel	27.23	1	1	Medicinal contaminated sharps waste	N/A	167.33	N/A	29.25	N/A	196.58	N/A
		Polycarbonate	26.68					203.30	N/A	28.66	N/A	231.96	N/A
		Silicone	5.53					18.47	N/A	5.94	N/A	24.41	N/A
		General plastics	0.54					1.79	N/A	0.58	N/A	2.37	N/A
		Copper	0.3					1.14	N/A	0.32	N/A	1.47	N/A
		Zinc	0.3					1.25	N/A	0.32	N/A	1.58	N/A
		Nickel	0.3					3.72	N/A	0.32	N/A	4.04	N/A
	Packaging	Nylon (polyamide) 6 polymer	14.01			Infectious waste	Domestic waste	128.05	N/A	7.98	2.41	136.03	130.46

		High density polyethylene resin	14.01					27.04	N/A	7.98	2.41	35.02	29.45
		Paper	8.28					12.34	N/A	4.71	1.42	17.05	13.76
		Polypropylene oriented film	4.4					15.09	N/A	2.50	0.76	17.60	15.85
Laparoscopic tissue retrieval system	Product	Nylon (polyamide) 6 polymer	2.37	1	1	Infectious waste	Non-infectious offensive waste	21.66	N/A	1.35	0.59	23.01	22.25
	Packaging	Low density polyethylene film	3.55				Domestic waste	9.23	N/A	2.02	0.61	11.25	9.84
		Paper	3.02					4.50	N/A	1.72	0.52	6.22	5.02
Light handle	Product	Low density polyethylene film	4.78	1	1	Infectious waste	Non-infectious offensive waste	12.43	N/A	2.72	1.19	15.15	13.62
	Packaging	Low density polyethylene film	3.38				Domestic waste	8.79	N/A	1.92	0.58	10.71	9.37
		Paper	1.93					2.88	N/A	1.10	0.33	3.97	3.21
Nail scrubbing brush	Product	Low density polyethylene resin	9.01	1	1	Domestic waste	N/A	18.74	N/A	1.55	N/A	20.29	N/A
		Polyurethane flexible foam	2.05					9.92	N/A	0.35	N/A	10.27	N/A
		Polypropylene injection moulding	0.91					4.09	N/A	0.16	N/A	4.24	N/A
	Packaging	Low density polyethylene film	1.31					3.41	N/A	0.23	N/A	3.63	N/A

		Paper	0.6					0.89	N/A	0.10	N/A	1.00	N/A
Needle (green)	Product	Stainless steel	0.2	1	1	Medicinal contaminated sharps waste	N/A	1.23	N/A	0.21	N/A	1.44	N/A
		Polypropylene injection moulding	0.05					0.22	N/A	0.05	N/A	0.28	N/A
	Packaging	High density polyethylene resin	0.52			Infectious waste	Domestic waste	1.00	N/A	0.30	0.09	1.30	1.09
		Low density polyethylene film	0.12					0.31	N/A	0.07	0.02	0.38	0.33
		Paper	0.11					0.16	N/A	0.06	0.02	0.23	0.18
Needle counter	Product	Acrylonitrile Butadiene Styrene	44.50	1	1	Medicinal contaminated sharps waste	N/A	167.32	N/A	47.80	N/A	215.12	N/A
		Polyurethane rigid foam	4.00					17.04	N/A	4.30	N/A	21.34	N/A
	Packaging	Low density polyethylene film	4.38			Infectious waste	Domestic waste	11.39	N/A	2.49	0.75	13.88	12.14
		Polypropylene oriented film	1.15					3.94	N/A	0.65	0.20	4.60	4.14
Nonwoven dressing (6x7 cm)	Product	Cotton fabric	0.42	1	1	Infectious waste	Non-infectious offensive waste	2.83	N/A	0.24	0.10	3.07	2.94
		Low density polyethylene film	0.02					0.05	N/A	0.01	0.005	0.06	0.06
	Packaging	Paper	1.15				Domestic waste	1.71	N/A	0.65	0.20	2.37	1.91
		Low density polyethylene film	1.06					2.76	N/A	0.60	0.18	3.36	2.94
Port (12 mm)	Product	Polycarbonate	58.84	1	1		N/A	448.36	N/A	63.20	N/A	511.56	N/A

						Medicinal contaminated sharps waste							
		Polypropylene injection moulding	6.29					28.24	N/A	6.76	N/A	35.00	N/A
		Silicone	3.86					12.89	N/A	4.15	N/A	17.04	N/A
		Stainless steel	1.29					7.93	N/A	1.39	N/A	9.31	N/A
		Low density polyethylene resin	1.6					3.33	N/A	1.72	N/A	5.05	N/A
	Packaging	Nylon (polyamide) 6 polymer	5.09			Infectious waste	Domestic waste	46.52	N/A	2.90	0.87	49.42	47.40
		High density polyethylene resin	8.29					16.00	N/A	4.72	1.42	20.72	17.42
		Low density polyethylene film	0.46					1.20	N/A	0.26	0.08	1.46	1.28
Port (5 mm, dual pack)	Product	Polycarbonate	59.83	1	1	Medicinal contaminated sharps waste	N/A	455.90	N/A	64.27	N/A	520.17	N/A
		Polypropylene injection moulding	7.38					33.14	N/A	7.93	N/A	41.06	N/A
		Silicone	4.36					14.56	N/A	4.68	N/A	19.25	N/A
		Low density polyethylene resin	1.42					2.95	N/A	1.53	N/A	4.48	N/A
	Packaging	Nylon (polyamide) 6 polymer	5.29			Infectious waste	Domestic waste	48.35	N/A	3.01	0.91	51.36	49.26
		High density polyethylene resin	8.54					16.48	N/A	4.86	1.47	21.34	17.95

Pressure saline infusion bag	Product	Rubber	45.52	1	1	Infectious waste	N/A	129.73	N/A	25.92	N/A	155.65	N/A
		Nylon (polyamide) 6 polymer	33.94					310.21	N/A	19.32	N/A	329.53	N/A
		High density polyethylene resin	25.16					42.21	N/A	12.45	N/A	54.66	N/A
		Acrylonitrile Butadiene Styrene	21.87					48.56	N/A	14.32	N/A	62.88	N/A
		Polyvinyl-chloride general	9.57					29.67	N/A	5.45	N/A	35.12	N/A
		Polypropylene injection moulding	3.63					16.30	N/A	2.07	N/A	18.37	N/A
	Packaging	Low density polyethylene film	7.25					18.85	N/A	4.13	N/A	22.98	N/A
Reinforced skin closure strip	Product	General polyethylene	0.66	1	1	Clinical waste	N/A	1.68	N/A	0.71	N/A	2.39	N/A
	Packaging	Paper	1.49			Infectious waste	Non-infectious offensive waste	2.22	N/A	0.85	0.37	3.07	2.59
		Low density polyethylene film	0.74					1.92	N/A	0.42	0.18	2.35	2.11
Specimen pot (40 ml 4% formaldehyde)	Product	4% Formaldehyde	£0.20	1	1	Clinical waste	N/A	37.63	N/A	N/A	N/A	37.63	N/A
	(Product weight-for waste)		40					N/A	N/A	42.97	N/A	42.97	N/A
	Product	Polypropylene injection moulding	6.53			Infectious waste	Non-infectious	29.32	N/A	3.72	1.63	33.04	30.95

		High density polyethylene resin	5.19				offensive waste	10.02	N/A	2.95	1.29	12.97	11.31
Specimen pot (not pre-filled)	Product	Polypropylene injection moulding	28.77	1	1	Infectious waste	Non-infectious offensive waste	129.18	N/A	16.38	7.16	145.56	136.34
Suction irrigation	Product	Polyvinylchloride general	283.76	1	1	Infectious waste	Non-infectious offensive waste	879.66	N/A	161.55	70.64	1,041.20	950.29
		Polypropylene injection moulding	39.67					76.56	N/A	22.58	9.88	99.15	86.44
		High density polyethylene resin	25.96					174.45	N/A	14.78	6.46	189.23	180.91
		Aluminium cast	14.5					97.44	N/A	8.26	3.61	105.70	101.05
	Packaging	Paper	28.30				Domestic waste	73.58	N/A	16.11	4.86	89.69	78.44
		Low density polyethylene film	20.67					39.89	N/A	11.77	3.55	51.66	43.44
Suction receptacle	Product	High density polyethylene resin	72.62	1	1	Infectious waste	Non-infectious offensive waste	140.15	N/A	41.34	18.08	181.49	158.22
		Low density polyethylene resin	72.62					151.04	N/A	41.34	18.08	192.38	169.12
Surgical blade (11)	Product	Stainless steel	0.46	1	1	Medicinal contaminated sharps waste	N/A	2.83	N/A	0.49	N/A	3.32	N/A
	Packaging	Aluminium foil	0.51			Infectious waste	Domestic waste	3.81	N/A	0.29	0.09	4.10	3.90

Surgical blade (15)	Product	Stainless steel	0.39	1	1	Medicinal contaminated sharps waste	N/A	2.40	N/A	0.42	N/A	2.82	N/A
	Packaging	Aluminium foil	0.52			Infectious waste	Domestic waste	3.88	N/A	0.30	0.09	4.18	3.97
Suture (braided, absorbable, 3-0)	Product	Stainless steel	0.408	1	1	Medicinal contaminated sharps waste	N/A	2.51	N/A	0.44	N/A	2.95	N/A
		Nylon (polyamide) 6 polymer	0.102					0.93	N/A	0.11	N/A	1.04	N/A
	Packaging	High density polyethylene resin	0.6			Infectious waste	Domestic waste	1.16	N/A	0.34	0.10	1.50	1.26
		Low density polyethylene film	0.12					0.31	N/A	0.07	0.02	0.38	0.33
		Paper	0.11					0.16	N/A	0.06	0.02	0.23	0.18
Suture (monofilament, absorbable, 3-0)	Product	Stainless steel	0.26	1	1	Medicinal contaminated sharps waste	N/A	1.60	N/A	0.28	N/A	1.88	N/A
		Nylon (polyamide) 6 polymer	0.09					0.82	N/A	0.10	N/A	0.92	N/A
	Packaging	Aluminium foil	1.22			Infectious waste	Domestic waste	9.11	N/A	0.69	0.21	9.81	9.32
		Paper	0.91					1.36	N/A	0.52	0.16	1.87	1.51
		Polypropylene oriented film	0.52					1.78	N/A	0.30	0.09	2.08	1.87
		Low density polyethylene film	0.5					1.30	N/A	0.28	0.09	1.58	1.39
Suture (monofilament	Product	Stainless steel	0.26	1	1	Medicinal contaminat	N/A	1.60	N/A	0.28	N/A	1.88	N/A

, absorbable, 1)		Nylon (polyamide) 6 polymer	0.09			ed sharps waste		0.82	N/A	0.10	N/A	0.92	N/A
	Packaging	Aluminium foil	1.22			Infectious waste	Domestic waste	9.11	N/A	0.69	0.21	9.81	9.32
		Paper	0.91					1.36	N/A	0.52	0.16	1.87	1.51
		Polypropylene oriented film	0.52					1.78	N/A	0.30	0.09	2.08	1.87
		Low density polyethylene film	0.5					1.30	N/A	0.28	0.09	1.58	1.39
Syringe (10 ml)	Product	Polypropylene injection moulding	3.01	1	1	Infectious waste	Non-infectious offensive waste	13.51	N/A	1.71	0.75	15.23	14.26
		General polyethylene	3.01					7.65	N/A	1.71	0.75	9.36	8.39
		Rubber	0.25					0.71	N/A	0.14	0.06	0.85	0.77
	Packaging	Low density polyethylene film	0.45				Domestic waste	1.17	N/A	0.26	0.08	1.43	1.25
		Paper	0.39					0.58	N/A	0.22	0.07	0.80	0.65
Syringe (20 ml)	Product	Polypropylene injection moulding	7.10	1	1	Infectious waste	Non-infectious offensive waste	31.90	N/A	4.04	1.77	35.94	33.67
		General polyethylene	7.10					18.04	N/A	4.04	1.77	22.09	19.81
		Rubber	0.59					1.69	N/A	0.34	0.15	2.02	1.83
	Packaging	Low density polyethylene film	1.11				Domestic waste	2.89	N/A	0.63	0.19	3.52	3.08
		Paper	0.72					1.07	N/A	0.41	0.12	1.48	1.20

Tonsil swab pack	Product	Cotton fabric	5.81	1	1	Infectious waste	Non-infectious offensive waste	39.39	N/A	3.31	1.45	42.70	40.84
	Packaging	Paper	1.92				Domestic waste	2.86	N/A	1.09	0.33	3.95	3.19
		Low density polyethylene film	0.96					2.50	N/A	0.55	0.16	3.04	2.66
Pharmaceuticals													
Carbon dioxide (from 3 kg cylinder containing 450 L)	Product and packaging	Carbon dioxide liquid	1 litre	1	1	N/A	N/A	6.00	N/A	N/A	N/A	6.00	N/A
Chlorhexidine 1% from 500 ml container (50 ml)	Product and packaging	Chlorhexidine 2%	£0.28	1	1	N/A	N/A	53.65	N/A	N/A	N/A	53.65	N/A
Levobupivacaine 2.5 mg per 10 ml (10 ml)	Product	Levobupivi-caine	10.00	1	1	N/A	N/A	230.00	N/A	N/A	N/A	230.00	N/A
	Packaging	Low density polyethylene resin	2.65			Infectious waste	Domestic waste	5.51	N/A	1.51	0.46	7.02	5.97
		Low density polyethylene film	0.46					1.20	N/A	0.26	0.08	1.46	1.28
		Paper	0.40					0.60	N/A	0.23	0.07	0.82	0.66
Sodium Chloride 0.9%	Product and packaging	Sodium chloride	£1.50	1	1	N/A	N/A	287.40	N/A	0.00	N/A	287.40	287.40

for irrigation (1 L bag)	(Packaging -weight for waste)		30.03			Infectious waste	Domestic waste	0.00	N/A	17.10	5.16	17.10	5.16
Sodium Chloride 0.9% from 1 litre bottle (50 ml)	Product and packaging	Sodium chloride	£0.20	1	1	N/A	N/A	37.94	N/A	N/A	N/A	37.94	N/A
Cleaning products, waste													
Black waste bag (domestic waste) with cable tie	Product	Polypropylene oriented film	22.37	1	1	Domestic waste	N/A	76.73	N/A	3.84	N/A	80.57	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	0.44	N/A	24.02	N/A
Clear bin bag (for diathermy quiver)	Product	Low density polyethylene film	12.48	1	1	Non-infectious offensive waste	N/A	32.45	N/A	3.11	N/A	35.55	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	0.64	N/A	24.22	N/A
Clear bin bag (recycling) with cable tie	Product	Low density polyethylene film	15.01	1	1	Domestic waste	N/A	39.03	N/A	2.58	N/A	41.60	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	0.44	N/A	24.02	N/A
Disinfectant sachet	Product	Disinfectant	£0.70	1	4	Infectious waste	N/A	33.53	N/A	N/A	N/A	33.53	N/A
	(Packaging - weight for waste)		5.81					N/A	N/A	0.83	N/A	0.83	N/A
Disinfectant wipe	Product	Non-woven polyester	3.34	1	1	Infectious waste	Clinical waste	18.57	N/A	1.90	3.59	20.47	22.16

Green bag (linen laundering) with cable tie	Product	Low density polyethylene film	16.47	1	4	Domestic waste	N/A	10.71	N/A	0.71	N/A	11.41	N/A
		Nylon (polyamide) 6 polymer	2.58					5.90	N/A	0.11	N/A	6.01	N/A
Mop head	Product	Nylon (polyamide) 6 polymer	70.36	1	4	Infectious waste	Clinical waste	160.77	N/A	10.01	18.89	170.79	179.67
		High density polyethylene resin	30.16					14.55	N/A	4.29	8.10	18.84	22.65
Orange waste bag (infectious waste, large) with cable tie	Product	Polypropylene oriented film	70.61	1	1	Infectious waste	N/A	242.19	N/A	40.20	N/A	282.39	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	1.47	N/A	25.05	N/A
Orange waste bag (infectious waste, small) with cable tie	Product	Polypropylene oriented film	27.75	1	1	Infectious waste	N/A	95.18	N/A	15.80	N/A	110.98	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	1.47	N/A	25.05	N/A
Red bag (linen laundering) with cable tie	Product	Polypropylene oriented film	29.22	1	4	Domestic waste	N/A	25.06	N/A	1.25	N/A	26.31	N/A
		Nylon (polyamide) 6 polymer	2.58					5.90	N/A	0.11	N/A	6.01	N/A
Yellow/ black waste bag (non-infectious offensive waste, large) with cable tie	Product	Polypropylene oriented film	24.93	1	1	Non-infectious offensive waste	N/A	85.51	N/A	6.21	N/A	91.72	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	0.64	N/A	24.22	N/A
Yellow/ black waste bag	Product	Polypropylene oriented film	17.16	1	1	Non-infectious	N/A	44.62	N/A	4.27	N/A	48.89	N/A

(non-infectious offensive waste, small) with cable tie		Nylon (polyamide) 6 polymer	2.58			offensive waste		23.58	N/A	0.64	N/A	24.22	N/A

Supplementary table 14: Carbon footprint of reusable instrument sets used for tonsillectomy

Table includes all reusable instrument sets used across all observed operations, and the carbon footprint per set. Sets used for individual operations varied. The material composition of products was determined through packaging and manufacturer information where available, and alternatively through expert assessment, taking into account available emission factors. Weight reported as total for a given product (accounting for multiple products where relevant). 'Use' equates to sterilisation of instruments, determined per set. All waste of given product disposed of using consistent waste stream (A). CO_2e= carbon dioxide equivalents

Category	Product	Material(s)	Weight (g)	Number of uses	Waste stream A	Carbon footprint per use (g CO_2e)		
						Production	Use	Waste stream A
Tonsillectomy set A								
Sterile barrier system	Basket	Stainless steel	1053.09	116	Scrap metal recycling	55.79	See total	0.1933
	Container	Aluminium cast	2996.54	1,000	Scrap metal recycling	20.14		0.0638
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89		1.0134
Instruments and set products	Adenoid St Clair Thompson curette	Stainless steel	90.00	2,000	Scrap metal recycling	0.28	See total	0.0010
	Beckman curette	Stainless steel	60.20	2,000	Scrap metal recycling	0.18		0.0006
	Bipolar diathermy lead	Rubber	85.94	50	Non-infectious offensive waste	4.90		0.4279
		Copper	9.55			0.73		0.0475

	Bipolar diathermy forceps (8")	Stainless steel	30.46	40	Medicinal contaminated sharps waste	4.68		0.8180
		Nylon (polyamide) 6 polymer	3.38			0.77		0.0909
	Birkett straight tonsil forceps	Stainless steel	42.26	1,348	Scrap metal recycling	0.19		0.0007
	Boyle Davis gag	Stainless steel	94.72	1,540	Scrap metal recycling	0.38		0.0013
	Boyle Davis tongue plate (64 mm)	Stainless steel	41.74	1,540	Scrap metal recycling	0.17		0.0006
	Boyle Davis tongue plate (74 mm)	Stainless steel	67.86	1,540	Scrap metal recycling	0.27		0.0009
	Boyle Davis tongue plate (89 mm)	Stainless steel	76.12	1,540	Scrap metal recycling	0.30		0.0011
	Boyle Davis tongue plate (99 mm)	Stainless steel	78.95	1,540	Scrap metal recycling	0.32		0.0011
	Bulldog clip	Stainless steel	48.76	385	Scrap metal recycling	0.78		0.0027
	Dennis Browne forceps	Stainless steel	79.55	1,540	Scrap metal recycling	0.32		0.0011
	Dissecting forceps (long, toothed)	Stainless steel	30.22	2,118	Scrap metal recycling	0.09		0.0003
	Draffin bipod stand (long) x2	Stainless steel	209.38	2,310	Scrap metal recycling	0.56		0.0019
	Draffin bipod stand (short) x2	Stainless steel	180.27	2,310	Scrap metal recycling	0.48		0.0017
	Gag guard	Low density polyethylene resin	1.98	1	Clinical waste	4.12	N/A	2.1268
	Gwyne Evans tonsil dissector	Stainless steel	31.70	2,695	Scrap metal recycling	0.07	See total	0.0003
	Hurd dissector/ pillar retractor	Stainless steel	56.31	2,695	Scrap metal recycling	0.13		0.0004
	Kidney dish (20 cm)	Polypropylene injection moulding	51.29	385	Non-infectious offensive waste	0.60		0.0332
	Luc forceps (large)	Stainless steel	59.24	1,540	Scrap metal recycling	0.24		0.0008

	Metzenbaum curved scissors	Stainless steel	41.74	809	Scrap metal recycling	0.32		0.0011
	Negus curved artery forceps (large)	Stainless steel	44.32	2,118	Scrap metal recycling	0.13		0.0004
	Negus knot pusher	Stainless steel	46.43	3,465	Scrap metal recycling	0.08		0.0003
	Wilson tonsil artery forceps	Stainless steel	34.29	2,118	Scrap metal recycling	0.10		0.0003
Total tonsillectomy set A=2,279.47 g CO_2e						**115.84**	**2,153.96**	**9.66**
Tonsillectomy set B								
Sterile Barrier System	Basket	Stainless steel	1245.17	116	Scrap metal recycling	65.96	See total	0.2286
	Container	Aluminium cast	2996.54	1000	Scrap metal recycling	20.14		0.0638
	Filter paper	Paper	3.55	1	Infectious waste	5.29	N/A	2.0211
	Identification tag	High density polyethylene resin	8.21	46	Non-infectious offensive waste	0.34	See total	0.0444
	Kit list	Paper	4.85	1	Infectious waste	7.23	N/A	2.7612
	Tamper proof tags	General plastics	1.78	1	Infectious waste	5.89		1.0134
Instruments and set products	Bag plain closure (H)	Paper	13.69	1	Infectious waste	20.40		7.7939
	Bipolar diathermy lead	Rubber	85.94	50	Non-infectious offensive waste	4.90	See total	0.4279
		Copper	9.55			0.73		0.0475
	Bipolar forceps (8")	Stainless steel	30.46	40	Medicinal contaminated sharps waste	4.68		0.8180
		Nylon (polyamide) 6 polymer	3.38	40	Medicinal contaminated sharps waste	0.77		0.0909

	Birketts straight tonsil forceps	Stainless steel	42.26	1348	Scrap metal recycling	0.19		0.0007
	Boyle Davis gag (adult)	Stainless steel	107.36	1540	Scrap metal recycling	0.43		0.0015
	Boyle Davis gag (paediatric)	Stainless steel	94.77	1540	Scrap metal recycling	0.38		0.0013
	Bulldog clip	Stainless steel	48.76	385	Scrap metal recycling	0.78		0.0027
	Diathermy quiver	Polypropylene injection moulding	96.09	770	Non-infectious offensive waste	0.56		0.0311
	Doughty tongue plate (3.5")	Stainless steel	68.72	1540	Scrap metal recycling	0.27		0.0010
	Doughty tongue plate (4")	Stainless steel	82.85	1540	Scrap metal recycling	0.33		0.0011
	Draffin bipod stand x 2	Stainless steel	192.50	2310	Scrap metal recycling	0.51		0.0018
	Gag guard	Low density polyethylene resin	3.05	1	Infectious waste	6.34	N/A	1.7364
	Gallipot (60 ml) x2	Polypropylene injection moulding	8.40	1	Infectious waste	37.72		4.7822
	Gwyne Evans tonsil dissector	Stainless steel	31.70	2695	Scrap metal recycling	0.07	See total	0.0003
	Kidney dish (25 cm) x2	Polypropylene injection moulding	98.88	385	Non-infectious offensive waste	1.15		0.0639
	Luc forceps (large)	Stainless steel	59.24	1540	Scrap metal recycling	0.24		0.0008
	Masson needle holder (10")	Stainless steel	78.95	1925	Scrap metal recycling	0.25		0.0009
	Mcindoe curved scissors (7")	Stainless steel	39.44	809	Scrap metal recycling	0.30		0.0010
	Mollison pillar retractor	Stainless steel	36.74	2118	Scrap metal recycling	0.11		0.0004
	Negus curved artery forceps (large)	Stainless steel	44.32	2118	Scrap metal recycling	0.13		0.0004
	Negus knot pusher	Stainless steel	46.43	3465	Scrap metal recycling	0.08		0.0003

	Small receiver x2	Polypropylene injection moulding	102.58	385	Non-infectious offensive waste	1.20		0.0663
	Towel clip (ball/socket)	Stainless steel	62.00	1348	Scrap metal recycling	0.28		0.0010
	Treves plain dissecting forceps (5")	Stainless steel	22.67	1925	Scrap metal recycling	0.07		0.0003
	Waugh toothed dissecting forceps (8")	Stainless steel	39.42	2118	Scrap metal recycling	0.11		0.0004
	Wilson tonsil artery forceps	Stainless steel	34.29	2118	Scrap metal recycling	0.10		0.0003
	Woods ENT scissors	Stainless steel	55.02	1540	Scrap metal recycling	0.22		0.0008
	Yankauer sucker	Stainless steel	63.92	2503	Scrap metal recycling	0.16		0.0005
					Total tonsillectomy set B=2,364.29 g CO_2e	**188.32**	**2,153.96**	**22.01**

Supplementary table 15: Carbon footprint of reusable (non-set) and single-use products used for tonsillectomy
Table includes all single-use products used across all observed operations listed here and the carbon footprint per product as listed. Products used for individual operations varied, alongside number of products used. The material composition of products was determined through packaging and manufacturer information where available, and alternatively through expert assessment, taking into account available emission factors. Weight reported as total for a given product (accounting for multiple products where relevant). 'Use' equates to linen laundering of reusable linens. Carbon footprint per use equates to a single use of a product in a single operation. CO_2e= carbon dioxide equivalents, ops.= operations

Product	Component	Material(s)	Weight (g), or cost where specified with (£)	Number of uses	Number of ops per use	Waste stream A	Waste stream B	Carbon footprint per use (g CO_2e)					
								Production	Use	Waste stream A	Waste stream B	Total (waste A)	Total (waste B)
Reusable patient drapes													
Reusable ENT split head drape (two 42"x42")	Product	Polyethylene terephthalate	738.99	75	1	Clothing recycling	N/A	39.73	340.33	0.21	N/A	380.27	N/A
	Packaging	Paper	35.70	1	1	Domestic waste	Infectious waste	53.19	N/A	6.13	20.3245	59.33	73.52
		Nylon (polyamide) 6 polymer	2.20					20.11	N/A	0.38	1.2525	20.49	21.36
Reusable personal protective equipment													
Reusable surgical gown (including hand towels)	Product	Polyethylene terephthalate	303.70	75	1	Clothing recycling	N/A	16.33	139.86	0.09	N/A	156.28	N/A
		Rubber	15.98					0.61	7.36	0.005	N/A	7.97	N/A
		Paper	13.41	1	1	Domestic waste		19.98	N/A	2.30	N/A	22.28	N/A
	Packaging	General polyethylene	6.42					16.31	N/A	1.10	N/A	17.41	N/A
		Paper	19.90					29.65	N/A	3.42	N/A	33.07	N/A

Reusable surgical hat	Product	Cotton fabric	26.58	75	5	Clothing recycling	N/A	0.48	2.45	0.002	N/A	2.93	N/A
Reusable scrubs	Product	Cotton fabric	421.17	75	5	Clothing recycling	N/A	7.61	38.79	0.02	N/A	46.43	N/A
Single-use personal protective equipment													
Gloves (non-sterile, one pair)	Product	Rubber	6.45	1	1	Clinical waste	Infectious waste	18.38	N/A	6.93	3.67	25.31	22.05
Sterile gloves (one pair)	Product	Rubber	27.31	1	1	Clinical waste	Infectious waste	77.83	N/A	29.33	15.55	107.17	93.38
	Packaging	General polyethylene	5.98			Domestic waste	N/A	15.19	N/A	1.03	N/A	16.22	N/A
		Paper	5.91					8.81	N/A	1.02	N/A	9.82	N/A
Surgical face mask	Product	Polypropylene oriented film	4.36	1	1	Clinical waste	Infectious waste	14.95	N/A	4.68	2.48	19.64	17.44
Surgical face mask with eye protection	Product	Polypropylene oriented film	6.23	1	1	Clinical waste	Infectious waste	21.37	N/A	6.69	3.55	28.06	24.92
		Low density polyethylene film	4.04					10.50	N/A	4.34	2.30	14.84	12.80
Surgical hat	Product	Polypropylene oriented film	3.54	1	5	Clinical waste	Infectious waste	2.43	N/A	0.76	0.40	3.19	2.83
Single-use patient or table drapes													
Patient drape (fenestrated ENT drape)	Product	Low density polyethylene film	17.98	1	1	Clinical waste	N/A	46.75	N/A	19.31	N/A	66.06	N/A
		Nylon (polyamide) 6 polymer	17.98					164.34	N/A	19.31	N/A	183.65	N/A
	Packaging	Low density polyethylene film	9.03			Domestic waste	N/A	23.48	N/A	1.55	N/A	25.03	N/A
Table drape (instruments)	Product	Polyvinylchloride general	122.17	1	1	Clinical waste	N/A	378.73	N/A	131.23	69.55	509.95	448.28

		Polypropylene oriented film	61.09					209.54	N/A	65.62	34.78	275.16	244.32
	Packaging	Low density polyethylene film	6.49			Domestic waste	N/A	16.87	N/A	1.11	3.69	17.99	20.57
		Paper	12.64					18.83	N/A	2.17	7.20	21.00	26.03
		Polypropylene oriented film	9.05					31.04	N/A	1.55	5.15	32.60	36.19
Single-use equipment and medical devices													
Coblation™ wand	Product	Low density polyethylene resin	74.55	1	1	Clinical waste	N/A	155.06	N/A	80.08	N/A	235.14	N/A
		Polyvinylchloride general	37.27					115.54	N/A	40.03	N/A	155.57	N/A
		Polycarbonate	17.47			Medicinal contaminated sharps waste	N/A	133.12	N/A	18.77	N/A	151.89	N/A
		Stainless steel	17.47					107.35	N/A	18.77	N/A	126.12	N/A
	Packaging	Paper	56.74			Domestic waste	N/A	84.54	N/A	9.75	N/A	94.29	N/A
		General polyethylene	53.83					136.73	N/A	9.25	N/A	145.98	N/A
		Polypropylene oriented film	6.58					22.57	N/A	1.13	N/A	23.70	N/A
Kidney dish	Product	Paper	18.98	1	1	Clinical waste	N/A	28.28	N/A	20.39	N/A	48.67	N/A
	Packaging	Low density polyethylene film	5.86			Domestic waste	N/A	15.24	N/A	1.01	N/A	16.24	N/A
		Paper	4.89					7.29	N/A	0.84	N/A	8.13	N/A
Filter needle	Product	Stainless steel	0.40	1	1	Medicinal contaminated sharps waste	N/A	2.46	N/A	0.43	N/A	2.89	N/A
		Polypropylene injection moulding	0.10					0.45	N/A	0.11	N/A	0.56	N/A

	Packaging	High density polyethylene resin	0.59			Domestic waste	N/A	1.14	N/A	0.10	N/A	1.24	N/A
		Low density polyethylene film	0.23					0.60	N/A	0.04	N/A	0.64	N/A
		Paper	0.11					0.16	N/A	0.02	N/A	0.18	N/A
Gallipot	Product	Polypropylene injection moulding	6.40	1	1	Clinical waste	N/A	28.74	N/A	6.87	N/A	35.61	N/A
	Packaging	Paper	1.60			Domestic waste	N/A	2.38	N/A	0.27	N/A	2.66	N/A
		Low density polyethylene film	1.45					3.77	N/A	0.25	N/A	4.02	N/A
Incontinence pad	Product	Cotton padding	15.09	1	1	Infectious waste	N/A	19.32	N/A	8.59	N/A	27.91	N/A
		Low density polyethylene film	15.09					39.23	N/A	8.59	N/A	47.82	N/A
Braided silk tonsil ties	Product	Silk	1.15	1	1	Clinical waste	Infectious waste	41.56	N/A	1.24	0.65	42.80	42.22
	Packaging	Paper	2.01			Domestic waste	N/A	2.99	N/A	0.35	N/A	3.34	N/A
		Low density polyethylene film	0.58					1.51	N/A	0.10	N/A	1.61	N/A
Gauze (non-sterile)	Product	Cotton fabric	1.99	1	1	Clinical waste	N/A	13.49	N/A	2.14	N/A	15.63	N/A
Nail scrubbing brush	Product	Low density polyethylene resin	9.01	1	1	Domestic waste	Infectious waste	18.74	N/A	1.55	5.13	20.29	23.87
		Polyurethane flexible foam	2.05					9.92	N/A	0.35	1.17	10.27	11.09
		Polypropylene injection moulding	0.91			Domestic waste	N/A	4.09	N/A	0.16	N/A	4.24	N/A
	Packaging	Low density polyethylene film	1.31					3.41	N/A	0.23	N/A	3.63	N/A
		Paper	0.60					0.89	N/A	0.10	N/A	1.00	N/A
Suction tip	Product	Polyvinylchloride injection moulding	2.87	1	1	Clinical waste	Infectious waste	9.47	N/A	3.08	1.63	12.55	11.10

	Packaging	Low density polyethylene film	1.49			Domestic waste	Infectious waste	3.87	N/A	0.26	0.85	4.13	4.72
		Paper	1.20					1.79	N/A	0.21	0.68	1.99	2.47
Suction receptacle	Product	High density polyethylene resin	72.62	1	1	Clinical waste	Infectious waste	140.16	N/A	78.00	41.34	218.16	181.50
		Low density polyethylene resin	72.62					151.05	N/A	78.00	41.34	229.05	192.39
Suction tubing	Product	Polyvinylchloride injection moulding	121.21	1	1	Clinical waste	Infectious waste	399.99	N/A	130.20	69.01	530.19	469.00
	Packaging	Low density polyethylene film	3.08			Domestic waste	Infectious waste	8.01	N/A	0.53	1.75	8.54	9.76
		Paper	3.31					4.93	N/A	0.57	1.88	5.50	6.82
		Low density polyethylene film	2.32					6.03	N/A	0.40	1.32	6.43	7.35
Syringe (10 ml)	Product	Polypropylene injection moulding	3.01	1	1	Clinical waste	N/A	13.51	N/A	3.23	N/A	16.75	N/A
		General polyethylene	3.01					7.65	N/A	3.23	N/A	10.88	N/A
		Rubber	0.25					0.71	N/A	0.27	N/A	0.98	N/A
	Packaging	Low density polyethylene film	0.45			Domestic waste	N/A	1.17	N/A	0.08	N/A	1.25	N/A
		Paper	0.39					0.58	N/A	0.07	N/A	0.65	N/A
Tonsil swab pack	Product	Cotton fabric	5.81	1	1	Clinical waste	Infectious waste	39.39	N/A	6.24	3.31	45.63	42.70
	Packaging	Paper	1.92			Domestic waste	Infectious waste	2.86	N/A	0.33	1.09	3.19	3.95
		Low density polyethylene film	0.96					2.50	N/A	0.16	0.55	2.66	3.04
Yankauer sucker	Product	Polyvinylchloride injection moulding	18.68	1	1	Clinical waste	Infectious waste	61.64	N/A	20.06	10.63	81.71	72.28
	Packaging	Paper	2.19			Domestic waste	Infectious waste	3.26	N/A	0.38	1.25	3.64	4.51

		Low density polyethylene film	2.17					5.64	N/A	0.37	1.24	6.01	6.88
Specimen pot (40 ml 4% formalde-hyde)	Product	4% Formaldehyde	£0.20	1	1	Clinical waste	N/A	37.63	N/A	N/A	N/A	37.63	N/A
	Product (weight-for waste)		40					N/A	N/A	42.97	N/A	42.97	N/A
	Packaging	Polypropylene injection moulding	6.53					29.32	N/A	7.01	N/A	36.33	N/A
		High density polyethylene resin	6.53					33.89	N/A	7.01	N/A	40.90	N/A
Pharmaceuticals													
Bupivacaine 0.5% with 1:200,000 adrenaline (10 ml)	Product	Bupivacaine hydrochloride	10.00	1	1	N/A	N/A	230.00	N/A	N/A	N/A	230.00	N/A
	Packaging	Glass general	6.38			Medicinal contaminated sharps waste		9.19	N/A	6.85	N/A	16.04	N/A
Chirocaine 2.5 mg per ml (10 ml)	Product	Bupivacaine hydrochloride	10.00	1	1	N/A	N/A	230.00	N/A	N/A	N/A	230.00	N/A
	Packaging	High density polyethylene resin	0.55	1	1	Domestic waste		1.06	N/A	0.09	N/A	1.16	N/A
		Low density polyethylene resin	4.70					9.78	N/A	0.81	N/A	10.58	N/A
		Low density polyethylene resin	3.16			Clinical waste		6.57	N/A	3.39	N/A	9.97	N/A
Sodium chloride 0.9% from 1 litre bottle (150 ml)	Product and packaging	Sodium Chloride 0.9% from 1 litre bottle	£0.59	1	1	N/A	N/A	113.81	N/A	N/A	N/A	113.81	N/A
Sodium chloride 0.9%,	Product and packaging	Sodium chloride 0.9% intravenous	£1.38	1	1	Clinical waste	N/A	264.41	N/A	27.04	N/A	264.41	N/A

intravenous infusion bag (500 ml)	Packaging (weight for waste)	infusion bag (500 ml)	25.17					N/A	N/A	27.04	N/A	27.04	N/A
Yellow soft paraffin BP 100% from 15 g tube	Product	Petroleum slack wax	0.79	1	1	N/A	N/A	0.85	N/A	N/A	N/A	0.85	N/A
Cleaning products, waste													
Black waste bag (domestic waste) with cable tie	Product	Polypropylene oriented film	22.37	1	1	Domestic waste	N/A	76.73	N/A	3.84	N/A	80.57	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	0.44	N/A	24.02	N/A
Clear waste bag (for swab count)	Product	Low density polyethylene film	22.78	1	1	Clinical waste	Infectious waste	59.23	N/A	24.47	12.97	83.70	72.20
Clear waste bag (recycling) with cable tie	Product	Low density polyethylene film	15.01	1	1	Domestic waste	N/A	39.03	N/A	2.58	N/A	41.60	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	0.44	N/A	24.02	N/A
Disinfectant sachet	Product	Disinfectant	£0.70	1	5	Domestic waste	N/A	26.82	N/A	N/A	N/A	26.82	N/A
	Packaging (weight for waste)		5.81					N/A	N/A	0.20	N/A	0.20	N/A
Disinfectant wipe	Product	Non-woven polyester	2.30	1	1	Clinical waste	Infectious waste	12.79	N/A	2.47	1.31	15.26	14.10
Green bag (linen laundering) with cable tie	Product	Low density polyethylene film	29.22	1	5	Domestic waste	N/A	15.19	N/A	1.00	N/A	16.20	N/A
		Nylon (polyamide) 6 polymer	2.58					4.72	N/A	0.09	N/A	4.80	N/A

Mop head	Product	Nylon (polyamide) 6 polymer	70.36	1	5	Clinical waste	Infectious waste	128.62	N/A	15.12	8.01	143.73	136.63
		High density polyethylene resin	30.16					11.64	N/A	6.48	3.43	18.12	15.08
Orange waste bag (infectious waste) with cable tie	Product	Polypropylene oriented film	70.61	1	1	Infectious waste	N/A	242.19	N/A	40.20	N/A	282.39	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	1.47	N/A	25.05	N/A
Yellow waste bag (clinical waste) with cable tie	Product	Polypropylene oriented film	28.15	1	1	Clinical waste	N/A	96.55	N/A	30.24	N/A	126.79	N/A
		Nylon (polyamide) 6 polymer	2.58					23.58	N/A	2.77	N/A	26.35	N/A

Supplementary table 16: Products and waste streams used for carpal tunnel decompression operation 1-10

Operation number C1=carpal tunnel decompression one etc. All waste of given product disposed of using consistent waste stream (A). See Supplementary table 6 and Supplementary table 7 for waste stream A (product dependent)

Product		Number of products used Waste stream A used for product, followed by packaging where relevant									
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Minor op set		1	1	1	1	1	1	1	1	1	1
Reusable scrubs		5	5	5	6	7	5	8	5	5	6
Reusable tourniquet pressure cuff		1	1	1	1	0	0	0	1	1	1
Hand pack	Patient drape (fenestrated hand drape)	1	1	1	1	1	1	1	1	1	1
	Table drape (instruments)	1	1	1	1	1	1	1	1	1	1
	'Hand pack' packaging (drape component)	1	1	1	1	1	1	1	1	1	1
	Bowl	2	2	2	2	2	2	2	2	2	2
	Foam cube	2	2	2	2	2	2	2	2	2	2
	Gauze swab	1	1	1	1	1	1	1	1	1	1
	Kidney dish	1	1	1	1	1	1	1	1	1	1
	Light cover	1	1	1	1	1	1	1	1	1	1
	Needle counter	1	1	1	1	1	1	1	1	1	1
	Surgical blade	2	2	2	2	2	2	2	2	2	2
	Syringe (20 ml)	1	1	1	1	1	1	1	1	1	1
	'Hand pack' packaging (single-use equipment component)	1	1	1	1	1	1	1	1	1	1
Gloves (non-sterile, pair)		2	2	2	4	3	3	4	3	3	4
Sterile gloves (pair)		3	3	3	2	2	3	3	2	1	2
Sterile gloves (two pairs)		1	1	1	0	0	0	0	1	0	1
Sterile gloves (two pair, latex free)		0	0	0	1	1	0	0	0	1	0
Surgical face mask		6	6	6	6	1	1	6	3	3	5
Surgical face mask with eye protection		0	0	0	1	2	3	2	2	2	1
Surgical gown (including hand towels)		3	3	3	3	3	3	3	4	2	4

Surgical hat	5	5	5	6	7	5	8	5	5	6
Visor	0	0	0	0	0	0	0	0	1	0
Crepe bandage (7.5 cm wide)	1	1	1	1	1	1	1	1	1	1
Elasticated fabric dressing strip	3	3	3	2	2	2	2	2	0	2
Gauze (individual piece)	0	0	0	0	1	1	1	0	0	1
Gauze (sterile pack)	1	2	3	4	1	0	0	0	0	0
Incontinence pad	1	1	1	1	1	1	1	1	1	1
Nail scrubbing brush	3	1	0	1	3	1	0	2	2	0
Needle (blue)	0	0	0	0	0	1	1	0	1	1
Needle (green)	1	1	1	1	1	1	1	1	0	0
Needle (red)	1	1	1	1	1	0	0	0	0	0
Non-woven dressing	1	1	1	1	1	1	1	1	1	1
Skin marker	1	1	1	0	1	1	1	0	0	0
Stockinette tubular bandage	1	1	1	1	0	0	0	0	1	1
Surgical blade	1	1	0	0	1	0	0	0	0	0
Suture (monofilament, non-absorbable, 4-0)	1	0	0	1	0	0	0	1	0	1
Suture (monofilament, non-absorbable 5-0)	0	1	1	0	1	1	1	0	1	0
Syringe (10 ml)	1	1	1	1	0	0	0	1	0	1
Syringe (20 ml)	0	0	0	0	1	1	1	0	1	0
Tape (clear)	0	0	0	0	0	0	0	0	1	0
Undercast padding	1	1	1	1	1	1	1	1	1	1
Bupivacaine hydrochloride 0.5% (10 ml)	1	1	1	1	0	0	0	0	1	0
Chlorhexidine 2% from 500 ml container (100 ml)	1	1	1	1	1	1	1	1	1	1
Hyaluronidase 1500 I.U. (10 ml)	0	0	0	1	0	0	0	0	1	0
Levobupivacaine 5 mg per 10 ml (10 ml)	0	0	0	0	0	0	0	1	0	1
Lidocaine 1% (10 ml)	1	1	1	1	0	0	0	0	1	0
Lidocaine 1% with adrenaline 1:200,000 (20 ml)	0	0	0	0	1	1	1	0	0	0
Sodium Chloride 0.9% from 1 litre bottle (100 ml)	1	1	1	1	1	1	1	1	1	1

Clear bin bag (linen laundering)	1	1	1	1	1	1	1	1	1	1
Disinfectant sachet	1	1	1	1	1	1	1	1	1	1
Disinfectant wipe	8	7	5	5	4	5	3	12	5	6
Orange waste bag (infectious waste) with cable tie from theatre	1	1	1	1	1	1	1	1	1	1
Orange waste bag (infectious waste) with cable tie from scrub room	1	1	1	1	1	1	1	1	1	1
Mop head	1	1	1	1	1	1	1	1	1	1
Red bag (linen laundering) with cable tie	1	1	1	1	1	1	1	1	1	1

Supplementary table 17: Products and waste streams used for inguinal hernia repair operation 1-6
Operation number H1=inguinal hernia operation one etc. All waste of given product disposed of using consistent waste stream (A). See Supplementary table 8 and Supplementary table 9 for waste stream A and B (product dependent)

Product	**Number of products used Waste stream A or B used for product, followed by packaging where relevant**					
	H1	**H2**	**H3**	**H4**	**H5**	**H6**
General basic set (A)	1 A,A	1 A,A	0	0	0	0
General basic set (B)	0	0	1 A,A	1 A,A	1 A,A	1 A,A
Roberts artery forceps	1 A,A	0	0	0	0	0
Collingwood Stewart hernia forceps	0	0	0	1 A,A	0	0
High fluid drape	0	0	1 A,A	1 A,A	1 A,A	1 A,A
Huck towel	0	0	0	1 A,A	1 A,A	1 A,A
Low fluid drape	1 A,A	1 A,A	0	0	0	0
Reusable surgical gown (including hand towels)	1 B,B	1 B,B	0	2 A,A	0	2 A,A
Reusable surgical hat	0	0	2 A	0	0	0
Reusable scrubs	5 A	4 A	6 A	5 A	5 A	5 A
Diathermy pad lead	1 A	1 A	1 A	1 A	1 A	1 A
Shaver base	1 B	1 B	1 A	1 A	1 A	
Gloves (non-sterile, pair)	7 B	5 B	4 A	4 A	7 A	8 A
Sterile gloves (pair)	2 B,B	2 B,B	3 A,A	1 A,A	1 A,A	1 A,A
Sterile gloves (two pairs)	0	0	1 A,A	1 A,A	2 A,A	2 A,A
Sterile gloves (one pair, latex free)	1 B,B	1 B,B	0	2 A,A	0	0
Sterile under-gloves (pair)	1 B,B	1 B,B	0	0	0	0
Surgical face mask	1 B	1 B	3 A	5 A	2 A	2 A
Surgical face mask with eye protection	0	0	0	0	1 A	1 A
Surgical gown (including hand towels)	1 B,B	1 B,B	3 A,A	1 A,A	3 A,A	1 A,A
Surgical hat	5 B	4 B	4 A	5 A	6 A	3 A
Patient drape (incise drape, with iodine)	0	0	0	1 A,A	0	0
Table drape (instruments)	0	0	1 A,A	2 A,A	1 A,A	1 A,A
Absorbent towel pack	0	0	1 A,A	0	0	0

Diathermy pad	3 B,B	1 B,B	1 A,A	1 A,A	1 A,A	1 A,A
Diathermy tip	0	0	1 A,A	0	0	0
Gauze (sterile pack, 10x7.5 cm)	4 B,B	3 B,B	2 A,A	1 A,A	2 A,A	2 A,A
Gauze (sterile pack, 30x30 cm)	0	0	1 A,A	0	0	0
Gauze (sterile pack, 10x10 cm)	2 B,B	2 B,B	0	0	0	0
Incontinence pad	3 B	3 B	2 A	1 A	1 A	1 A
Kidney dish	1 B,B	1 B,B	0	0	0	0
Light handle	1 B,B	1 B,B	2 A,A	2 A,A	1 A,A	0
Mesh	1 B	1 B	1 A	1 A	1 A	1 A
Monopolar diathermy with smoke evacuation system	1 B,B	1 B,B	0	2 A,A	1 A,A	1 A,A
Nail scrubbing brush	2 B,B	1 B,B	1 A,A	0	1 A,A	0
Needle (green)	1 A,B	1 A,B	1 A,A	1 A,A	0	1 A,A
Needle counter	1 A,B	1 A,B	1 A,A	1 A,A	1 A,A	1 A,A
Nonwoven dressing (10x20 cm)	1 B,A	1 B,A	1 A,A	1 A,A	1 A,A	1 A,A
Nonwoven dressing (10x30 cm)	1 A,A	1 A,A	0	0	0	0
Pre-operative adhesive glove	3 B,B	3 B,B	1 A,A	1 A,A	1 A,A	0
Reinforced skin closure strip	1 A,A	1 A,A	0	0	0	0
Shaver head	1 A,B	1 A,B	1 A,A	1 A,A	1 A,A	0
Specimen pot (40 ml 4% formaldehyde)	1 A	1 A	0	0	0	0
Surgical blade (10)	1 A,B	1 A,B	1 A,A	1 A,A	1 A,A	1 A,A
Surgical suspensory bandage	1 A,A	1 A,A	0	0	0	0
Suture (braided, absorbable, 0)	1 A,A	0	0	0	0	0
Suture (braided, absorbable, 2-0)	1 A,B	1 A,B	4 A,A	2 A,A	1 A,A	1 A,A
Suture (monofilament, absorbable, 3-0)	1 A,B	1 A,B	1 A,A	1 A,A	1 A,A	1 A,A
Suture (monofilament, nonabsorbable, 1)	1 A,B	1 A,B	0	0	1 A,A	1 A,A
Suture (monofilament, nonabsorbable, 2-0)	3 AB	3 A,B	2 A,A	0	0	0
Syringe (20 ml)	3 B,B	3 B,B	1 A,A	1 A,A	0	1 A,A
Chlorhexidine 1% from 500 ml container (100 ml)	0	0	1	1	1	1
Levobupivacaine 5mg per10 ml (10 ml)	6 A	6 A	0	0	0	3
Povidone iodine 10% from 500 ml container (60 ml)	1 A,A	1 A,A	0	0	0	0

Sodium Chloride 0.9% from 1 litre bottle (50 ml)	1	1	1	1	1	1
Topical skin adhesive (0.8 g)	0	0	0	1	0	0
Black waste bag (domestic waste) with cable tie	1 A	1 A	0	0	0	0
Chlorine tablet	2 A	2 A	0	0	0	0
Clear bin bag (for swab count)	1 A	1 A	0	0	0	0
Clear bin bag (recycling) with cable tie	0	0	1 A	1 A	1 A	1 A
Disinfectant sachet	0	0	1 A	1 A	1 A	1 A
Disinfectant wipe	8 B	5 B	7 A	6 A	7 A	7 A
Green bag (linen laundering) with cable tie	1 A	1 A	1 A	1 A	1 A	1 A
Mop head	1 B	1 B	1 A	1 A	1 A	1 A
Orange waste bag (infectious waste, large) with cable tie	0	0	1 A	1 A	1 A	1 A
Orange waste bag (infectious waste, small) with cable tie	0	0	1 A	1 A	1 A	1 A
Red bag (linen laundering) with cable tie	1 A	1 A	1 A	1 A	1 A	1 A
Yellow waste bag (clinical waste) with cable tie	1 A	1 A	0	0	0	0

Supplementary table 18: Products and waste streams used for knee arthroplasty 1-10

Operation number K1=carpal tunnel decompression one etc. All waste of given product disposed of using consistent waste stream (A), aside from B for packaging of surgical gowns, orthopaedic hood for K2 and K3. See Supplementary table 10 and Supplementary table 11 for waste stream A and B (product dependent)

Product		Number of products used									
		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10
Basic major orthopaedic set		1	1	1	1	1	1	1	1	1	1
Bipolar diathermy		0	0	0	0	0	0	1	0	0	0
Blunt Hohman bone elevator		0	0	0	0	0	0	0	1	1	0
Cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8)		0	0	0	0	0	1	1	0	0	0
Cruciate retaining femoral and tibial trialing set (size 3-6)		0	1	1	1	1	1	1	1	1	1
Diathermy extras		0	0	0	0	0	1	0	0	0	0
Diathermy lead		0	0	0	0	0	0	1	0	0	0
Femoral and tibial preparation set (size 3-6)		1	1	1	1	1	1	1	1	1	1
Knee navigation set		0	0	0	0	0	0	0	1	0	0
Lanes tissue forceps		1	0	1	0	0	0	0	1	1	1
Light cover		1	1	1	1	1	1	1	1	1	1
Light handle		1	1	1	2	1	1	1	1	1	1
Miscellaneous knee system set		1	1	1	1	1	1	1	1	1	1
Non-toothed lamina spreader (large)		0	1	1	0	0	0	0	0	0	0
Non-toothed lamina spreader (small)		0	0	0	1	0	0	0	0	0	0
Orthopaedic surgical drill set		1	1	1	1	1	1	1	1	1	1
Patella preparation and trialing set		1	0	1	1	0	1	1	1	1	0
Posterior stabilised femoral and tibial trialing set (size 3-6)		1	0	0	0	1	0	0	1	0	0
Semb bone holding forceps		1	1	1	0	0	1	1	1	1	1
Reusable shaver base		0	0	0	0	1 A	0	1 A	0	0	0
Reusable scrubs		6	7	7	5	6	5	5	5	5	5
Knee pack	Surgical gown	1	1	1	1	1	1	1	1	1	1
	Knee pack packaging (gown component)	1	1	1	1	1	1	1	1	1	1
	Patient drape (240x150 cm)	1	1	1	1	1	1	1	1	1	1

	Patient drape (90 x75 cm)	1	1	1	1	1	1	1	1	1	1
	Patient drape (extremity, 230x325 cm)	1	1	1	1	1	1	1	1	1	1
	Patient drape (impervious, split, 152x177 cm)	1	1	1	1	1	1	1	1	1	1
	Patient drape (Mayo cover, 75x144 cm) x2	1	1	1	1	1	1	1	1	1	1
	Patient drape (pouch fluid collection, 40x35 cm)	1	1	1	1	1	1	1	1	1	1
	Patient drape (stockinette, impervious, 30x120 cm)	1	1	1	1	1	1	1	1	1	1
	Table drape (140x90 cm)	1	1	1	1	1	1	1	1	1	1
	Table drape (fan folded, 140x190 cm)	1	1	1	1	1	1	1	1	1	1
	Knee pack packaging (patient and instrument table drape component)	1	1	1	1	1	1	1	1	1	1
	Bowl (250 ml) x2	1	1	1	1	1	1	1	1	1	1
	Bowl (500 ml)	1	1	1	1	1	1	1	1	1	1
	Cast padding bandage x2	1	1	1	1	1	1	1	1	1	1
	Crepe bandage x2	1	1	1	1	1	1	1	1	1	1
	Diathermy bag	1	1	1	1	1	1	1	1	1	1
	Diathermy tip cleaner	1	1	1	1	1	1	1	1	1	1
	Kidney dish x3	1	1	1	1	1	1	1	1	1	1
	Light cover	1	1	1	1	1	1	1	1	1	1
	Monopolar diathermy	1	1	1	1	1	1	1	1	1	1
	Needle counter	1	1	1	1	1	1	1	1	1	1
	Skin marker pen	1	1	1	1	1	1	1	1	1	1
	Suction tubing	1	1	1	1	1	1	1	1	1	1
	Surgical blade (10) x3	1	1	1	1	1	1	1	1	1	1
	Swab gauze (10x7.5 cm) x5	1	1	1	1	1	1	1	1	1	1
	Swab gauze (30x30 cm) x10	1	1	1	1	1	1	1	1	1	1

	Towel dressing (2 in pack)	1	1	1	1	1	1	1	1	1	1
	Tray (small)	1	1	1	1	1	1	1	1	1	1
	Yankauer sucker	1	1	1	1	1	1	1	1	1	1
	Knee pack packaging (equipment component)	1	1	1	1	1	1	1	1	1	1
Gloves (non-sterile, pair)		7	7	8	7	7	5	6	10	7	7
Orthopaedic hood		3	2	2	2	3	0	0	2	3	3
Sterile gloves (pair)		0	5	5	7	6	6	8	5	5	7
Sterile gloves (two pairs)		8	2	2	3	1	1	2	2	3	3
Sterile gloves (two pair, latex free)		0	0	1	0	1	1	0	0	0	0
Surgical face mask		3	4	2	3	2	3	1	5	4	2
Surgical face mask with eye protection		1	1	3	1	1	3	2	0	0	0
Surgical gown (including hand towels)		3	2	2	3	3	2	2	3	4	3
Surgical hat		6	7	7	5	6	2	2	5	5	5
Sweat bands for hood x3		3	2	2	2	3	0	0	2	3	3
Patient drape (adhesive split sheet)		0	0	0	0	0	0	0	1	1	0
Patient drape (clear U drape)		0	1	1	1	1	0	0	0	0	1
Patient drape (incise drape)		0	0	0	0	0	1	1	0	0	0
Patient drape (incise drape, with iodine)		1	1	1	1	1	0	0	0	0	1
Table drape (instruments)		2	2	2	2	2	2	2	2	2	2
Adhesive operative towel		0	0	0	1	0	0	0	0	0	0
Batteries for knee navigation set (x3)		0	0	0	0	0	0	0	3	0	0
Border dressing (10x30 cm)		1	1	1	1	2	1	2	1	1	2
Border dressing (6x8 cm)		0	0	0	0	0	0	0	1	1	0
Catheter tip syringe		0	1	0	0	0	0	0	0	0	0
Cement mixing and delivery system		1	1	1	1	1	1	1	1	1	1
Cement mixing bowl		0	0	0	0	0	0	1	0	0	0
Crepe bandage (15 cm wide)		0	0	0	0	1	0	0	0	0	0
Cruciate retaining femoral implant		0	1	1	0	0	1	0		1	1

Diathermy bag	0	0	1	1	0	0	0	1	1	0
Diathermy tip	0	0	0	0	0	0	0	0	0	1
Diathermy tip cleaner	1	1	1	1	1	1	1	1	1	1
Elasticated fabric dressing strip	2	2	2	2	2	2	2	2	2	2
Gauze (individual piece)	1	1	1	1	0	0	0	0	0	0
Gauze (sterile pack)	0	0	0	0	0	0	0	0	0	0
High-vacuum wound drainage	0	0	0	0	0	1	1	0	0	0
Incontinence pad	2	3	1	1	1	1	1	1	1	1
Intravenous infusion giving set	1	1	1	1	1	1	1	0	0	1
Marker pen and ruler	0	0	0	0	0	0	0	1	0	0
Monopolar diathermy	0	0	0	0	0	0	0	0	1	0
Nail scrubbing brush	0	0	0	3	3	3	3	3	3	3
Needle (green)	1	1	1	1	0	0	0	0	0	0
Needle (red)	1	1	1	1	1	1	1	0	0	1
Needle (white)	2	2	2	2	2	1	1	2	2	2
Posterior stabilised femoral implant	1	0	0	1	1	0	0	1	0	0
Pre-operative adhesive glove	0	0	0	0	1	0	1	0	0	0
Primary tibial baseplate implant	1	1	1	1	1	1	1	1	1	1
Pulsed lavage system	1	1	1	1	1	1	1	1	1	1
Saw blade	1	1	1	2	1	1	1	1	1	1
Self-adherent bandage	1	0	0	0	0	0	0	0	0	0
Shaver head	0	0	0	0	1	0	1	0	0	0
Skin stapler	0	0	0	1	1	0	0	1	1	1
Sticky label	1	1	1	1	1	0	0	0	0	0
Suction receptacle	1	1	1	1	1	1	1	1	1	1
Suction tip	0	0	0	0	0	0	1	0	0	0
Suction tubing	0	0	1	0	0	1	0	0	0	0
Surgical blade (10)	0	1	1	0	0	0	1	0	0	0
Suture (braided, absorbable, 2-0)	1	1	1	1	0	0	0	1	1	1

Suture (monofilament, absorbable, 3-0, 643)	0	0	0	0	0	1	1	0	0	0
Suture (monofilament, absorbable 3-0, 696)	2	2	2	0	0	0	0	0	0	0
Suture (braided, absorbable 1-0, 803)	1	1	1	3	0	3	3	2	2	3
Suture (braided, absorbable 1-0, 932)	0	0	0	0	3	0	0	0	0	0
Swab tray (large)	1	1	1	1	2	2	1	1	1	1
Swab tray (small)	1	1	1	1	1	1	1	1	1	1
Symmetric patella implant	1	0	1	1	0	1	1	1	1	0
Syringe (20 ml)	1	1	1	1	1	1	1	0	0	1
Syringe (50 ml)	2	2	2	1	1	2	2	4	4	2
Tibial bearing insert cruciate retaining implant	1	1	1	1	0	0	1		1	1
Tibial bearing insert posterior stabilised implant	0	0	0	0	1	0	2	1	0	0
Tourniquet pressure cuff (leg)	1	1	1	1	1	1	1	1	1	1
Transparent film adhesive dressing	1	0	0	0	0	0	1	0	0	0
Tubular support bandage	0	0	0	0	1	1	1	1	1	1
Wound closure strips	2	2	2	0	0	0	0	0	2	0
Adrenaline 1mg in 1ml (1ml)	1	1	1	1	1	1	1	0	0	1
Bone cement mix (with gentamicin)	0	0	0	1	0	1	2	0	0	0
Bone cement mix (with tobramycin)	2	2	2	0	2	0	0	2	2	2
Chlorhexidine 2% from 500 ml bottle (150 ml)	1	1	1	1	1	0	0	0	0	1
Chlorhexidine gluconate in 70% denatured ethanol with 4ml red stain solution from 200 ml bottle (150 ml)	1	0	0	1	1	0	0	0	0	1
Iodinated povidone 10% w/w alcoholic tincture from 500 ml bottle (50 ml)	0	0	0	1	0	1	1	1	1	0
Ketorolac tromethamine 30mg in 1 ml (1 ml)	1	1	1	1	1	1	1	0	0	1
Levobupivacaine 2.5mg per ml (10 ml)	0	0	0	0	0	0	0	4	4	0
Ropivacaine 75mg in 10 ml (10 ml)	2	2	2	2	2	2	2	0	0	2

Sodium chloride 0.9% (100 ml)	1	2	1	1	1	1	1	1	1	1
Sodium chloride 0.9% for irrigation (3 L bag)	1	1	1	1	1	1	1	1	1	1
Topical skin adhesive (0.8 g)	1	0	0	0	0	0	0	0	0	0
Anatomical waste bin	1	1	1	1	1	1	1	1	1	1
Clear bin bag (linen laundering)	1	1	1	1	1	1	1	1	1	1
Clear waste bag (recycling) with cable tie	1	1	1	1	1	1	1	1	1	1
Disinfectant sachet	1	1	1	1	1	1	1	1	1	1
Disinfectant wipe	50	45	50	16	62	22	25	20	25	30
Orange waste bag (infectious waste) with cable tie from theatre	2	2	2	2	2	2	2	2	2	2
Orange waste bag (infectious waste) with cable tie from scrub room	1	0	0	1	1	1	1	1	1	1
Mop head	1	1	1	1	1	1	1	1	1	1
Red bag (linen laundering) with cable tie	1	1	1	1	1	1	1	1	1	1
Yellow/ black waste bag (non-infectious offensive waste) with cable tie from scrub room	0	1	1	0	0	0	0	0	0	0

Supplementary table 19: Products and waste streams used for laparoscopic cholecystectomy operation 1-6

Operation number L1=laparoscopic cholecystectomy operation one etc. See Supplementary table 12 and Supplementary table 13 for waste stream A and B (product dependent)

Product	Number of products used or volume where specified Waste stream A or B used for product, followed by packaging where relevant					
	L1	**L2**	**L3**	**L4**	**L5**	**L6**
General basic set	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
General laparoscopic set	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
Laparoscope set (10 mm, 0 degree)	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
Diathermy lead	0	0	1 A,A	0	0	0
Laparoscopic grasping forceps	0	0	0	1 A,A	0	0
Quiver and clip	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
High fluid drape	1 A,N	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
Huck towel	0	1 A,A	0	1 A,B	1 A,B	1 A,B
Reusable surgical gown (including hand towels)	1 A,A	1 A,A	3 A,A	2 A,B	0	1 A,B
Reusable surgical gown (including hand towels) double pack	0	1 A,A	0	1 A,A	1 A,A	1 A,A
Reusable surgical hat	0	0	0	1 A	1 A	1 A
Scrubs	7 A	7 A	6 A	6 A	6 A	6 A
Diathermy pad lead	1 A	1 A	1 A	1 A	1 A	1 A
Gloves (non-sterile, pair)	8 A	7 A	6 A	5 B	6 B	3 B
Sterile gloves (pair)	0	1 A,A	3 A,A	2 B,A	2 B,A	2 B,A
Sterile gloves (two pairs)	3 A,A	3 A,A	0	1 B,A	1 B,A	2 B,A
Sterile gloves (one pair, latex free)	0	0	1 A,A	0	0	0
Surgical face mask	0	2 A	3 A	3 B	2 B	4 B
Surgical face mask with eye protection	1 A	1 A	0	0	1 B	0
Surgical gown (including hand towels)	2 A,A	0	0	0	1 B,A	1 B,A
Surgical hat	7 A	7 A	6 A	5 B	5 B	5 B
Table drape (instrument)	1 A,A	1 A,A	1 A,A	1 B,B	1 B,B	1 B,B
Absorbent towel pack	1 A,A	0	0	0	0	0

Anti-fog endoscopic demister	0	1 A,A	1 A,A	1 B,B	1 B,B	1 B,B
Diathermy pad	1 A,A	1 A,A	1 A,A	1 B,B	1 B,B	1 B,B
Endoscopic clip applier	1 A,A	1 A,A	1 A,A	1 A,B	1 A,B	1 A,B
Gauze (sterile pack)	2 A,A	1 A,A	1 A,A	2 B,B	2 B,B	2 B,B
Incontinence pad	1 A	1 A	1 A	1 B	2 B	1 B
Insufflating tubing	1 A,A	1 A,A	1 A,A	1 B,B	1 B,B	1 B,B
Laparoscope cover	1 A,A	1 A,A	1 A,A	1 B,B	1 B,B	1 B,B
Laparoscopic scissors	1 A,A	1 A,A	1 A,A	1 A,B	0	1 A,B
Laparoscopic tissue retrieval system	1 A,A	1 A,A	1 A,A	1 B,B	1 B,B	1 B,B
Light handle	1 A,A	0	0	0	0	0
Nail scrubbing brush	0	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
Needle (green)	1 A,A	1 A,A	1 A,A	1 A,B	1 A,B	1 A,B
Needle counter	1 A,A	1 A,A	1 A,A	1 A,B	1 A,B	1 A,B
Nonwoven dressing (6x7 cm)	4 A,A	4 A,A	4 A,A	4 B,B	3 B,B	4 B,B
Port (12 mm)	1 A,A	2 A,A	1 A,A	2 A,B	2 A,B	2 A,B
Port (5 mm, dual pack)	1 A,A	1 A,A	1 A,A	1 A,B	1 A,B	1 A,B
Pressure saline infusion bag	0	0	1 A,A	0	0	0
Reinforced skin closure strip	0	1 A,A	1 A,A	0	1 A,B	0
Specimen pot (40 ml 4% formaldehyde)	0	1 A,A	1 A,A	0	0	0
Specimen pot (not pre-filled)	1 A	0	0	1 B	1 B	1 B
Suction irrigation	0	0	1 A,A	1 B,B	0	1 B,B
Suction receptacle	0	0	1 A	1 B	0	0
Surgical blade (11)	1 A,A	0	0	0	0	0
Surgical blade (15)	0	1 A,A	0	1 A,B	1 A,B	1 A,B
Suture (braided, absorbable, 3-0)	0	1 A,A	1 A,A	2 A,B	2 A,B	1 A,B
Suture (monofilament, absorbable, 3-0)	1 A,A	0	0	0	0	0
Suture (monofilament, absorbable, 1)	1 A,A	2 A,A	2 A,A	1 A,B	1 A,B	1 A,A
Syringe (10 ml)	1 A,A	1 A,A	1 A,A	1 B,B	1 B,B	1 B,B
Syringe (20 ml)	2 A,A	1 A,A	1 A,A	2 B,B	1 B,B	1 B,B
Tonsil swab pack	0	1 A,A	0	1 B,B	1 B,B	1 B,B

Carbon dioxide (from 3 kg cylinder containing 450 L)	28.5 litres	51.3 litres	102.7 litres	144 litres	74.5 litres	22.3 litres
Chlorhexidine 1% from 500 ml container (50 ml)	1	1	1	1	1	1
Levobupivacaine 2.5mg per10 ml (10 ml)	4 A	3 A	3 A	3 B	3 B	3 B
Sodium Chloride 0.9% for irrigation (1 L bag)	0	0	1 A	2 B	0	0
Sodium Chloride 0.9% from 1 litre bottle (50 ml)	1	1	1	1	1	1
Black waste bag (domestic waste) with cable tie	0	0	0	2	2	2
Clear bin bag (quiver diathermy)	1 A	1 A	1 A	1 A	1 A	1 A
Clear bin bag (recycling) with cable tie	1 A	1 A	1 A	0	0	0
Disinfectant sachet	1 A	1 A	1 A	1 B	1 B	1 B
Disinfectant wipe	8 A	7 A	5 A	4 B	15 B	6 B
Green bag (linen laundering) with cable tie	1 A	1 A	1 A	1 A	1 A	1 A
Mop head	1 A	1 A	1 A	1 B	1 B	1 B
Orange waste bag (infectious waste, large) with cable tie	1 A	1 A	1 A	0	0	0
Orange waste bag (infectious waste, small) with cable tie	1 A	1 A	1 A	0	0	0
Red bag (linen laundering) with cable tie	1 A	1 A	1 A	1 A	1 A	1 A
Yellow/ black waste bag (non-infectious offensive waste, large) with cable tie	0	0	0	1 A	1 A	1 A
Yellow/ black waste bag (non-infectious offensive waste, small) with cable tie	0	0	0	1 A	1 A	1 A

Supplementary table 20: Products and waste streams used for tonsillectomy operation 1-10

Operation number T1=tonsillectomy one etc. See Supplementary table 14 and Supplementary table 15 for waste stream A and B (product dependent)

Product	Number of products used Waste stream A or B used for product, followed by packaging where relevant									
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Tonsillectomy set (set A for T1, T4-T10; set B for T2, T3)	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
Reusable ENT split head drape (two 42"x42")	0	1 A,B	1 A,A	0	0	0	0	0	0	0
Reusable surgical gown (including hand towels)	2 A,A	2 A,A	2 A,A	2 A,A	2 A,A	2 A,A	2 A,A	2 A,A	2 A,A	2 A,A
Reusable surgical hat	3 A	0	0	2 A	2 A	3 A	2 A	3 A	2 A	3 A
Reusable scrubs	4 A	4 A	4 A	4 A	4 A	6 A	5 A	7 A	6 A	6 A
Gloves (non-sterile, one pair)	1 A	2 B	2 B	2 A	2 A	1 A	1 A	1 A	3 A	3 A
Sterile gloves (one pair)	3 A,A	3 B,A	3 B,A	2 A,A	2 A,A	2 A,A	2 A,A	2 A,A	2 A,A	2 A,A
Surgical face mask	2 A	0	2 B	0	0	1 A	1 A	1 A	1 A	0
Surgical face mask with eye protection	0	2 B	0	0	0	1 A	1 A	1 A	0	0
Surgical hat	1 A	4 B	4 B	2 A	2 A	3 A	3 A	4 A	4 A	3 A
Patient drape (fenestrated ENT drape)	1 A,A	0	0	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
Table drape (instruments)	1 A,A	1 B,B	1 B,B	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
Coblation™ wand	0	0	0	0	0	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
Kidney dish	1 A,A	0	0	0	0	0	0	0	0	0
Filter needle	1 A,A	0	0	0	0	0	0	0	0	0
Gallipot	1 A,A	0	0	0	0	2 A,A	2 A,A	2 A,A	2 A,A	2 A,A
Incontinence pad	0	0	1 A	0	0	0	0	0	0	0
Braided silk tonsil ties	1 A,A	2 B,A	1 B,A	0	0	0	0	0	0	0
Gauze (non-sterile)	2 A	0	0	0	0	0	0	0	0	0
Nail scrubbing brush	1 A,A	1 B,A	0	0	0	1 A,A	0	0	0	0
Suction tip	0	1 BB	0	1 AA	1 AA	1 AA	1 AA	1 AA	1 AA	1 AA
Suction receptacle	1 A	1 B	1 B	1 A	1 A	1 A	1 A	1 A	1 A	1 A
Suction tubing	1 A	1 B	1 B	1 A	1 A	1 A	1 A	1 A	1 A	1 A

Syringe (10 ml)	1 A,A	0	0	0	0	0	0	0	0	0
Tonsil swab pack	1 A,A	3 B,B	4 B,A	2 A,A	1 A,A	2 A,A	2 A,A	2 A,A	1 A,A	1 A,A
Yankauer sucker	1 A,A	1 B,B	1 B,B	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
Specimen pot (40 ml 4% formaldehyde)	0	1 A	0	0	0	0	0	0	0	0
Bupivacaine 0.5% with 1:200,000 adrenaline (10 ml)	1 A,A	1 A,A	1 A,A	0	0	0	0	0	0	0
Chirocaine 2.5mg per ml (10 ml)	0	0	0	0	0	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
Sodium chloride 0.9% from 1 litre bottle (150 ml)	1	1	1	1	1	1	1	1	1	1
Sodium chloride 0.9%, intravenous infusion bag (500 ml)	0	0	0	0	0	1 A,A	1 A,A	1 A,A	1 A,A	1 A,A
Yellow soft paraffin BP 100% from 15 g tube	0	1	1	1	1	1	1	1	1	1
Black waste bag (domestic waste) with cable tie	1 A	0	0	1 A	1 A	1 A	1 A	1 A	1 A	1 A
Clear waste bag (for swab count)	1 A	1 B	1 B	1 A	1 A	1 A	1 A	1 A	1 A	1 A
Clear waste bag (recycling) with cable tie	1 A	2 A	2 A	1 A	1 A	1 A	1 A	1 A	1 A	1 A
Disinfectant sachet	1 A	1 A	1 A	1 A	1 A	1 A	1 A	1 A	1 A	1 A
Disinfectant wipe	5 A	6 B	6 B	3 A	3 A	6 A	4 A	4 A	8 A	5 A
Green bag (linen laundering) with cable tie	1 A	1 A	1 A	1 A	1 A	1 A	1 A	1 A	1 A	1 A
Mop head	1 A	1 B	1 B	1 A	1 A	1 A	1 A	1 A	1 A	1 A
Orange waste bag (infectious waste) with cable tie	0	1 A	1 A	0	0	0	0	0	0	0
Yellow waste bag (clinical waste) with cable tie	1 A	0	0	1 A	1 A	1 A	1 A	1 A	1 A	1 A

Supplementary table 21: Carbon footprint of carpal tunnel decompression operations impact assessment
Carbon footprint for each product type depends on factors including the product, number of products used, waste stream, and number of operations in which product was used. C1= carpal tunnel decompression operation one etc. CO_2e=carbon dioxide equivalents

Product	**Carbon footprint (g CO_2e)**										
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**Mean average**
Minor op set	1,922.18	1,922.18	1,922.18	1,922.18	1,922.18	1,922.18	1,922.18	1,922.18	1,922.18	1,922.18	**1,922.18**
Carbon footprint reusable minor op set (g CO_2e)	1,922.18	1,922.18	1,922.18	1,922.18	1,922.18	1,922.18	1,922.18	1,922.18	1,922.18	1,922.18	**1,922.18**
Reusable scrubs	232.16	232.16	232.16	278.59	325.02	232.16	371.45	232.16	232.16	278.59	**264.66**
Carbon footprint reusable personal protective equipment (g CO_2e)	232.16	232.16	232.16	278.59	325.02	232.16	371.45	232.16	232.16	278.59	**264.66**
Reusable tourniquet pressure cuff	79.45	79.45	79.45	79.45	0	0	0	79.45	79.45	79.45	**55.61**
Carbon footprint reusable non-set equipment (g CO_2e)	79.45	79.45	79.45	79.45	0	0	0	79.45	79.45	79.45	**55.61**
Gloves (non-sterile, pair)	44.11	44.11	44.11	88.22	66.16	66.16	88.22	66.16	66.16	88.22	**66.16**
Sterile gloves (pair)	372.44	372.44	372.44	248.29	248.29	372.44	372.44	248.29	124.15	248.29	**297.95**
Sterile gloves (two pairs)	185.44	185.44	185.44	0	0	0	0	185.44	0	185.44	**92.72**
Sterile gloves (two pair, latex free)	0	0	0	180.69	180.69	0	0	0	180.69	0	**54.21**
Surgical face mask	104.62	104.62	104.62	104.62	17.44	17.44	104.62	52.31	52.31	87.19	**74.98**
Surgical face mask with eye protection	0	0	0	37.72	75.44	113.16	75.44	75.44	75.44	37.72	**49.04**
Surgical gown (including hand towels)	1,996.07	1,996.07	1,996.07	1,996.07	1,996.07	1,996.07	1,996.07	2,661.43	1,330.71	2,661.43	**2.062.60**

Surgical hat		17.70	17.70	17.70	21.24	24.78	17.70	28.32	17.70	17.70	21.24	**20.17**
Visor		0	0	0	0	0	0	0	0	43.25	0	**4.32**
Carbon footprint single-use personal protective equipment (g CO_2e)		2,720.38	2,720.38	2,720.38	2,676.85	2,608.87	2,582.96	2,665.10	3,306.77	1,890.41	3,329.52	**2,722.16**
Hand pack	Patient drape (fenestrated hand drape)	2,739.93	2,739.93	2,739.93	2,739.93	2,739.93	2,739.93	2,739.93	2,739.93	2,739.93	2,739.93	**2,739.93**
	Table drape (instruments)	1,049.85	1,049.85	1,049.85	1,049.85	1,049.85	1,049.85	1,049.85	1,049.85	1,049.85	1,049.85	**1,049.85**
	Hand pack packaging (drape component)	91.28	91.28	91.28	91.28	91.28	91.28	91.28	91.28	91.28	91.28	**91.28**
Carbon footprint single-use patient and instrument table drapes (g CO_2e)		3,881.05	3,881.05	3,881.05	3,881.05	3,881.05	3,881.05	3,881.05	3,881.05	3,881.05	3,881.05	**3,881.05**
Hand pack	Bowl	127.24	127.24	127.24	127.24	127.24	127.24	127.24	127.24	127.24	127.24	**127.24**
	Foam cube	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	**18.50**
	Gauze swab	188.36	188.36	188.36	188.36	188.36	188.36	188.36	188.36	188.36	188.36	**188.36**
	Kidney dish	147.07	147.07	147.07	147.07	147.07	147.07	147.07	147.07	147.07	147.07	**147.07**
	Light cover	15.15	15.15	15.15	15.15	15.15	15.15	15.15	15.15	15.15	15.15	**15.15**
	Needle counter	236.83	236.83	236.83	236.83	236.83	236.83	236.83	236.83	236.83	236.83	**236.83**
	Surgical blade	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52	**14.52**
	Syringe (20 ml)	26.64	26.64	26.64	26.64	26.64	26.64	26.64	26.64	26.64	26.64	**26.64**
	Hand packaging (single-use equipment component)	14.03	14.03	14.03	14.03	14.03	14.03	14.03	14.03	14.03	14.03	**14.03**
Crepe bandage (7.5 cm wide)		308.90	308.90	308.90	308.90	308.90	308.90	308.90	308.90	308.90	308.90	**308.90**
Elasticated fabric dressing strip		6.67	6.67	6.67	4.45	4.45	4.45	4.45	4.45	0	4.45	**4.67**

Gauze (individual piece)	0	0	0	0	37.19	37.19	37.19	0	0	37.19	**14.88**
Gauze (sterile pack)	203.26	406.53	609.79	813.06	203.26	0	0	0	0	0	**223.59**
Incontinence pad	95.65	95.65	95.65	95.65	95.65	95.65	95.65	95.65	95.65	95.65	**95.65**
Nail scrubbing brush	134.85	44.95	0	44.95	134.85	44.95	0	89.90	89.90	0	**58.44**
Needle (blue)	0	0	0	0	0	3.18	3.18	0	3.18	3.18	**1.27**
Needle (green)	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	0	0	**2.90**
Needle (red)	5.62	5.62	5.62	5.62	5.62	0	0	0	0	0	**2.81**
Non-woven dressing	10.17	10.17	10.17	10.17	10.17	10.17	10.17	10.17	10.17	10.17	**10.17**
Skin marker	54.56	54.56	54.56	0	54.56	54.56	54.56	0	0	0	**32.74**
Stockinette tubular bandage	83.34	83.34	83.34	83.34	0	0	0	0	83.34	83.34	**50**
Surgical blade	7.00	7.00	0	0	7.00	0	0	0	0	0	**2.10**
Suture (monofilament, non-absorbable, 4-0)	7.43	0	0	7.43	0	0	0	7.43	0	7.43	**2.97**
Suture (monofilament, non-absorbable 5-0)	0	7.43	7.43	0	7.43	7.43	7.43	0	7.43	0	**4.46**
Syringe (10 ml)	27.67	27.67	27.67	27.67	0	0	0	27.67	0	27.67	**16.60**
Syringe (20 ml)	0	0	0	0	65.05	65.05	65.05	0	65.05	0	**26.02**
Tape (clear)	0	0	0	0	0	0	0	0	4.95	0	**0.50**
Undercast padding	52.02	52.02	52.02	52.02	52.02	52.02	52.02	52.02	52.02	52.02	**52.02**
Carbon footprint single-use equipment and medical devices (g CO_2e)	1,789.11	1,902.48	2,053.79	2,245.23	1,778.12	1,475.52	1,430.57	1,388.16	1,508.94	1,418.34	**1,699.03**

Bupivacaine hydrochloride 0.5% (10 ml)	249.94	249.94	249.94	249.94	0	0	0	0	249.94	0	**124.97**
Chlorhexidine 2% from 500 ml container (100 ml)	107.30	107.30	107.30	107.30	107.30	107.30	107.30	107.30	107.30	107.30	**107.30**
Hyaluronidase 1500 I.U. (10 ml)	0	0	0	387.85	0	0	0	0	387.85	0	**77.57**
Levobupivacaine 5mg per 10 ml (10 ml)	0	0	0	0	0	0	0	239.30	0	239.30	**47.86**
Lidocaine 1% (10 ml)	301.68	301.68	301.68	301.68	0	0	0	0	301.68	0	**150.84**
Lidocaine 1% with adrenaline 1:200,000 (20 ml)	0	0	0	0	702.05	702.05	702.05	0	0	0	**210.62**
Sodium Chloride 0.9% from 1 litre bottle (100 ml)	75.87	75.87	75.87	75.87	75.87	75.87	75.87	75.87	75.87	75.87	**75.87**
Carbon footprint pharmaceuticals (g CO_2e)	734.79	734.79	734.79	1,122.64	885.22	885.22	885.22	422.47	1,122.64	422.47	**795.03**
Clear bin bag (linen laundering)	12.52	12.52	12.52	12.52	12.52	12.52	12.52	12.52	12.52	12.52	**12.52**
Disinfectant sachet	27.49	27.49	27.49	27.49	27.49	27.49	27.49	27.49	27.49	27.49	**27.49**
Disinfectant wipe	112.78	98.68	70.49	70.49	56.39	70.49	42.29	169.17	70.49	84.58	**84.58**
Orange waste bag (infectious waste) with cable tie from theatre	307.44	307.44	307.44	307.44	307.44	307.44	307.44	307.44	307.44	307.44	**307.44**
Orange waste bag (infectious waste) with cable tie from scrub room	61.49	61.49	61.49	61.49	61.49	61.49	61.49	61.49	61.49	61.49	**61.49**
Mop head	151.71	151.71	151.71	151.71	151.71	151.71	151.71	151.71	151.71	151.71	**151.71**
Red bag (linen laundering) with cable tie	25.85	25.85	25.85	25.85	25.85	25.85	25.85	25.85	25.85	25.85	**25.85**
Carbon footprint cleaning products, waste (g CO_2e)	699.27	685.17	656.98	656.98	642.88	656.98	628.78	755.66	656.98	671.07	**671.07**
Total Carbon footprint (g CO_2e)	**12,058.38**	**12,157.65**	**12,280.77**	**12,862.96**	**12,043.34**	**11,636.07**	**11,784.36**	**11,987.90**	**11,293.81**	**12,002.67**	**12,010.79**

Supplementary table 22: Carbon footprint of inguinal hernia repair operations impact assessment
Carbon footprint for each product type depends on factors including the product, number of products used, waste stream, and number of operations in which product was used. H1= inguinal hernia operation one etc. CO_2e=carbon dioxide equivalents

Product	**Carbon footprint (g CO_2e)**						
	H1	**H2**	**H3**	**H4**	**H5**	**H6**	**Mean average**
General basic set (set A for H1, H2; set B for H3-6)	3,017.22	3,017.22	2,395.86	2,395.86	2,395.86	2,395.86	**2,602.98**
Roberts artery forceps	197.07	0	0	0	0	0	**32.84**
Collingwood Stewart hernia forceps	0	0	0	197.10	0	0	**32.85**
Carbon footprint reusable sets and individually wrapped instruments (g CO_2e)	3,214.29	3,017.22	2,395.86	2,592.96	2,395.86	2,395.86	**2,668.68**
High fluid drape	0.00	0.00	1098.42	1098.42	1098.42	1098.42	**732.28**
Huck towel	0.00	0.00	0.00	123.51	123.51	123.51	**61.76**
Low fluid drape	744.54	744.54	0.00	0.00	0.00	0.00	**248.18**
Carbon footprint reusable patient drapes (g CO_2e)	744.54	744.54	1,098.42	1,221.93	1,221.93	1,221.93	**1,042.21**
Reusable surgical gown (including hand towels)	300.69	300.69	0.00	505.34	0.00	505.34	**268.68**
Reusable surgical hat	0.00	0.00	7.33	0.00	0.00	0.00	**1.22**
Reusable scrubs	290.19	232.16	348.23	290.19	290.19	290.19	**290.19**
Carbon footprint reusable personal protective equipment (g CO_2e)	590.88	532.84	355.56	795.54	290.19	795.54	**560.09**
Diathermy pad lead	9.24	9.24	9.24	9.24	9.24	9.24	**9.24**
Shaver base	0.47	0.47	0.44	0.44	0.44	0.00	**0.38**

Carbon footprint non-set reusable equipment (g CO_2e)	9.71	9.71	9.68	9.68	9.68	9.24	**9.62**
Gloves (non-sterile, pair)	177.17	126.55	88.22	88.22	154.38	176.44	**135.16**
Sterile gloves (pair)	287.87	287.87	358.26	119.42	119.42	119.42	**215.38**
Sterile gloves (two pairs)	0.00	0.00	178.60	178.60	357.19	357.19	**178.60**
Sterile gloves (one pair, latex free)	125.61	125.61	0.00	204.95	0.00	0.00	**76.03**
Sterile under-gloves (pair)	108.14	108.14	0.00	0.00	0.00	0.00	**36.05**
Surgical face mask	19.64	19.64	52.31	87.19	34.87	34.87	**41.42**
Surgical face mask with eye protection	0.00	0.00	0.00	0.00	37.72	37.72	**12.57**
Surgical gown (including hand towels)	774.01	774.01	1980.58	660.19	1980.58	660.19	**1138.26**
Surgical hat	19.93	15.94	14.16	17.70	21.24	10.62	**16.60**
Carbon footprint single-use patient drape and instrument table drape (g CO_2e)	1,512.37	1,457.76	2,672.12	1,356.25	2,705.40	1,396.45	**1,850.06**
Patient drape (incise drape, with iodine)	0.00	0.00	0.00	116.09	0.00	0.00	**19.35**
Table drape (instruments)	0.00	0.00	775.39	1550.78	775.39	775.39	**646.16**
Carbon footprint single-use personal protective equipment (g CO_2e)	0	0	775.39	1,666.87	775.39	775.39	**665.51**
Absorbent towel pack	0.00	0.00	75.77	0.00	0.00	0.00	**12.63**
Diathermy pad	228.43	76.14	69.67	69.67	69.67	69.67	**97.21**
Diathermy tip	0.00	0.00	17.08	0.00	0.00	0.00	**2.85**
Gauze (sterile pack, 10x7.5 cm)	666.16	499.62	318.22	159.11	318.22	318.22	**379.92**

Gauze (sterile pack, 30x30 cm)	0.00	0.00	713.28	0.00	0.00	0.00	**118.88**
Gauze (sterile pack, 10x10 cm)	426.93	426.93	0.00	0.00	0.00	0.00	**142.31**
Incontinence pad	272.90	272.90	151.46	75.73	75.73	75.73	**154.08**
Kidney dish	73.04	73.04	0.00	0.00	0.00	0.00	**24.35**
Light handle	30.14	30.14	59.67	59.67	29.84	0.00	**34.91**
Mesh	279.26	279.26	229.30	229.30	229.30	229.30	**245.95**
Monopolar diathermy with smoke evacuation system	741.95	741.95	0.00	1282.93	641.46	641.46	**674.96**
Nail scrubbing brush	103.92	51.96	39.43	0.00	39.43	0.00	**39.12**
Needle (green)	3.33	3.33	3.63	3.63	0.00	3.63	**2.92**
Needle counter	252.74	252.74	254.94	254.94	254.94	254.94	**254.20**
Nonwoven dressing (10x20 cm)	24.66	24.66	23.48	23.48	23.48	23.48	**23.87**
Nonwoven dressing (10x30 cm)	49.99	49.99	0.00	0.00	0.00	0.00	**16.66**
Pre-operative adhesive glove	41.97	41.97	11.80	11.80	11.80	0.00	**19.89**
Reinforced skin closure strip	8.92	8.92	0.00	0.00	0.00	0.00	**2.97**
Shaver head	47.46	47.46	46.96	46.96	46.96	0.00	**39.30**
Specimen pot (40 ml 4% formaldehyde)	132.52	132.52	0.00	0.00	0.00	0.00	**44.17**
Surgical blade (10)	7.92	7.92	8.10	8.10	8.10	8.10	**8.04**
Surgical suspensory bandage	201.21	201.21	0.00	0.00	0.00	0.00	**67.07**

Suture (braided, absorbable, 0)	16.89	0.00	0.00	0.00	0.00	0.00	**2.82**
Suture (braided, absorbable, 2-0)	16.89	16.89	72.57	36.28	18.14	18.14	**29.82**
Suture (monofilament, absorbable, 3-0)	16.89	16.89	18.14	18.14	18.14	18.14	**17.73**
Suture (monofilament, nonabsorbable, 1)	16.89	16.89	0.00	0.00	18.14	18.14	**11.68**
Suture (monofilament, nonabsorbable, 2-0)	50.67	50.67	36.28	0.00	0.00	0.00	**22.94**
Syringe (20 ml)	215.40	215.40	65.05	65.05	0.00	65.05	**104.33**
Carbon footprint single-use equipment and medical devices (g CO_2e)	3,927.07	3,539.39	2,214.85	2,344.80	1,803.36	1,744.01	**2,595.58**
Chlorhexidine 1% from 500 ml container (100 ml)	0.00	0.00	107.30	107.30	107.30	107.30	**71.53**
Levobupivacaine 5mg per 10 ml (10 ml)	1446.45	1446.45	0.00	0.00	0.00	717.91	**601.80**
Povidone iodine 10% from 500 ml container (60 ml)	183.24	183.24	0.00	0.00	0.00	0.00	**61.08**
Sodium Chloride 0.9% from 1 litre bottle (50 ml)	37.94	37.94	37.94	37.94	37.94	37.94	**37.94**
Topical skin adhesive (0.8 g)	0.00	0.00	0.00	3924.51	0.00	0.00	**654.09**
Carbon footprint pharmaceuticals (g CO_2e)	1,667.63	1,667.63	145.23	4,069.74	145.23	863.14	**1,426.43**
Black waste bag (domestic waste) with cable tie	104.60	104.60	0.00	0.00	0.00	0.00	**34.87**
Chlorine tablet	14.03	14.03	0.00	0.00	0.00	0.00	**4.68**
Clear bin bag (for swab count)	72.21	72.21	0.00	0.00	0.00	0.00	**24.07**
Clear bin bag (recycling) with cable tie	0.00	0.00	65.63	65.63	65.63	65.63	**43.75**
Disinfectant sachet	0.00	0.00	34.36	34.36	34.36	34.36	**22.90**

Disinfectant wipe	177.26	110.79	143.30	122.83	143.30	143.30	**140.13**
Green bag (linen laundering) with cable tie	17.42	17.42	17.42	17.42	17.42	17.42	**17.42**
Mop head	202.32	202.32	189.63	189.63	189.63	189.63	**193.86**
Orange waste bag (infectious waste, large) with cable tie	0.00	0.00	307.44	307.44	307.44	307.44	**204.96**
Orange waste bag (infectious waste, small) with cable tie	0.00	0.00	136.03	136.03	136.03	136.03	**90.69**
Red bag (linen laundering) with cable tie	32.32	32.32	32.32	32.32	32.32	32.32	**32.32**
Yellow waste bag (clinical waste) with cable tie	153.14	153.14	0.00	0.00	0.00	0.00	**51.05**
Carbon footprint cleaning products, waste (g CO_2e)	773.29	706.81	926.13	905.66	926.13	926.13	**860.69**
Total Carbon footprint (g CO_2e)	**12,439.78**	**11,675.91**	**10,593.23**	**14,963.44**	**10,273.18**	**10,127.69**	**11,678.87**

Supplementary table 23: Carbon footprint of knee arthroplasty operations impact assessment
Carbon footprint for each product type depends on factors including the product, number of products used, waste stream, and number of operations in which product was used. K1= knee arthroplasty operation one etc. CO_2e=carbon dioxide equivalents

Product	**Carbon footprint (g CO_2e)**										
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**	**K10**	**Mean average**
Basic major orthopaedic set	2,288.88	2,288.88	2,288.88	2,288.88	2,288.88	2,288.88	2,288.88	2,288.88	2,288.88	2,288.88	**2,288.88**
Bipolar diathermy	0	0	0	0	0	0	223.04	0	0	0	**22.30**
Blunt Hohman bone elevator	0	0	0	0	0	0	0	199.17	199.17	0	**39.83**
Cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8)	0	0	0	0	0	2,365.63	2,365.63	0	0	0	**473.13**
Cruciate retaining femoral and tibial trialing set (size 3-6)	0	2,229.12	2,229.12	2,229.12	2,229.12	2,229.12	2,229.12	2,229.12	2,229.12	2,229.12	**2,006.21**
Diathermy extras	0	0	0	0	0	277.33	0	0	0	0	**27.73**
Diathermy lead	0	0	0	0	0	0	220.93	0	0	0	**22.09**
Femoral and tibial preparation set (size 3-6)	2,235.42	2,235.42	2,235.42	2,235.42	2,235.42	2,235.42	2,235.42	2,235.42	2,235.42	2,235.42	**2,235.42**
Knee navigation set	0	0	0	0	0	0	0	2,245.46	0	0	**224.55**
Lanes tissue forceps	198.68	0	198.68	0	0	0	0	198.68	198.68	198.68	**99.34**
Light cover	198.18	198.18	198.18	198.18	198.18	198.18	198.18	198.18	198.18	198.18	**198.18**
Light handle	198.17	198.17	198.17	396.33	198.17	198.17	198.17	198.17	198.17	198.17	**217.98**
Miscellaneous knee system set	2,239.23	2,239.23	2,239.23	2,239.23	2,239.23	2,239.23	2,239.23	2,239.23	2,239.23	2,239.23	**2,239.23**
Non-toothed lamina spreader (large)	0	223.88	223.88	0	0	0	0	0	0	0	**44.78**

Non-toothed lamina spreader (small)	0	0	0	200.58	0	0	0	0	0	0	**20.06**
Orthopaedic surgical drill set	2,255.92	2,255.92	2,255.92	2,255.92	2,255.92	2,255.92	2,255.92	2,255.92	2,255.92	2,255.92	**2,255.92**
Patella preparation and trialing set	2,239.47	0	2,239.47	2,239.47	0	2,239.47	2,239.47	2,239.47	2,239.47	0	**1,567.63**
Posterior stabilised femoral and tibial trialing set (size 3-6)	2,249.72	0	0	0	2,249.72	0	0	2,249.72	0	0	**674.92**
Semb bone holding forceps	187.57	187.57	187.57	0	0	187.57	187.57	187.57	187.57	187.57	**150.06**
Carbon footprint reusable sets and individually wrapped instruments (g CO_2e)	14,291.24	12,056.37	14,494.52	14,283.14	13,894.63	16,714.91	16,881.56	18,964.54	14,469.81	12,031.17	**14,808.19**
Reusable scrubs	464.31	541.70	541.70	386.93	464.31	386.93	386.93	386.93	386.93	386.93	**433.36**
Carbon footprint reusable personal protective equipment (g CO_2e)	464.31	541.70	541.70	386.93	464.31	386.93	386.93	386.93	386.93	386.93	**433.36**
Reusable shaver base	0	0	0	0	0.44	0	0.44	0	0	0	**0.09**
Carbon footprint reusable non-set equipment (g CO_2e)	0	0	0	0	0.44	0	0.44	0	0	0	**0.09**
Knee pack: Surgical gown	1,089.14	1,089.14	1,089.14	1,089.14	1,089.14	1,089.14	1,089.14	1,089.14	1,089.14	1,089.14	**1,089.14**
Knee pack: Knee pack packaging (gown component)	55.62	55.62	55.62	55.62	55.62	55.62	55.62	55.62	55.62	55.62	**55.62**
Gloves (non-sterile, pair)	154.38	154.38	176.44	154.38	154.38	110.27	132.33	220.55	154.38	154.38	**156.59**
Orthopaedic hood	2,023.32	1,331.30	1,331.30	1,348.88	2,023.32	0.00	0.00	1,348.88	2,023.32	2,023.32	**1,345.37**
Sterile gloves (pair)	0.00	620.73	620.73	869.02	744.87	744.87	993.17	620.73	620.73	869.02	**670.39**
Sterile gloves (two pairs)	1,483.53	370.88	370.88	556.33	185.44	185.44	370.88	370.88	556.33	556.33	**500.69**
Sterile gloves (two pair, latex free)	0.00	0.00	180.69	0.00	180.69	180.69	0.00	0.00	0.00	0.00	**54.21**

Surgical face mask		52.31	69.75	34.87	52.31	34.87	52.31	17.44	87.19	69.75	34.87	**50.57**
Surgical face mask with eye protection		37.72	37.72	113.16	37.72	37.72	113.16	75.44	0.00	0.00	0.00	**45.26**
Surgical gown (including hand towels)		2,033.38	1,336.08	1,336.08	2,033.38	2,033.38	1,336.08	1,336.08	2,033.38	2,711.18	2,033.38	**1,826.14**
Surgical hat		84.95	99.10	99.10	70.79	84.95	28.32	28.32	70.79	70.79	70.79	**70.79**
Sweat bands for hood x3		58.50	39.00	39.00	39.00	58.50	0.00	0.00	39.00	58.50	58.50	**39.00**
Carbon footprint single-use personal protective equipment (g CO_2e)		7,072.85	5,203.69	5,447.00	6,306.56	6,682.88	3,915.40	4,117.91	5,936.15	7,409.72	6,945.35	**5,903.75**
Knee pack	Patient drape (240x150 cm)	1,163.39	1,163.39	1,163.39	1,163.39	1,163.39	1,163.39	1,163.39	1,163.39	1,163.39	1,163.39	**1,163.39**
	Patient drape (90 x75 cm)	228.66	228.66	228.66	228.66	228.66	228.66	228.66	228.66	228.66	228.66	**228.66**
	Patient drape (extremity, 230x325 cm)	1,635.81	1,635.81	1,635.81	1,635.81	1,635.81	1,635.81	1,635.81	1,635.81	1,635.81	1,635.81	**1,635.81**
	Patient drape (impervious, split, 152x177 cm)	644.18	644.18	644.18	644.18	644.18	644.18	644.18	644.18	644.18	644.18	**644.18**
	Patient drape (Mayo cover, 75x144 cm) x2	842.38	842.38	842.38	842.38	842.38	842.38	842.38	842.38	842.38	842.38	**842.38**
	Patient drape (pouch fluid collection, 40x35 cm)	1,287.00	1,287.00	1,287.00	1,287.00	1,287.00	1,287.00	1,287.00	1,287.00	1,287.00	1,287.00	**1,287.00**
	Patient drape (stockinette, impervious, 30x120 cm)	583.69	583.69	583.69	583.69	583.69	583.69	583.69	583.69	583.69	583.69	**583.69**
	Table drape (140x90 cm)	1,405.53	1,405.53	1,405.53	1,405.53	1,405.53	1,405.53	1,405.53	1,405.53	1,405.53	1,405.53	**1,405.53**
	Table drape (fan folded, 140x190 cm)	1,038.07	1,038.07	1,038.07	1,038.07	1,038.07	1,038.07	1,038.07	1,038.07	1,038.07	1,038.07	**1,038.07**
	Knee pack packaging (patient and instrument table drape component)	342.79	342.79	342.79	342.79	342.79	342.79	342.79	342.79	342.79	342.79	**342.79**
Patient drape (adhesive split sheet)		0.00	0.00	0.00	0.00	0.00	0.00	0.00	990.16	990.16	0.00	**198.03**

Patient drape (clear U drape)		0.00	440.77	440.77	440.77	440.77	0.00	0.00	0.00	0.00	440.77	**220.38**
Patient drape (incise drape)		0.00	0.00	0.00	0.00	0.00	290.25	290.25	0.00	0.00	0.00	**58.05**
Patient drape (incise drape, with iodine)		240.07	240.07	240.07	240.07	240.07	0.00	0.00	0.00	0.00	240.07	**144.04**
Table drape (instruments)		3,008.99	3,008.99	3,008.99	3,008.99	3,008.99	3,008.99	3,008.99	3,008.99	3,008.99	3,008.99	**3,008.99**
Carbon footprint single-use patient and instrument table drapes (g CO_2e)		12,420.56	12,861.33	12,861.33	12,861.33	12,861.33	12,470.74	12,470.74	13,170.64	13,170.64	12,861.33	**12,800.99**
Knee pack	Bowl (250 ml) x2	66.99	66.99	66.99	66.99	66.99	66.99	66.99	66.99	66.99	66.99	**66.99**
	Bowl (500 ml)	91.73	91.73	91.73	91.73	91.73	91.73	91.73	91.73	91.73	91.73	**91.73**
	Cast padding bandage x2	187.95	187.95	187.95	187.95	187.95	187.95	187.95	187.95	187.95	187.95	**187.95**
	Crepe bandage x2	550.02	550.02	550.02	550.02	550.02	550.02	550.02	550.02	550.02	550.02	**550.02**
	Diathermy bag	62.49	62.49	62.49	62.49	62.49	62.49	62.49	62.49	62.49	62.49	**62.49**
	Diathermy tip cleaner	10.97	10.97	10.97	10.97	10.97	10.97	10.97	10.97	10.97	10.97	**10.97**
	Kidney dish x3	114.82	114.82	114.82	114.82	114.82	114.82	114.82	114.82	114.82	114.82	**114.82**
	Light cover	14.14	14.14	14.14	14.14	14.14	14.14	14.14	14.14	14.14	14.14	**14.14**
	Monopolar diathermy	240.15	240.15	240.15	240.15	240.15	240.15	240.15	240.15	240.15	240.15	**240.15**
	Needle counter	214.29	214.29	214.29	214.29	214.29	214.29	214.29	214.29	214.29	214.29	**214.29**
	Skin marker pen	22.05	22.05	22.05	22.05	22.05	22.05	22.05	22.05	22.05	22.05	**22.05**
	Suction tubing	436.63	436.63	436.63	436.63	436.63	436.63	436.63	436.63	436.63	436.63	**436.63**
	Surgical blade (10) x3	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	**8.10**

	Swab gauze (10x7.5 cm) x5	32.48	32.48	32.48	32.48	32.48	32.48	32.48	32.48	32.48	32.48	**32.48**
	Swab gauze (30x30 cm) x10	135.15	135.15	135.15	135.15	135.15	135.15	135.15	135.15	135.15	135.15	**135.15**
	Towel dressing (2 in pack)	43.62	43.62	43.62	43.62	43.62	43.62	43.62	43.62	43.62	43.62	**43.62**
	Tray (small)	589.06	589.06	589.06	589.06	589.06	589.06	589.06	589.06	589.06	589.06	**589.06**
	Yankauer sucker	65.70	65.70	65.70	65.70	65.70	65.70	65.70	65.70	65.70	65.70	**65.70**
	Knee pack packaging (equipment component)	145.07	145.07	145.07	145.07	145.07	145.07	145.07	145.07	145.07	145.07	**145.07**
Adhesive operative towel		0	0	0	309.29	0	0	0	0	0	0	**30.93**
Batteries for knee navigation set (x3)		0	0	0	0	0	0	0	286.07	0	0	**28.61**
Border dressing (10x30 cm)		47.76	47.76	47.76	47.76	95.51	47.76	95.51	47.76	47.76	95.51	**62.08**
Border dressing (6x8 cm)		0	0	0	0	0	0	0	11.24	11.24	0	**2.25**
Catheter tip syringe		0.00	79.10	0	0	0	0	0	0	0	0	**7.91**
Cement mixing and delivery system		1,314.98	1,314.98	1,314.98	1,314.98	1,314.98	1,314.98	1,314.98	1,314.98	1,314.98	1,314.98	**1,314.98**
Cement mixing bowl		0	0	0	0	0	0	2035.94	0	0	0	**203.59**
Crepe bandage (15 cm wide)		0	0	0	0	605.98	0	0	0	0	0	**60.60**
Cruciate retaining femoral implant		0.00	5,518.27	5,518.27	0	0	5,518.27	0	0	5,518.27	5,518.27	**2,759.13**
Diathermy bag		0	0	75.26	75.26	0	0	0	75.26	75.26	0	**30.11**
Diathermy tip		0	0	0	0	0	0	0	0	0	17.08	**1.71**
Diathermy tip cleaner		69.67	69.67	69.67	69.67	69.67	69.67	69.67	69.67	69.67	69.67	**69.67**

Elasticated fabric dressing strip	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	**4.45**
Gauze (individual piece)	37.19	37.19	37.19	37.19	0	0	0	0	0	0	**14.88**
Gauze (sterile pack)	201.49	0	0	0	0	0	0	0	0	0	**20.15**
High-vacuum wound drainage	0	0	0	0	0	745.53	745.53	0	0	0	**149.11**
Incontinence pad	401.59	602.39	200.80	200.80	200.80	200.80	200.80	200.80	200.80	200.80	**261.03**
Intravenous infusion giving set	116.82	116.82	116.82	116.82	116.82	116.82	116.82	0.00	0.00	116.82	**93.45**
Marker pen and ruler	0	0	0	0	0	0	0	23.71	0	0	**2.37**
Monopolar diathermy	0	0	0	0	0	0	0	0	147.64	0	**14.76**
Nail scrubbing brush	0	0	0	134.85	134.85	134.85	134.85	134.85	134.85	134.85	**94.40**
Needle (green)	3.63	3.63	3.63	3.63	0	0	0	0	0	0	**1.45**
Needle (red)	5.62	5.62	5.62	5.62	5.62	5.62	5.62	0.00	0.00	5.62	**4.50**
Needle (white)	9.32	9.32	9.32	9.32	9.32	4.66	4.66	9.32	9.32	9.32	**8.39**
Posterior stabilised femoral implant	8821.07	0	0	8821.07	8821.07	0	0	8821.07	0	0	**3528.43**
Pre-operative adhesive glove	0	0	0	0	11.80	0	11.80	0	0	0	**2.36**
Primary tibial baseplate implant	2,996.83	2,996.83	2,996.83	2,996.83	2,996.83	2,996.83	2,996.83	2,996.83	2,996.83	2,996.83	**2,996.83**
Pulsed lavage system	3,726.63	3,726.63	3,726.63	3,726.63	3,726.63	3,726.63	3,726.63	3,726.63	3,726.63	3,726.63	**3,726.63**
Saw blade	186.52	186.52	186.52	373.05	186.52	186.52	186.52	186.52	186.52	186.52	**205.18**
Self-adherent bandage	342.20	0	0	0	0	0	0	0	0	0	**34.22**

Shaver head	0	0	0	0	46.96	0.00	46.96	0	0	0	**9.39**
Skin stapler	0	0	0	368.11	368.11	0	0	368.11	368.11	368.11	**184.06**
Sticky label	1.34	1.34	1.34	1.34	1.34	0	0	0	0	0	**0.67**
Suction receptacle	192.38	192.38	192.38	192.38	192.38	192.38	192.38	192.38	192.38	192.38	**192.38**
Suction tip	0	0	0	0	0	0	58.07	0	0	0	**5.81**
Suction tubing	0	0	492.93	0	0	492.93	0	0	0	0	**98.59**
Surgical blade (10)	0.00	8.10	8.10	0	0	0	8.10	0	0	0	**2.43**
Suture (braided, absorbable, 2-0)	25.83	25.83	25.83	25.83	0	0	0	25.83	25.83	25.83	**18.08**
Suture (monofilament, absorbable, 3-0, 643)	0	0	0	0	0	17.00	17.00	0	0	0	**3.40**
Suture (monofilament, absorbable 3-0, 696)	33.99	33.99	33.99	0	0	0	0	0	0	0	**10.20**
Suture (braided, absorbable 1-0, 803)	25.83	25.83	25.83	77.48	0	77.48	77.48	51.65	51.65	77.48	**49.07**
Suture (braided, absorbable 1-0, 932)	0	0	0	0	71.13	0	0	0	0	0	**7.11**
Swab tray (large)	268.37	268.37	268.37	268.37	536.74	536.74	268.37	268.37	268.37	268.37	**322.05**
Swab tray (small)	128.39	128.39	128.39	128.39	128.39	128.39	128.39	128.39	128.39	128.39	**128.39**
Symmetric patella implant	512.49	0.00	512.49	512.49	0	512.49	512.49	512.49	512.49	0	**358.74**
Syringe (20 ml)	65.05	65.05	65.05	65.05	65.05	65.05	65.05	0	0	65.05	**52.04**
Syringe (50 ml)	273.84	273.84	273.84	136.92	136.92	273.84	273.84	547.68	547.68	273.84	**301.23**

Tibial bearing insert cruciate retaining implant	1014.01	1014.01	1014.01	1014.01	0	0	1014.01	0	1014.01	1014.01	**709.80**
Tibial bearing insert posterior stabilised implant	0	0	0	0	1109.59	0.00	2219.18	1109.59	0	0	**443.84**
Tourniquet pressure cuff (leg)	980.50	980.50	980.50	980.50	980.50	980.50	980.50	980.50	980.50	980.50	**980.50**
Transparent film adhesive dressing	15.02	0	0	0	0	0	15.02	0	0	0	**3.00**
Tubular support bandage	0	0	0	0	214.75	214.75	214.75	214.75	214.75	214.75	**128.85**
Wound closure strips	14.93	14.93	14.93	0	0	0	0	0	14.93	0	**5.97**
Carbon footprint single-use equipment and medical devices (g CO_2e)	24,869.11	20,783.12	21,383.10	25,049.46	25,184.11	21,596.31	20,773.59	25,340.27	21,794.69	21,037.44	**22,781.12**
Adrenaline 1mg in 1ml (1ml)	36.45	36.45	36.45	36.45	36.45	36.45	36.45	0.00	0.00	36.45	**29.16**
Bone cement mix (with gentamicin)	0.00	0.00	0.00	13,202.78	0.00	13,202.78	26,405.56	0.00	0.00	0.00	**5,281.11**
Bone cement mix (with tobramycin)	26,426.55	26,426.55	26,426.55	0.00	26,426.55	0.00	0.00	26,426.55	26,426.55	26,426.55	**18,498.59**
Chlorhexidine 2% from 500 ml bottle (150 ml)	160.94	160.94	160.94	160.94	160.94	0.00	0.00	0.00	0.00	160.94	**96.57**
Chlorhexidine gluconate in 70% denatured ethanol with 4ml red stain solution from 200 ml bottle (150 ml)	982.90	0.00	0.00	982.90	982.90	0.00	0.00	0.00	0.00	982.90	**393.16**
Iodinated povidone 10% w/w alcoholic tincture from 500 ml bottle (50 ml)	0.00	0.00	0.00	92.16	0.00	92.16	92.16	92.16	92.16	0.00	**46.08**
Ketorolac tromethamine 30mg in 1ml (1ml)	262.16	262.16	262.16	262.16	262.16	262.16	262.16	0.00	0.00	262.16	**209.73**
Levobupivacaine 2.5mg per ml (10 ml)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	957.21	957.21	0.00	**191.44**
Ropivacaine 75mg in 10 ml (10 ml)	779.33	779.33	779.33	779.33	779.33	779.33	779.33	0.00	0.00	779.33	**623.47**
Sodium chloride 0.9% (100 ml)	115.98	231.96	115.98	115.98	115.98	115.98	115.98	115.98	115.98	115.98	**127.58**

Sodium chloride 0.9% for irrigation (3 L bag)	917.91	917.91	917.91	917.91	917.91	917.91	917.91	917.91	917.91	917.91	**917.91**
Topical skin adhesive (0.8 g)	3,924.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**392.45**
Carbon footprint pharmaceuticals (g CO_2e)	33,606.74	28,815.31	28,699.33	16,550.62	29,682.23	15,406.78	28,609.56	28,509.81	28,509.81	29,682.23	**26,807.24**
Anatomical waste bin	208.26	208.26	208.26	208.26	208.26	208.26	208.26	208.26	208.26	208.26	**208.26**
Clear bin bag (linen laundering)	20.86	20.86	20.86	20.86	20.86	20.86	20.86	20.86	20.86	20.86	**20.86**
Clear waste bag (recycling) with cable tie	65.63	65.63	65.63	65.63	65.63	65.63	65.63	65.63	65.63	65.63	**65.63**
Disinfectant sachet	137.43	137.43	137.43	137.43	137.43	137.43	137.43	137.43	137.43	137.43	**137.43**
Disinfectant wipe	704.87	634.38	704.87	225.56	874.04	310.14	352.44	281.95	352.44	422.92	**486.36**
Orange waste bag (infectious waste) with cable tie from theatre	614.88	614.88	614.88	614.88	614.88	614.88	614.88	614.88	614.88	614.88	**614.88**
Orange waste bag (infectious waste) with cable tie from scrub room	102.48	0.00	0.00	102.48	102.48	102.48	102.48	102.48	102.48	102.48	**81.98**
Mop head	252.84	252.84	252.84	252.84	252.84	252.84	252.84	252.84	252.84	252.84	**252.84**
Red bag (linen laundering) with cable tie	43.09	43.09	43.09	43.09	43.09	43.09	43.09	43.09	43.09	43.09	**43.09**
Yellow/ black waste bag (non-infectious offensive waste) with cable tie from scrub room	0.00	38.65	38.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**7.73**
Carbon footprint cleaning products, waste (g CO_2e)	2,150.34	2,016.02	2,086.51	1,671.03	2,319.51	1,755.61	1,797.90	1,727.42	1,797.90	1,868.39	**1,919.06**
Total Carbon footprint (g CO_2e)	94,875.15	82,277.53	85,513.48	77,109.05	91,089.44	72,246.68	85,038.63	94,035.76	87,539.51	84,812.83	**85,453.81**

Supplementary table 24: Carbon footprint of laparoscopic cholecystectomy operations impact assessment
Carbon footprint for each product type depends on factors including the product, number of products used, waste stream, and number of operations in which product was used. L1= laparoscopic cholecystectomy operation one etc. CO_2e=carbon dioxide equivalents

Product	**Carbon footprint (g CO_2e)**						
	L1	**L2**	**L3**	**L4**	**L5**	**L6**	**Mean average**
General basic set	2,395.86	2,395.86	2,395.86	2,395.86	2,395.86	2,395.86	**2,395.86**
General laparoscopic set	2,231.95	2,231.95	2,231.95	2,231.95	2,231.95	2,231.95	**2,231.95**
Laparoscope set (10 mm, 0 degree)	1,778.07	1,778.07	1,778.07	1,778.07	1,778.07	1,778.07	**1,778.07**
Diathermy lead	0	0	204.22	0	0	0	**34.04**
Laparoscopic grasping forceps	0	0	0	216.35	0	0	**36.06**
Quiver and clip	198.08	198.08	198.08	198.08	198.08	198.08	**198.08**
Carbon footprint reusable sets and individually wrapped instruments (g CO_2e)	6,603.97	6,603.97	6,808.19	6,820.32	6,603.97	6,603.97	**6,674.06**
High fluid drape reusable components	1098.42	1098.42	1098.42	1076.84	1076.84	1076.84	**1087.63**
Huck towel reusable components	0	123.51	0	113.48	113.48	113.48	**77.33**
Carbon footprint reusable patient drapes (g CO_2e)	1,098.42	1,221.93	1,098.42	1,190.32	1,190.32	1,190.32	**1,164.96**
Surgical gown (including hand towels) reusable components	252.67	252.67	758.02	505.34	0	252.67	**336.90**
Surgical gown (including hand towels) double pack reusable components	0	405.54	0	405.54	405.54	405.54	**270.36**
Surgical hat	0	0	0	3.66	3.66	3.66	**1.83**
Scrubs	406.27	406.27	348.23	348.23	348.23	348.23	**367.58**

Carbon footprint reusable personal protective equipment (g CO_2e)	658.94	1,064.49	1,106.25	1,262.78	757.44	1,010.11	**976.67**
Diathermy pad lead	9.24	9.24	9.24	9.24	9.24	9.24	**9.24**
Carbon footprint non-set reusable equipment (g CO_2e)	9.24	9.24	9.24	9.24	9.24	9.24	**9.24**
Table drape (instrument)	775.39	775.39	775.39	705.47	705.47	705.47	**740.43**
Carbon footprint single-use patient drape and instrument table drape (g CO_2e)	775.39	775.39	775.39	705.47	705.47	705.47	**740.43**
Gloves (non-sterile, pair)	176.44	154.38	132.33	99.94	119.93	59.96	**123.83**
Sterile gloves (pair)	0	119.42	358.26	221.34	221.34	221.34	**190.28**
Sterile gloves (two pairs)	535.79	535.79	0	165.10	165.10	330.19	**288.66**
Sterile gloves (one pair, latex free)	0	0	102.47	0	0	0	**17.08**
Surgical face mask	0	34.87	52.31	48.12	32.08	64.16	**38.59**
Surgical face mask with eye protection	37.72	37.72	0	0	34.43	0	**18.31**
Surgical gown (including hand towels)	1320.38	0	0	0	613.31	613.31	**424.50**
Surgical hat	24.78	24.78	21.24	16.28	16.28	16.28	**19.94**
Carbon footprint single-use personal protective equipment (g CO_2e)	2,095.10	906.96	666.60	550.77	1,202.47	1,305.25	**1,121.19**
Absorbent towel pack	75.77	0	0	0	0	0	**12.63**
Anti-fog endoscopic demister	0	682.36	682.36	674.57	674.57	674.57	**564.74**
Diathermy pad	69.67	69.67	69.67	65.42	65.42	65.42	**67.55**

Endoscopic clip applier	1,646.34	1,646.34	1,646.34	1,532.96	1,532.96	1,532.96	**1,589.65**
Gauze (sterile pack)	318.22	159.11	159.11	300.64	300.64	300.64	**256.39**
Incontinence pad	75.73	75.73	75.73	66.06	132.12	66.06	**81.91**
Insufflating tubing	627.27	627.27	627.27	571.93	571.93	571.93	**599.60**
Laparoscope cover	146.42	146.42	146.42	131.68	131.68	131.68	**139.05**
Laparoscopic scissors	668.09	668.09	668.09	651.91	0.00	651.91	**551.35**
Laparoscopic tissue retrieval system	40.48	40.48	40.48	37.11	37.11	37.11	**38.80**
Light handle	29.84	0	0	0	0	0	**4.97**
Nail scrubbing brush	0	39.43	39.43	39.43	39.43	39.43	**32.86**
Needle (green)	3.63	3.63	3.63	3.33	3.33	3.33	**3.48**
Needle counter	254.94	254.94	254.94	252.74	252.74	252.74	**253.84**
Nonwoven dressing (6x7 cm)	35.45	35.45	35.45	31.38	23.53	31.38	**32.11**
Port (12 mm)	649.56	1,299.11	649.56	1,288.11	1,288.11	1,288.11	**1,077.09**
Port (5 mm, dual pack)	657.66	657.66	657.66	652.17	652.17	652.17	**654.92**
Pressure saline infusion bag	0	0	679.18	0	0	0	**113.20**
Reinforced skin closure strip	0	7.80	7.80	0	7.08	0	**3.78**
Specimen pot (40 ml 4% formaldehyde)	0	126.60	126.60	0	0	0	**42.20**
Specimen pot (not pre-filled)	145.56	0	0	136.34	136.34	136.34	**92.43**

Suction irrigation	0	0	1,576.63	1,440.58	0	1,440.58	**742.96**
Suction receptacle	0	0	373.87	327.34	0	0	**116.87**
Surgical blade (11)	7.42	0	0	0	0	0	**1.24**
Surgical blade (15)	0	7.00	0	6.79	6.79	6.79	**4.56**
Suture (braided, absorbable, 3-0)	0	6.09	6.09	11.53	11.53	5.76	**6.83**
Suture (monofilament, absorbable, 3-0)	18.14	0	0	0	0	0	**3.02**
Suture (monofilament, absorbable, 1)	18.14	36.28	36.28	16.89	16.89	16.89	**23.56**
Syringe (10 ml)	27.67	27.67	27.67	25.33	25.33	25.33	**26.50**
Syringe (20 ml)	130.11	65.05	65.05	119.17	59.59	59.59	**83.09**
Tonsil swab pack	0.00	49.70	0	46.69	46.69	46.69	**31.63**
Carbon footprint single-use equipment and medical devices (g CO_2e)	5,646.10	6,731.89	8,655.33	8,430.09	6,015.98	8,037.40	**7,252.80**
Carbon dioxide (from 3 kg cylinder containing 450 L)	171.00	307.80	616.20	864.00	447.00	133.80	**423.30**
Chlorhexidine 1% from 500 ml container (50 ml)	53.65	53.65	53.65	53.65	53.65	53.65	**53.65**
Levobupivacaine 2.5mg per 10 ml (10 ml)	957.21	717.91	717.91	713.72	713.72	713.72	**755.70**
Sodium Chloride 0.9% for irrigation (1 L bag)	0	0	304.49	585.11	0.00	0.00	**148.27**
Sodium Chloride 0.9% from 1 litre bottle (50 ml)	37.94	37.94	37.94	37.94	37.94	37.94	**37.94**
Carbon footprint pharmaceuticals (g CO_2e)	1,219.79	1,117.29	1,730.18	2,254.42	1,252.30	939.10	**1,418.85**
Black waste bag (domestic waste) with cable tie	0	0	0	209.19	209.19	209.19	**104.60**

Clear bin bag (quiver diathermy)	59.78	59.78	59.78	59.78	59.78	59.78	**59.78**
Clear bin bag (recycling) with cable tie	65.63	65.63	65.63	0	0	0	**32.81**
Disinfectant sachet	34.36	34.36	34.36	33.78	33.78	33.78	**34.07**
Disinfectant wipe	163.78	143.30	102.36	77.61	291.03	116.41	**149.08**
Green bag (linen laundering) with cable tie	17.42	17.42	17.42	17.42	17.42	17.42	**17.42**
Mop head	189.63	189.63	189.63	181.58	181.58	181.58	**185.61**
Orange waste bag (infectious waste, large) with cable tie	307.44	307.44	307.44	0	0	0	**153.72**
Orange waste bag (infectious waste, small) with cable tie	136.03	136.03	136.03	0	0	0	**68.02**
Red bag (linen laundering) with cable tie	32.32	32.32	32.32	32.32	32.32	32.32	**32.32**
Yellow/ black waste bag (non-infectious offensive waste, large) with cable tie	0	0	0	115.94	115.94	115.94	**57.97**
Yellow/ black waste bag (non-infectious offensive waste, small) with cable tie	0	0	0	73.11	73.11	73.11	**36.56**
Carbon footprint cleaning products, waste (g CO_2e)	1,006.38	985.91	944.96	800.72	1,014.14	839.53	**931.94**
Total Carbon footprint (g CO_2e)	**19,113.34**	**19,417.07**	**21,794.56**	**22,024.14**	**18,751.33**	**20,640.39**	**20,290.14**

Supplementary table 25: Carbon footprint of tonsillectomy operations impact assessment
Carbon footprint for each product type depends on factors including the product, number of products used, waste stream, and number of operations in which product was used. T1= tonsillectomy operation one etc. CO_2e=carbon dioxide equivalents

Product	Carbon footprint (g CO2e)										
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**Mean average**
Tonsillectomy set (set A for T1, T4-T10; set B for T2, T3)	2,279.47	2,364.29	2,364.29	2,279.47	2,279.47	2,279.47	2,279.47	2,279.47	2,279.47	2,279.47	**2,296.43**
Carbon footprint reusable set (g CO_2e)	2,279.47	2,364.29	2,364.29	2,279.47	2,279.47	2,279.47	2,279.47	2,279.47	2,279.47	2,279.47	**2,296.43**
Reusable ENT split head drape (two 42"x42")	0	475.15	460.08	0	0	0	0	0	0	0	**93.52**
Carbon footprint reusable patient drapes (g CO_2e)	0	475.15	460.08	0	0	0	0	0	0	0	**93.52**
Reusable surgical gown (including hand towels)	474.03	474.03	474.03	474.03	474.03	474.03	474.03	474.03	474.03	474.03	**474.03**
Reusable surgical hat	8.79	0	0	5.86	5.86	8.79	5.86	8.79	5.86	8.79	**5.86**
Reusable scrubs	185.72	185.72	185.72	185.72	185.72	278.59	232.16	325.02	278.59	278.59	**232.16**
Carbon footprint reusable personal protective equipment (g CO_2e)	668.54	659.75	659.75	665.61	665.61	761.40	712.04	807.83	758.47	761.40	**712.04**
Gloves (non-sterile, one pair)	25.31	44.11	44.11	50.62	50.62	25.31	25.31	25.31	75.93	75.93	**44.26**
Sterile gloves (one pair)	399.62	358.26	358.26	266.41	266.41	266.41	266.41	266.41	266.41	266.41	**298.10**
Surgical face mask	39.28	0	34.87	0	0	19.64	19.64	19.64	19.64	0	**15.27**
Surgical face mask with eye protection	0	75.44	0	0	0	42.90	42.90	42.90	0	0	**20.42**

Surgical hat	3.19	11.33	11.33	6.38	6.38	9.57	9.57	12.76	12.76	9.57	**9.28**
Carbon footprint single-use personal protective equipment (g CO_2e)	467.39	489.13	448.57	323.41	323.41	363.83	363.83	367.02	374.74	351.91	**387.32**
Patient drape (fenestrated ENT drape)	274.74	0	0	274.74	274.74	274.74	274.74	274.74	274.74	274.74	**219.79**
Table drape (instruments)	856.70	775.39	775.39	856.70	856.70	856.70	856.70	856.70	856.70	856.70	**840.44**
Carbon footprint single-use patient and instrument table drapes (g CO_2e)	1,131.44	775.39	775.39	1,131.44	1,131.44	1,131.44	1,131.44	1,131.44	1,131.44	1,131.44	**1,060.23**
Coblation™ wand	0	0	0	0	0	932.68	932.68	932.68	932.68	932.68	**466.34**
Kidney dish	73.04	0	0	0	0	0	0	0	0	0	**7.30**
Filter needle	5.50	0	0	0	0	0	0	0	0	0	**0.55**
Gallipot	42.29	0	0	0	0	84.58	84.58	84.58	84.58	84.58	**46.52**
Incontinence pad	0	0	75.73	0	0	0	0	0	0	0	**7.57**
Braided silk tonsil ties	47.75	94.33	47.16	0	0	0	0	0	0	0	**18.92**
Gauze (non-sterile)	31.26	0	0	0	0	0	0	0	0	0	**3.13**
Nail scrubbing brush	39.43	43.83	0	0	0	39.43	0	0	0	0	**12.27**
Suction tip	0	18.30	0	18.68	18.68	18.68	18.68	18.68	18.68	18.68	**14.90**
Suction receptacle	447.21	373.89	373.89	447.21	447.21	447.21	447.21	447.21	447.21	447.21	**432.55**
Suction tubing	550.66	492.93	489.47	550.66	550.66	550.66	550.66	550.66	550.66	550.66	**538.77**

Syringe (10 ml)	30.50	0	0	0	0	0	0	0	0	0	**3.05**
Tonsil swab pack	51.48	149.09	194.20	102.97	51.48	102.97	102.97	102.97	51.48	51.48	**96.11**
Yankauer sucker	91.36	83.67	83.67	91.36	91.36	91.36	91.36	91.36	91.36	91.36	**89.82**
Specimen pot (40 ml 4% formaldehyde)	0	157.83	0	0	0	0	0	0	0	0	**15.78**
Carbon footprint single-use equipment and medical devices (g CO_2e)	1,410.49	1,413.87	1,264.13	1,210.88	1,159.39	2,267.57	2,228.14	2,228.14	2,176.65	2,176.65	**1,753.59**
Bupivacaine 0.5% with 1:200,000 adrenaline (10 ml)	246.04	246.04	246.04	0	0	0	0	0	0	0	**73.81**
Chirocaine 2.5mg per ml (10 ml)	0	0	0	0	0	251.71	251.71	251.71	251.71	251.71	**125.85**
Sodium chloride 0.9% from 1 litre bottle (150 ml)	113.81	113.81	113.81	113.81	113.81	113.81	113.81	113.81	113.81	113.81	**113.81**
Sodium chloride 0.9%, intravenous infusion bag (500 ml)	0	0	0	0	0	291.44	291.44	291.44	291.44	291.44	**145.72**
Yellow soft paraffin BP 100% from 15 g tube	0	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	**0.77**
Carbon footprint single-use pharmaceuticals (g CO_2e)	359.85	360.70	360.70	114.66	114.66	657.81	657.81	657.81	657.81	657.81	**459.96**
Black waste bag (domestic waste) with cable tie	104.60	0	0	104.60	104.60	104.60	104.60	104.60	104.60	104.60	**83.68**
Clear waste bag (for swab count)	83.70	72.20	72.20	83.70	83.70	83.70	83.70	83.70	83.70	83.70	**81.40**
Clear waste bag (recycling) with cable tie	65.63	131.26	131.26	65.63	65.63	65.63	65.63	65.63	65.63	65.63	**78.75**

Disinfectant sachet	27.02	27.02	27.02	27.02	27.02	27.02	27.02	27.02	27.02	27.02	**27.02**
Disinfectant wipe	76.29	84.58	84.58	45.78	45.78	91.55	61.03	61.03	122.07	76.29	**74.90**
Green bag (linen laundering) with cable tie	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	**21.00**
Mop head	161.85	151.71	151.71	161.85	161.85	161.85	161.85	161.85	161.85	161.85	**159.82**
Orange waste bag (infectious waste) with cable tie	0	307.44	307.44	0	0	0	0	0	0	0	**61.49**
Yellow waste bag (clinical waste) with cable tie	153.14	0	0	153.14	153.14	153.14	153.14	153.14	153.14	153.14	**122.52**
Carbon footprint cleaning products, waste (g CO_2e)	693.24	795.21	795.21	662.72	662.72	708.50	677.98	677.98	739.01	693.24	**710.58**
Total carbon footprint (g CO_2e)	7,010.41	7,333.49	7,128.11	6,388.19	6,336.71	8,170.02	8,050.70	8,149.69	8,117.59	8,051.92	**7,473.68**

Supplementary table 26: Mean average carbon footprint of products used for carpal tunnel decompression

Mean average carbon footprint of products used across ten carpal tunnel decompression operations (C1-C10), in order of contribution. Mean is dependent upon number of products used, and number of operations using the product. CO_2e= carbon dioxide equivalents.

Product category	Product	Mean average carbon footprint (g CO_2e)	Percentage of mean average total (%)	Cumulative percentage (%)
Single-use patient or instrument table drape	Patient drape (fenestrated hand drape)	2,740	22.81	22.81
Single-use personal protective equipment	Surgical gown (including hand towels)	2,063	17.17	39.99
Single-use patient or instrument table drape	Table drape (instruments)	1,050	8.74	48.73
Single-use equipment and medical devices	Crepe bandage (7.5 cm wide)	309	2.57	51.30
Cleaning products, waste bags	Orange waste bag (infectious waste) with cable tie from theatre	307	2.56	53.86
Single-use personal protective equipment	Sterile gloves (pair)	298	2.48	56.34
Reusable components from reusable set (minor op set)	Bipolar lead	268	2.23	58.57
Reusable personal protective equipment	Reusable scrubs	265	2.20	60.77
Single-use components from reusable set (minor op set)	Tray wrap (outer, 90x90 cm)	244	2.03	62.80
Single-use equipment and medical devices	Needle counter	237	1.97	64.78
Single-use equipment and medical devices	Gauze (sterile pack)	224	1.86	66.64
Reusable components from reusable set (minor op set)	Sponge holder forceps	222	1.85	68.48
Pharmaceuticals	Lidocaine 1% with adrenaline 1:200,000 (20 ml)	211	1.75	70.24
Single-use equipment and medical devices	Gauze swab	188	1.57	71.81
Reusable components from reusable set (minor op set)	Weitlaner retractor (3x4 teeth)	181	1.51	73.32
Cleaning products, waste bags	Mop head	152	1.26	74.58
Pharmaceuticals	Lidocaine 1% (10 ml)	151	1.26	75.83
Single-use equipment and medical devices	Kidney dish	147	1.22	77.06
Single-use equipment and medical devices	Bowl	127	1.06	78.12
Pharmaceuticals	Bupivacaine hydrochloride 0.5% (10 ml)	125	1.04	79.16
Single-use components from reusable set (minor op set)	Tray wrap (inner, 90x90 cm)	123	1.02	80.18
Reusable components from reusable set (minor op set)	Weitlaner retractor (2x3 teeth)	121	1.01	81.19
Pharmaceuticals	Chlorhexidine 2% from 500 ml container (100 ml)	107	0.89	82.08
Reusable components from reusable set (minor op set)	Suture scissor	103	0.86	82.94
Reusable components from reusable set (minor op set)	Crile wood needle holder	97	0.81	83.74
Single-use equipment and medical devices	Incontinence pad	96	0.80	84.54
Single-use personal protective equipment	Sterile gloves (two pairs)	93	0.77	85.31
Single-use patient or instrument table drape	Hand pack packaging (drape component)	91	0.76	86.07
Reusable components from reusable set (minor op set)	Towel clip	89	0.74	86.82
Cleaning products, waste bags	Disinfectant wipe	85	0.70	87.52
Pharmaceuticals	Hyaluronidase 1500 I.U. (10 ml)	78	0.65	88.17
Pharmaceuticals	Sodium Chloride 0.9% from 1 litre bottle (100 ml)	76	0.63	88.80
Single-use personal protective equipment	Surgical face mask	75	0.62	89.42
Reusable components from reusable set (minor op set)	BP scalpel handle	71	0.59	90.02

Reusable components from reusable set (minor op set)	McDonald dissector	69	0.57	90.59
Single-use personal protective equipment	Gloves (non-sterile, pair)	66	0.55	91.14
Reusable components from reusable set (minor op set)	Stevens tenotomy scissor	62	0.51	91.65
Cleaning products, waste bags	Orange waste bag (infectious waste) with cable tie from scrub room	61	0.51	92.16
Reusable components from reusable set (minor op set)	Adson dissecting toothed forceps	59	0.49	92.65
Single-use equipment and medical devices	Nail scrubbing brush	58	0.49	93.14
Non-set reusable equipment	Reusable tourniquet pressure cuff	56	0.46	93.60
Reusable components from reusable set (minor op set)	Mosquito artery forceps (curved)	54	0.45	94.06
Single-use personal protective equipment	Sterile gloves (two pair, latex free)	54	0.45	94.51
Reusable components from reusable set (minor op set)	Kilner cats paw retractor	53	0.44	94.95
Reusable components from reusable set (minor op set)	Bipolar diathermy forceps (small)	53	0.44	95.39
Single-use equipment and medical devices	Undercast padding	52	0.43	95.82
Single-use equipment and medical devices	Stockinette tubular bandage	50	0.42	96.24
Single-use personal protective equipment	Surgical face mask with eye protection	49	0.41	96.65
Pharmaceuticals	Levobupivacaine 5mg per 10 ml (10 ml)	48	0.40	97.04
Reusable components from reusable set (minor op set)	Gillies skin hook	41	0.34	97.39
Single-use equipment and medical devices	Skin marker	33	0.27	97.66
Cleaning products, waste bags	Disinfectant sachet	27	0.23	97.89
Single-use equipment and medical devices	Syringe (20 ml)	27	0.22	98.11
Single-use equipment and medical devices	Syringe (20 ml)	26	0.22	98.33
Cleaning products, waste bags	Red bag (linen laundering) with cable tie	26	0.22	98.54
Single-use personal protective equipment	Surgical hat	20	0.17	98.71
Single-use equipment and medical devices	Foam cube	18	0.15	98.86
Single-use equipment and medical devices	Syringe (10 ml)	17	0.14	99.00
Single-use equipment and medical devices	Light cover	15	0.13	99.13
Single-use equipment and medical devices	Gauze (individual piece)	15	0.12	99.25
Single-use equipment and medical devices	Surgical blade	15	0.12	99.37
Single-use equipment and medical devices	Hand packaging (single-use equipment component)	14	0.12	99.49
Cleaning products, waste bags	Clear bin bag (linen laundering)	13	0.10	99.59
Single-use equipment and medical devices	Non-woven dressing	10	0.08	99.68
Single-use components from reusable set (minor op set)	Kit list	10	0.08	99.76
Single-use equipment and medical devices	Elasticated fabric dressing strip	5	0.04	99.80
Single-use equipment and medical devices	Suture (monofilament, non-absorbable 5-0)	4	0.04	99.84
Single-use personal protective equipment	Visor	4	0.04	99.87
Single-use equipment and medical devices	Suture (monofilament, non-absorbable, 4-0)	3	0.02	99.90
Single-use equipment and medical devices	Needle (green)	3	0.02	99.92
Single-use equipment and medical devices	Needle (red)	3	0.02	99.95
Single-use equipment and medical devices	Surgical blade	2	0.02	99.96
Reusable components from reusable set (minor op set)	Metal tray (small)	1	0.01	99.98
Single-use equipment and medical devices	Needle (blue)	1	0.01	99.99
Reusable components from reusable set (minor op set)	Pin mat	1	0.005	99.99
Reusable components from reusable set (minor op set)	Identification tag	1	0.005	100.00
Single-use equipment and medical devices	Tape (clear)	0.50	0.004	100.00

Supplementary table 27: Mean average carbon footprint of products used for inguinal hernia repair
Mean average carbon footprint of products used across six inguinal hernia repair operations (H1-H6), in order of contribution. Mean is dependent upon number of products used, and number of operations using the product. CO_2e= carbon dioxide equivalents.

Product category	**Product**	**Mean average carbon footprint (g CO_2e)**	**Percentage of mean average total (%)**	**Cumulative percentage (%)**
Single-use personal protective equipment	Surgical gown (including hand towels)	1,138	9.75	9.75
Reusable patient or instrument table drapes	High fluid drape	732	6.27	16.02
Single-use equipment and medical devices	Monopolar diathermy with smoke evacuation system	675	5.78	21.80
Pharmaceuticals	Topical skin adhesive (0.8 g)	654	5.60	27.40
Single-use patient or instrument table drape	Table drape (instruments)	646	5.53	32.93
Pharmaceuticals	Levobupivacaine 5mg per 10 ml (10 ml)	602	5.15	38.08
Reusable components from reusable set (general basic set B)	Container	429	3.67	41.75
Single-use equipment and medical devices	Gauze (sterile pack, 10x7.5 cm)	380	3.25	45.00
Reusable personal protective equipment	Reusable scrubs	290	2.48	47.49
Reusable personal protective equipment	Reusable surgical gown (including hand towels)	269	2.30	49.79
Single-use equipment and medical devices	Needle counter	254	2.18	51.97
Reusable patient or instrument table drapes	Low fluid drape	248	2.13	54.09
Single-use equipment and medical devices	Mesh	246	2.11	56.20
Single-use personal protective equipment	Sterile gloves (pair)	215	1.84	58.04
Single-use components from reusable set (general basic set A)	Tray wrap (outer, 150x180 cm)	209	1.79	59.83
Single-use components from reusable set (general basic set A)	Tray wrap (inner, 150x180 cm)	205	1.76	61.59
Cleaning products, waste bags	Orange waste bag (infectious waste, large) with cable tie	205	1.75	63.34
Cleaning products, waste bags	Mop head	194	1.66	65.00
Single-use personal protective equipment	Sterile gloves (two pairs)	179	1.53	66.53
Single-use equipment and medical devices	Incontinence pad	154	1.32	67.85
Single-use equipment and medical devices	Gauze (sterile pack, 10x10 cm)	142	1.22	69.07
Cleaning products, waste bags	Disinfectant wipe	140	1.20	70.27
Single-use personal protective equipment	Gloves (non-sterile, pair)	135	1.16	71.43
Reusable components from reusable set (general basic set B)	Kidney dish (25 cm) x4	131	1.12	72.55
Single-use equipment and medical devices	Gauze (sterile pack, 30x30 cm)	119	1.02	73.56
Single-use equipment and medical devices	Syringe (20 ml)	104	0.89	74.46
Single-use equipment and medical devices	Diathermy pad	97	0.83	75.29
Cleaning products, waste bags	Orange waste bag (infectious waste, small) with cable tie	91	0.78	76.07
Reusable components from reusable set (general basic set B)	Rampley sponge holder forceps x4	85	0.72	76.79
Reusable components from reusable set (general basic set B)	Schnidt artery forceps x6	78	0.67	77.46

Single-use personal protective equipment	Sterile gloves (one pair, latex free)	76	0.65	78.11
Pharmaceuticals	Chlorhexidine 1% from 500 ml container (100 ml)	72	0.61	78.72
Reusable components from reusable set (general basic set B)	Towel clip x6	70	0.60	79.32
Reusable components from reusable set (general basic set B)	Spencer Wells curved artery forceps x4	69	0.59	79.91
Single-use equipment and medical devices	Surgical suspensory bandage	67	0.57	80.48
Reusable components from reusable set (general basic set A)	Sponge holder forceps x4	63	0.54	81.02
Reusable patient or instrument table drapes	Huck towel	62	0.53	81.55
Pharmaceuticals	Povidone iodine 10% from 500 ml container (60 ml)	61	0.52	82.07
Cleaning products, waste bags	Yellow waste bag (clinical waste) with cable tie	51	0.44	82.51
Reusable components from reusable set (general basic set B)	Spencer Wells straight artery forceps x6	48	0.41	82.92
Single-use components from reusable set (general basic set B)	Gallipot x3	48	0.41	83.33
Reusable components from reusable set (general basic set B)	Treves toothed dissecting forceps x6	46	0.40	83.72
Single-use equipment and medical devices	Specimen pot (40 ml 4% formaldehyde)	44	0.38	84.10
Cleaning products, waste bags	Clear bin bag (recycling) with cable tie	44	0.37	84.48
Reusable components from reusable set (general basic set B)	Basket	41	0.36	84.83
Single-use personal protective equipment	Surgical face mask	41	0.35	85.19
Reusable components from reusable set (general basic set B)	Czerny retractor x2	41	0.35	85.53
Reusable components from reusable set (general basic set B)	Halstead mosquito curved artery forceps x6	40	0.35	85.88
Single-use equipment and medical devices	Shaver head	39	0.34	86.22
Single-use equipment and medical devices	Nail scrubbing brush	39	0.33	86.55
Pharmaceuticals	Sodium Chloride 0.9% from 1 litre bottle (50 ml)	38	0.32	86.88
Single-use personal protective equipment	Sterile under-gloves (pair)	36	0.31	87.18
Reusable components from reusable set (general basic set B)	Diathermy lead	36	0.31	87.49
Reusable components from reusable set (general basic set B)	Travers self-retaining retractor	36	0.31	87.80
Single-use equipment and medical devices	Light handle	35	0.30	88.10
Cleaning products, waste bags	Black waste bag (domestic waste) with cable tie	35	0.30	88.39
Reusable components from reusable set (general basic set A)	Towel clip x5	35	0.30	88.69
Reusable components from reusable set (general basic set B)	Langenbeck retractor (medium) x2	34	0.29	88.99
Reusable components from reusable set (general basic set A)	Langenbeck medium retractor x2	34	0.29	89.28
Single-use components from reusable set (general basic set A)	Paper (90x90 cm)	34	0.29	89.56
Cleaning products, waste bags	Red bag (linen laundering) with cable tie	32	0.28	89.84
Reusable components from reusable set (general basic set B)	Diathermy quiver	32	0.27	90.11
Single-use equipment and medical devices	Suture (braided, absorbable, 2-0)	30	0.26	90.37
Reusable components from reusable set (general basic set B)	Lanes tissue forceps x2	28	0.24	90.60
Reusable components from reusable set (general basic set B)	Bipolar diathermy	26	0.23	90.83
Reusable components from reusable set (general basic set A)	Travers self-retaining retractor	26	0.22	91.05
Reusable components from reusable set (general basic set A)	Langenbeck small retractor x2	25	0.22	91.27
Single-use equipment and medical devices	Kidney dish	24	0.21	91.48
Reusable components of individually wrapped instruments (Collingwood Stewart hernia forceps)	Collingwood Stewart Hernia forceps	24	0.21	91.69
Reusable components of individually wrapped instruments (Roberts artery forceps)	Roberts artery forceps	24	0.21	91.89
Cleaning products, waste bags	Clear bin bag (for swab count)	24	0.21	92.10
Single-use equipment and medical devices	Nonwoven dressing (10x20 cm)	24	0.20	92.30
Reusable components from reusable set (general basic set A)	Dunhill artery forceps x5	24	0.20	92.51

Reusable components from reusable set (general basic set A)	Spencer Wells curved artery forceps x2	23	0.20	92.71
Reusable components from reusable set (general basic set B)	Mayo curved scissors	23	0.20	92.90
Single-use equipment and medical devices	Suture (monofilament, nonabsorbable, 2-0)	23	0.20	93.10
Cleaning products, waste bags	Disinfectant sachet	23	0.20	93.30
Reusable components from reusable set (general basic set A)	Diathermy lead	23	0.19	93.49
Reusable components from reusable set (general basic set A)	Czerny retractor x2	22	0.19	93.68
Reusable components from reusable set (general basic set A)	Mosquito fine artery forceps x5	22	0.19	93.87
Reusable components from reusable set (general basic set A)	Morris retractor	22	0.19	94.05
Reusable components from reusable set (general basic set A)	Diathermy quiver	20	0.17	94.23
Reusable components from reusable set (general basic set B)	Bonney toothed dissecting forceps	20	0.17	94.40
Single-use equipment and medical devices	Pre-operative adhesive glove	20	0.17	94.57
Reusable components from reusable set (general basic set A)	Lanes tissue forceps x2	20	0.17	94.74
Single-use patient or instrument table drape	Patient drape (incise drape, with iodine)	19	0.17	94.90
Reusable components from reusable set (general basic set B)	Mayo Hegar needle holder x2	19	0.16	95.07
Reusable components from reusable set (general basic set B)	BP scalpel handle (no. 4) x2	19	0.16	95.23
Single-use components from reusable set (general basic set B)	Bag plain closure (H)	19	0.16	95.39
Reusable components from reusable set (general basic set B)	Allis tissue forceps x2	19	0.16	95.55
Single-use equipment and medical devices	Suture (monofilament, absorbable, 3-0)	18	0.15	95.70
Cleaning products, waste bags	Green bag (linen laundering) with cable tie	17	0.15	95.85
Single-use equipment and medical devices	Nonwoven dressing (10x30 cm)	17	0.14	95.99
Single-use personal protective equipment	Surgical hat	17	0.14	96.14
Reusable components from reusable set (general basic set B)	Bulldog clip	16	0.14	96.28
Reusable components from reusable set (general basic set B)	BP scalpel handle (no. 3) x2	16	0.14	96.42
Reusable components from reusable set (general basic set B)	McIndoe plain diathermy forceps	16	0.14	96.56
Reusable components from reusable set (general basic set B)	Babcock tissue forceps x2	16	0.14	96.69
Reusable components from reusable set (general basic set A)	Mayo curved scissor	15	0.13	96.82
Reusable components from reusable set (general basic set B)	Mayo straight scissors	15	0.13	96.95
Single-use components from reusable set (general basic set A)	Tray lining (60x60 cm)	14	0.12	97.07
Reusable components from reusable set (general basic set A)	Mayo straight scissor	14	0.12	97.19
Reusable components from reusable set (general basic set A)	Allis tissue forceps x2	13	0.11	97.30
Single-use components from reusable set (general basic set A)	Gallipot x2	13	0.11	97.41
Single-use equipment and medical devices	Absorbent towel pack	13	0.11	97.52
Single-use personal protective equipment	Surgical face mask with eye protection	13	0.11	97.63
Reusable components from reusable set (general basic set B)	Plain dissecting forceps (7")	12	0.10	97.73
Reusable components from reusable set (general basic set A)	McIndoe plain diathermy forceps	12	0.10	97.83
Single-use equipment and medical devices	Suture (monofilament, nonabsorbable, 1)	12	0.10	97.93
Reusable components from reusable set (general basic set B)	McIndoe scissors	11	0.10	98.03
Reusable components from reusable set (general basic set A)	BP scalpel handle (no. 3) x2	11	0.09	98.12
Reusable components from reusable set (general basic set A)	Kidney dish (20 cm)	11	0.09	98.22
Reusable components from reusable set (general basic set B)	Stitch scissor	11	0.09	98.31
Reusable components from reusable set (general basic set A)	Debakey plan dissecting forceps x2	11	0.09	98.40
Reusable components from reusable set (general basic set A)	Babcock forceps x2	10	0.09	98.49
Reusable components from reusable set (general basic set A)	Gilles toothed dissecting forceps x2	10	0.09	98.57

Reusable components from reusable set (general basic set B)	Plain dissecting forceps (5")	10	0.08	98.66
Reusable components from reusable set (general basic set A)	Lahey cholecystectomy forceps	10	0.08	98.74
Reusable non-set equipment	Diathermy pad lead	9	0.08	98.82
Single-use components of individually wrapped instruments (Roberts artery forceps)	Flexible pouch	9	0.07	98.89
Single-use components of individually wrapped instruments (Collingwood Stewart hernia forceps)	Flexible pouch	9	0.07	98.97
Single-use components from reusable set (general basic set A)	Pulp tray (no.3)	8	0.07	99.04
Reusable components from reusable set (general basic set A)	Mayo Hegar needle holder	8	0.07	99.11
Single-use equipment and medical devices	Surgical blade (10)	8	0.07	99.18
Reusable components from reusable set (general basic set B)	Gillies toothed dissecting forceps	8	0.07	99.25
Reusable components from reusable set (general basic set A)	Hernia ring	8	0.07	99.31
Reusable components from reusable set (general basic set A)	Crile baby needle holder	8	0.07	99.38
Reusable components from reusable set (general basic set A)	Mcindoe curved scissor	8	0.07	99.45
Reusable components from reusable set (general basic set B)	Debakey dissecting forceps	7	0.06	99.51
Reusable components from reusable set (general basic set B)	McIndoe dissecting forceps	7	0.06	99.56
Single-use components from reusable set (general basic set B)	Kit list	7	0.06	99.62
Reusable components from reusable set (general basic set A)	BP scalpel handle (no. 4)	6	0.05	99.67
Reusable components from reusable set (general basic set A)	Baby Mixter forceps	5	0.05	99.72
Single-use components from reusable set (general basic set B)	Filter paper	5	0.04	99.76
Cleaning products, waste bags	Chlorine tablet	5	0.04	99.80
Single-use components from reusable set (general basic set B)	Tamper proof tags	5	0.04	99.84
Single-use components from reusable set (general basic set A)	Kit list	3	0.03	99.87
Single-use equipment and medical devices	Reinforced skin closure strip	3	0.03	99.89
Single-use equipment and medical devices	Needle (green)	3	0.03	99.92
Single-use equipment and medical devices	Diathermy tip	3	0.02	99.94
Single-use equipment and medical devices	Suture (braided, absorbable, 0)	3	0.02	99.97
Reusable components from reusable set (general basic set A)	Metal tray (medium)	2	0.01	99.98
Reusable personal protective equipment	Reusable surgical hat	1	0.01	99.99
Reusable non-set equipment	Shaver base	0.4	0.003	100.00
Reusable components from reusable set (general basic set B)	Identification tag	0.3	0.002	100.00
Reusable components from reusable set (general basic set A)	Identification tag	0.2	0.002	100.00
Reusable components of individually wrapped instruments (Roberts artery forceps)	Identification tag	0.1	0.001	100.00
Reusable components of individually wrapped instruments (Collingwood Stewart hernia forceps)	Identification tag	0.1	0.001	100.00

Supplementary table 28: Mean average carbon footprint of products used for knee arthroplasty
Mean average carbon footprint of products used across ten knee arthroplasty operations (K1-K10), in order of contribution. Mean is dependent upon number of products used, and number of operations using the product. CO_2e= carbon dioxide equivalents.

Product category	Product	Mean average carbon footprint (g CO_2e)	Percentage of mean average total (%)	Cumulative percentage (%)
Pharmaceuticals	Bone cement mix (with tobramycin)	18,499	21.65	21.65
Pharmaceuticals	Bone cement mix (with gentamicin)	5,281	6.18	27.83
Single-use equipment and medical devices	Pulsed lavage system	3,727	4.36	32.19
Single-use equipment and medical devices	Posterior stabilised femoral implant	3,528	4.13	36.32
Single-use patient or instrument table drape	Table drape (instruments)	3,009	3.52	39.84
Single-use equipment and medical devices	Primary tibial baseplate implant	2,997	3.51	43.35
Single-use equipment and medical devices	Cruciate retaining femoral implant	2,759	3.23	46.57
Single-use personal protective equipment	Surgical gown (including hand towels)	1,826	2.14	48.71
Single-use patient or instrument table drape	Patient drape (extremity, 230x325 cm)	1,636	1.91	50.63
Single-use patient or instrument table drape	Table drape (140x90 cm)	1,406	1.64	52.27
Single-use personal protective equipment	Orthopaedic hood	1,345	1.57	53.84
Single-use equipment and medical devices	Cement mixing and delivery system	1,315	1.54	55.38
Single-use patient or instrument table drape	Patient drape (pouch fluid collection, 40x35 cm)	1,287	1.51	56.89
Single-use patient or instrument table drape	Patient drape (240x150 cm)	1,163	1.36	58.25
Single-use personal protective equipment	Gown	1,089	1.27	59.53
Single-use patient or instrument table drape	Table drape (fan folded, 140x190 cm)	1,038	1.21	60.74
Single-use equipment and medical devices	Tourniquet pressure cuff (leg)	980	1.15	61.89
Pharmaceuticals	Sodium chloride 0.9% for irrigation (3 L bag)	918	1.07	62.96
Single-use patient or instrument table drape	Patient drape (Mayo cover, 75x144 cm) x2	842	0.99	63.95
Single-use equipment and medical devices	Tibial bearing insert cruciate retaining implant	710	0.83	64.78
Single-use personal protective equipment	Sterile gloves (pair)	670	0.78	65.56
Reusable components from reusable set (basic major orthopaedic set)	Container	644	0.75	66.32
Single-use patient or instrument table drape	Patient drape (impervious, split, 152x177 cm)	644	0.75	67.07
Reusable components from reusable set (miscellaneous knee system set)	Container	644	0.75	67.82
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Container	644	0.75	68.58
Reusable components from reusable set (orthopaedic surgical drill)	Container	644	0.75	69.33
Pharmaceuticals	Ropivacaine 75mg in 10 ml (10 ml)	623	0.73	70.06
Cleaning products, waste bags	Orange waste bag (infectious waste) with cable tie from theatre	615	0.72	70.78
Single-use equipment and medical devices	Tray (small)	589	0.69	71.47
Single-use patient or instrument table drape	Patient drape (stockinette, impervious, 30x120 cm)	584	0.68	72.15
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Container	579	0.68	72.83
Single-use equipment and medical devices	Crepe bandage x2	550	0.64	73.47

Single-use personal protective equipment	Sterile gloves (two pairs)	501	0.59	74.06
Cleaning products, waste bags	Disinfectant wipe	486	0.57	74.63
Reusable components from reusable set (patella preparation and trialing set)	Container	451	0.53	75.16
Single-use equipment and medical devices	Tibial bearing insert posterior stabilised implant	444	0.52	75.67
Single-use equipment and medical devices	Suction tubing	437	0.51	76.19
Reusable personal protective equipment	Reusable scrubs	433	0.51	76.69
Pharmaceuticals	Chlorhexidine gluconate in 70% denatured ethanol with 4ml red stain solution from 200 ml bottle (150 ml)	393	0.46	77.15
Pharmaceuticals	Topical skin adhesive (0.8 g)	392	0.46	77.61
Single-use equipment and medical devices	Symmetric patella implant	359	0.42	78.03
Single-use patient or instrument table drape	Knee pack packaging (patient and instrument table drape component)	343	0.40	78.43
Single-use equipment and medical devices	Swab tray (large)	322	0.38	78.81
Single-use equipment and medical devices	Syringe (50 ml)	301	0.35	79.16
Reusable components from reusable set (basic major orthopaedic set)	Heath mallet	283	0.33	79.49
Single-use equipment and medical devices	Incontinence pad	261	0.31	79.80
Cleaning products, waste bags	Mop head	253	0.30	80.10
Single-use equipment and medical devices	Monopolar diathermy	240	0.28	80.38
Single-use patient or instrument table drape	Patient drape (90 x75 cm)	229	0.27	80.64
Reusable components from reusable set (basic major orthopaedic set)	Cement gun	225	0.26	80.91
Single-use patient or instrument table drape	Patient drape (clear U drape)	220	0.26	81.17
Single-use equipment and medical devices	Needle counter	214	0.25	81.42
Reusable components from reusable set (patella preparation and trialing set)	Instruments (top tray, 5 products) product 1	211	0.25	81.66
Reusable components from reusable set (patella preparation and trialing set)	Instruments (top tray, 5 products) product 2	211	0.25	81.91
Reusable components from reusable set (patella preparation and trialing set)	Instruments (top tray, 5 products) product 3	211	0.25	82.16
Reusable components from reusable set (patella preparation and trialing set)	Instruments (top tray, 5 products) product 4	211	0.25	82.40
Reusable components from reusable set (patella preparation and trialing set)	Instruments (top tray, 5 products) product 5	211	0.25	82.65
Pharmaceuticals	Ketorolac tromethamine 30mg in 1ml (1ml)	210	0.25	82.90
Cleaning products, waste bags	Anatomical waste bin	208	0.24	83.14
Single-use equipment and medical devices	Saw blade	205	0.24	83.38
Single-use equipment and medical devices	Cement mixing bowl	204	0.24	83.62
Single-use patient or instrument table drape	Patient drape (adhesive split sheet)	198	0.23	83.85
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Container	193	0.23	84.08
Single-use equipment and medical devices	Suction receptacle	192	0.23	84.30
Pharmaceuticals	Levobupivacaine 2.5mg per ml (10 ml)	191	0.22	84.53
Single-use equipment and medical devices	Cast padding bandage x2	188	0.22	84.75
Single-use equipment and medical devices	Skin stapler	184	0.22	84.96
Reusable components of individually wrapped instruments (light handle)	Light cover	161	0.19	85.15
Single-use personal protective equipment	Gloves (non-sterile, pair)	157	0.18	85.33
Single-use equipment and medical devices	High-vacuum wound drainage	149	0.17	85.51
Reusable components of individually wrapped instruments (light cover)	Light cover	147	0.17	85.68
Single-use equipment and medical devices	Knee pack packaging (equipment component)	145	0.17	85.85
Single-use patient or instrument table drape	Patient drape (incise drape, with iodine)	144	0.17	86.02

Cleaning products, waste bags	Disinfectant sachet	137	0.16	86.18
Single-use equipment and medical devices	Swab gauze (30x30 cm) x10	135	0.16	86.34
Single-use equipment and medical devices	Tubular support bandage	129	0.15	86.49
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Container	129	0.15	86.64
Single-use equipment and medical devices	Swab tray (small)	128	0.15	86.79
Pharmaceuticals	Sodium chloride 0.9% (100 ml)	128	0.15	86.94
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 1	122	0.14	87.08
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 2	122	0.14	87.22
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 3	122	0.14	87.36
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 4	122	0.14	87.51
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 5	122	0.14	87.65
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 6	122	0.14	87.79
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 7	122	0.14	87.93
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 8	122	0.14	88.08
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 9	122	0.14	88.22
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 10	122	0.14	88.36
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 11	122	0.14	88.50
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 12	122	0.14	88.64
Reusable components from reusable set (orthopaedic surgical drill)	Instruments (13 products) product 13	122	0.14	88.79
Reusable components from reusable set (basic major orthopaedic set)	Bone nibbler x2	121	0.14	88.93
Reusable components of individually wrapped instruments (Semb bone holding forceps)	Semb bone holding forceps	121	0.14	89.07
Single-use equipment and medical devices	Kidney dish x3	115	0.13	89.20
Single-use equipment and medical devices	Suction tubing	99	0.12	89.32
Pharmaceuticals	Chlorhexidine 2% from 500 ml bottle (150 ml)	97	0.11	89.43
Reusable components from reusable set (basic major orthopaedic set)	Norfolk and Norwich retractor x2	94	0.11	89.54
Single-use equipment and medical devices	Nail scrubbing brush	94	0.11	89.65
Single-use equipment and medical devices	Intravenous infusion giving set	93	0.11	89.76
Single-use equipment and medical devices	Bowl (500 ml)	92	0.11	89.87
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 1	86	0.10	89.97
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 2	86	0.10	90.07
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 3	86	0.10	90.17
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 4	86	0.10	90.27
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 5	86	0.10	90.37
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 6	86	0.10	90.47
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 7	86	0.10	90.57
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 8	86	0.10	90.67
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 9	86	0.10	90.77
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 10	86	0.10	90.87
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 11	86	0.10	90.97
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 12	86	0.10	91.08
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (bottom tray, 13 products) product 13	86	0.10	91.18
Cleaning products, waste bags	Orange waste bag (infectious waste) with cable tie from scrub room	82	0.10	91.27

Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 1	74	0.086	91.36
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 2	74	0.086	91.44
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 3	74	0.086	91.53
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 4	74	0.086	91.62
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 5	74	0.086	91.70
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 6	74	0.086	91.79
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 7	74	0.086	91.87
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 8	74	0.086	91.96
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 9	74	0.086	92.05
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 10	74	0.086	92.13
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 11	74	0.086	92.22
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 12	74	0.086	92.31
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 13	74	0.086	92.39
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 14	74	0.086	92.48
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 15	74	0.086	92.56
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 16	74	0.086	92.65
Reusable components of individually wrapped instruments (Lanes tissue forceps)	Lanes tissue forceps	74	0.086	92.74
Single-use personal protective equipment	Surgical hat	71	0.083	92.82
Single-use equipment and medical devices	Diathermy tip cleaner	70	0.082	92.90
Single-use equipment and medical devices	Bowl (250 ml) x2	67	0.078	92.98
Reusable components from reusable set (basic major orthopaedic set)	McGoey punch	67	0.078	93.06
Single-use equipment and medical devices	Yankauer sucker	66	0.077	93.13
Cleaning products, waste bags	Clear waste bag (recycling) with cable tie	66	0.077	93.21
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 1	65	0.076	93.29
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 2	65	0.076	93.36
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 3	65	0.076	93.44
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 4	65	0.076	93.51
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 5	65	0.076	93.59
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 6	65	0.076	93.66
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 7	65	0.076	93.74
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 8	65	0.076	93.81
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 9	65	0.076	93.89
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 10	65	0.076	93.97
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 11	65	0.076	94.04
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 12	65	0.076	94.12
Reusable components from reusable set (miscellaneous knee system set)	Instruments (top tray, 13 products) product 13	65	0.076	94.19
Reusable components from reusable set (knee navigation set)	Container	64	0.075	94.27
Single-use equipment and medical devices	Diathermy bag	62	0.073	94.34
Single-use equipment and medical devices	Border dressing (10x30 cm)	62	0.073	94.41
Single-use equipment and medical devices	Crepe bandage (15 cm wide)	61	0.071	94.48
Reusable components from reusable set (miscellaneous knee system set)	Instruments (bottom tray, 12 products) product 1	58	0.068	94.55
Reusable components from reusable set (miscellaneous knee system set)	Instruments (bottom tray, 12 products) product 2	58	0.068	94.62
Reusable components from reusable set (miscellaneous knee system set)	Instruments (bottom tray, 12 products) product 3	58	0.068	94.69

Reusable components from reusable set (miscellaneous knee system set)	Instruments (bottom tray, 12 products) product 4	58	0.068	94.76
Reusable components from reusable set (miscellaneous knee system set)	Instruments (bottom tray, 12 products) product 5	58	0.068	94.83
Reusable components from reusable set (miscellaneous knee system set)	Instruments (bottom tray, 12 products) product 6	58	0.068	94.89
Reusable components from reusable set (miscellaneous knee system set)	Instruments (bottom tray, 12 products) product 7	58	0.068	94.96
Reusable components from reusable set (miscellaneous knee system set)	Instruments (bottom tray, 12 products) product 8	58	0.068	95.03
Reusable components from reusable set (miscellaneous knee system set)	Instruments (bottom tray, 12 products) product 9	58	0.068	95.10
Reusable components from reusable set (miscellaneous knee system set)	Instruments (bottom tray, 12 products) product 10	58	0.068	95.17
Reusable components from reusable set (miscellaneous knee system set)	Instruments (bottom tray, 12 products) product 11	58	0.068	95.24
Reusable components from reusable set (miscellaneous knee system set)	Instruments (bottom tray, 12 products) product 12	58	0.068	95.30
Single-use patient or instrument table drape	Patient drape (incise drape)	58	0.068	95.37
Reusable components from reusable set (basic major orthopaedic set)	Langenbeck retractor (large) x2	57	0.066	95.44
Reusable components from reusable set (basic major orthopaedic set)	Sponge holder x3	56	0.066	95.50
Single-use components of individually wrapped instruments (light handle)	Flexible pouch	56	0.066	95.57
Single-use personal protective equipment	Knee pack packaging (gown component)	56	0.065	95.64
Single-use personal protective equipment	Sterile gloves (two pair, latex free)	54	0.063	95.70
Single-use equipment and medical devices	Syringe (20 ml)	52	0.061	95.76
Single-use components of individually wrapped instruments (light cover)	Flexible pouch	51	0.060	95.82
Reusable components from reusable set (basic major orthopaedic set)	Basket	51	0.059	95.88
Single-use personal protective equipment	Surgical face mask	51	0.059	95.94
Single-use equipment and medical devices	Suture (braided, absorbable 1-0, 803)	49	0.057	96.00
Reusable components from reusable set (basic major orthopaedic set)	Hohmann lever bone x2	49	0.057	96.05
Reusable components from reusable set (basic major orthopaedic set)	Kocher artery forceps (7") x4	47	0.054	96.11
Pharmaceuticals	Iodinated povidone 10% w/w alcoholic tincture from 500 ml bottle (50 ml)	46	0.054	96.16
Single-use personal protective equipment	Surgical face mask with eye protection	45	0.053	96.21
Single-use equipment and medical devices	Towel dressing (2 in pack)	44	0.051	96.27
Cleaning products, waste bags	Red bag (linen laundering) with cable tie	43	0.050	96.32
Reusable components from reusable set (basic major orthopaedic set)	Curette	42	0.049	96.37
Reusable components from reusable set (basic major orthopaedic set)	Langenbeck retractor (medium) x2	40	0.047	96.41
Single-use personal protective equipment	Sweat bands for hood x3	39	0.046	96.46
Reusable components from reusable set (basic major orthopaedic set)	Capener gouge (large)	38	0.045	96.50
Reusable components from reusable set (basic major orthopaedic set)	Capener gouge (small)	38	0.045	96.55
Single-use equipment and medical devices	Self-adherent bandage	34	0.040	96.59
Reusable components from reusable set (basic major orthopaedic set)	Osteotome (8 mm)	33	0.039	96.63
Single-use equipment and medical devices	Swab gauze (10x7.5 cm) x5	32	0.038	96.66
Reusable components from reusable set (basic major orthopaedic set)	Osteotome (25 mm)	31	0.037	96.70
Single-use equipment and medical devices	Adhesive operative towel	31	0.036	96.74
Reusable components of individually wrapped instruments (non-toothed lamina spreader (large))	Non-toothed lamina spreader (large)	31	0.036	96.77
Single-use equipment and medical devices	Diathermy bag	30	0.035	96.81
Reusable components of individually wrapped instruments (blunt Hohman bone elevator)	Blunt Hohman bone elevator	30	0.035	96.84
Single-use components of individually wrapped instruments (Semb bone holding forceps)	Flexible pouch	29	0.034	96.88
Pharmaceuticals	Adrenaline 1mg in 1ml (1ml)	29	0.034	96.91
Single-use equipment and medical devices	Batteries for knee navigation set (x3)	29	0.033	96.94

Reusable components from reusable set (basic major orthopaedic set)	Bristow elevator	27	0.031	96.98
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 1	26	0.030	97.01
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 2	26	0.030	97.04
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 3	26	0.030	97.07
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 4	26	0.030	97.10
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 5	26	0.030	97.13
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 6	26	0.030	97.16
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 7	26	0.030	97.19
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 8	26	0.030	97.22
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 9	26	0.030	97.25
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 10	26	0.030	97.28
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 11	26	0.030	97.31
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 12	26	0.030	97.34
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 13	26	0.030	97.37
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 14	26	0.030	97.40
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 15	26	0.030	97.43
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (top tray, 16 products) product 16	26	0.030	97.46
Single-use components of individually wrapped instruments (Lanes tissue forceps)	Flexible pouch	26	0.030	97.49
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 1	25	0.030	97.52
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 2	25	0.030	97.55
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 3	25	0.030	97.58
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 4	25	0.030	97.61
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 5	25	0.030	97.64
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 6	25	0.030	97.67
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 7	25	0.030	97.70
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 8	25	0.030	97.72
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 9	25	0.030	97.75
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 10	25	0.030	97.78
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 11	25	0.030	97.81
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 12	25	0.030	97.84
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 13	25	0.030	97.87
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 14	25	0.030	97.90
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 15	25	0.030	97.93
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 16	25	0.030	97.96
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Instruments (top tray, 17 products) product 17	25	0.030	97.99
Reusable components from reusable set (basic major orthopaedic set)	Spencer Wells artery forceps (curved, 7") x2	25	0.029	98.02
Reusable components from reusable set (basic major orthopaedic set)	Mayo needle holder x 2	24	0.028	98.05
Reusable components from reusable set (basic major orthopaedic set)	Universal orange scissor	24	0.028	98.08
Reusable components from reusable set (basic major orthopaedic set)	Quiver	24	0.028	98.10
Single-use equipment and medical devices	Skin marker pen	22	0.026	98.13
Reusable components from reusable set (basic major orthopaedic set)	Towel clip x3	22	0.025	98.16
Cleaning products, waste bags	Clear bin bag (linen laundering)	21	0.024	98.18
Single-use equipment and medical devices	Gauze (sterile pack)	20	0.024	98.20

Reusable components from reusable set (basic major orthopaedic set)	Trethowan bone lever x2	20	0.023	98.23
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Tray	20	0.023	98.25
Single-use equipment and medical devices	Suture (braided, absorbable, 2-0)	18	0.021	98.27
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 12 products) product 1	18	0.021	98.29
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 12 products) product 2	18	0.021	98.31
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 12 products) product 3	18	0.021	98.33
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 12 products) product 4	18	0.021	98.35
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 12 products) product 5	18	0.021	98.37
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 12 products) product 6	18	0.021	98.40
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 12 products) product 7	18	0.021	98.42
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 12 products) product 8	18	0.021	98.44
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 12 products) product 9	18	0.021	98.46
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 12 products) product 10	18	0.021	98.48
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 12 products) product 11	18	0.021	98.50
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 12 products) product 12	18	0.021	98.52
Reusable components from reusable set (basic major orthopaedic set)	Bone hook	16	0.019	98.54
Reusable components from reusable set (basic major orthopaedic set)	Mayo scissors (curved, 6")	16	0.018	98.56
Reusable components of individually wrapped instruments (bipolar diathermy)	Bipolar diathermy forceps	15	0.018	98.57
Reusable components from reusable set (basic major orthopaedic set)	Spencer Wells artery forceps (straight, 5") x2	15	0.018	98.59
Reusable components of individually wrapped instruments (diathermy lead)	Diathermy lead	15	0.018	98.61
Reusable components from reusable set (miscellaneous knee system set)	Tray	15	0.018	98.63
Reusable components of individually wrapped instruments (non-toothed lamina spreader (small))	Non-toothed lamina spreader (small)	15	0.017	98.65
Single-use equipment and medical devices	Gauze (individual piece)	15	0.017	98.66
Single-use equipment and medical devices	Monopolar diathermy	15	0.017	98.68
Reusable components from reusable set (basic major orthopaedic set)	Scalpel handle (no. 4) x2	15	0.017	98.70
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Tray	15	0.017	98.71
Reusable components from reusable set (basic major orthopaedic set)	Scalpel handle (no. 4L)	14	0.017	98.73
Single-use equipment and medical devices	Light cover	14	0.017	98.75
Single-use components of individually wrapped instruments (non-toothed lamina spreader (large))	Flexible pouch	14	0.016	98.76
Reusable components from reusable set (patella preparation and trialing set)	Tray	14	0.016	98.78
Reusable components from reusable set (basic major orthopaedic set)	BP scalpel handle (no. 3) x2	13	0.015	98.80
Reusable components from reusable set (basic major orthopaedic set)	Mayo scissors (straight, 6")	12	0.014	98.81
Reusable components from reusable set (basic major orthopaedic set)	Curette (double ended)	12	0.014	98.82
Reusable components from reusable set (basic major orthopaedic set)	Bonney toothed dissecting forceps	12	0.013	98.84
Reusable components from reusable set (basic major orthopaedic set)	BP scalpel handle (no. 3L)	11	0.013	98.85
Single-use equipment and medical devices	Diathermy tip cleaner	11	0.013	98.86
Reusable components from reusable set (basic major orthopaedic set)	McIndoe scissor	10	0.012	98.87
Single-use components of individually wrapped instruments (blunt Hohman bone elevator)	Flexible pouch	10	0.012	98.89
Single-use equipment and medical devices	Suture (monofilament, absorbable 3-0, 696)	10	0.012	98.90
Single-use components from reusable set (basic major orthopaedic set)	Kit list	10	0.012	98.91
Single-use components from reusable set (miscellaneous knee system set)	Kit list	10	0.012	98.92
Single-use components from reusable set (femoral and tibial preparation set (size 3-6))	Kit list	10	0.012	98.93
Single-use components from reusable set (orthopaedic surgical drill)	Kit list	10	0.012	98.94

Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 1	10	0.011	98.96
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 2	10	0.011	98.97
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 3	10	0.011	98.98
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 4	10	0.011	98.99
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 5	10	0.011	99.00
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 6	10	0.011	99.01
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 7	10	0.011	99.02
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 8	10	0.011	99.04
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 9	10	0.011	99.05
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 10	10	0.011	99.06
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 11	10	0.011	99.07
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 12	10	0.011	99.08
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 13	10	0.011	99.09
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 14	10	0.011	99.10
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 15	10	0.011	99.12
Reusable components from reusable set (knee navigation set)	Instruments (bottom tray, 16 products) product 16	10	0.011	99.13
Single-use equipment and medical devices	Shaver head	9	0.011	99.14
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 1	9	0.011	99.15
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 2	9	0.011	99.16
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 3	9	0.011	99.17
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 4	9	0.011	99.18
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 5	9	0.011	99.19
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 6	9	0.011	99.20
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 7	9	0.011	99.21
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 8	9	0.011	99.22
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 9	9	0.011	99.23
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 10	9	0.011	99.24
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 11	9	0.011	99.25
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 12	9	0.011	99.27
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 13	9	0.011	99.28

Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 14	9	0.011	99.29
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 15	9	0.011	99.30
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 16	9	0.011	99.31
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 17	9	0.011	99.32
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 18	9	0.011	99.33
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (top tray, 19 products) product 19	9	0.011	99.34
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 1	9	0.011	99.35
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 2	9	0.011	99.36
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 3	9	0.011	99.37
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 4	9	0.011	99.38
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 5	9	0.011	99.39
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 6	9	0.011	99.40
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 7	9	0.011	99.41
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 8	9	0.011	99.42
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 9	9	0.011	99.44
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 10	9	0.011	99.45
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 11	9	0.011	99.46
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 12	9	0.011	99.47
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 13	9	0.011	99.48
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 14	9	0.011	99.49
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 15	9	0.011	99.50
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 16	9	0.011	99.51

Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 17	9	0.011	99.52
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Instruments (bottom tray, 18 products) product 18	9	0.011	99.53
Single-use components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Kit list	9	0.011	99.54
Single-use equipment and medical devices	Needle (white)	8	0.010	99.55
Reusable components from reusable set (orthopaedic surgical drill)	Tray	8	0.010	99.56
Single-use equipment and medical devices	Surgical blade (10) x3	8	0.009	99.57
Single-use equipment and medical devices	Catheter tip syringe	8	0.009	99.58
Cleaning products, waste bags	Yellow/ black waste bag (non-infectious offensive waste) with cable tie from scrub room	8	0.009	99.59
Reusable components from reusable set (basic major orthopaedic set)	Stitch scissor	8	0.009	99.60
Reusable components from reusable set (basic major orthopaedic set)	Gillies toothed dissecting forceps	7	0.009	99.61
Single-use components from reusable set (basic major orthopaedic set)	Filter paper	7	0.009	99.61
Single-use components from reusable set (miscellaneous knee system set)	Filter paper	7	0.009	99.62
Single-use components from reusable set (femoral and tibial preparation set (size 3-6))	Filter paper	7	0.009	99.63
Single-use components from reusable set (orthopaedic surgical drill)	Filter paper	7	0.009	99.64
Single-use equipment and medical devices	Suture (braided, absorbable 1-0, 932)	7	0.008	99.65
Reusable components from reusable set (basic major orthopaedic set)	Treves dissecting forceps	7	0.008	99.66
Single-use components from reusable set (patella preparation and trialing set)	Kit list	7	0.008	99.67
Single-use components of individually wrapped instruments (diathermy extras)	Flexible pouch	7	0.008	99.67
Single-use components of individually wrapped instruments (bipolar diathermy)	Flexible pouch	7	0.008	99.68
Single-use components of individually wrapped instruments (diathermy lead)	Flexible pouch	7	0.008	99.69
Single-use components from reusable set (basic major orthopaedic set)	Tamper proof tags	7	0.008	99.70
Single-use components from reusable set (miscellaneous knee system set)	Tamper proof tags	7	0.008	99.71
Single-use components from reusable set (femoral and tibial preparation set (size 3-6))	Tamper proof tags	7	0.008	99.71
Single-use components from reusable set (orthopaedic surgical drill)	Tamper proof tags	7	0.008	99.72
Reusable components from reusable set (basic major orthopaedic set)	Galabin ligature carrier	7	0.008	99.73
Single-use components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Filter paper	7	0.008	99.74
Reusable components of individually wrapped instruments (diathermy extras)	Diathermy lead	6	0.008	99.75
Single-use components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Tamper proof tags	6	0.007	99.75
Single-use equipment and medical devices	Wound closure strips	6	0.007	99.76
Reusable components from reusable set (basic major orthopaedic set)	McDonald dissector	6	0.007	99.77
Single-use equipment and medical devices	Suction tip	6	0.007	99.77
Reusable components of individually wrapped instruments (diathermy extras)	Bipolar diathermy forceps	5	0.006	99.78
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Tray	5	0.006	99.79
Single-use components of individually wrapped instruments (non-toothed lamina spreader (small))	Flexible pouch	5	0.006	99.79
Single-use components from reusable set (patella preparation and trialing set)	Filter paper	5	0.006	99.80
Reusable components of individually wrapped instruments (diathermy extras)	Monopolar diathermy	5	0.006	99.80
Single-use components from reusable set (patella preparation and trialing set)	Tamper proof tags	5	0.006	99.81
Single-use equipment and medical devices	Needle (red)	4	0.005	99.81
Single-use equipment and medical devices	Elasticated fabric dressing strip	4	0.005	99.82
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 1	4	0.004	99.82

Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 2	4	0.004	99.83
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 3	4	0.004	99.83
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 4	4	0.004	99.84
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 5	4	0.004	99.84
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 6	4	0.004	99.84
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 7	4	0.004	99.85
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 8	4	0.004	99.85
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 9	4	0.004	99.86
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 10	4	0.004	99.86
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 11	4	0.004	99.86
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 12	4	0.004	99.87
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 13	4	0.004	99.87
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 14	4	0.004	99.88
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 15	4	0.004	99.88
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Instruments (bottom tray, 16 products) product 16	4	0.004	99.89
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Tray	4	0.004	99.89
Single-use equipment and medical devices	Suture (monofilament, absorbable, 3-0, 643)	3	0.004	99.89
Reusable components from reusable set (basic major orthopaedic set)	Pin for instruments	3	0.004	99.90
Reusable components of individually wrapped instruments (diathermy extras)	Tray	3	0.004	99.90
Single-use equipment and medical devices	Transparent film adhesive dressing	3	0.004	99.90
Single-use components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Kit list	3	0.004	99.91
Single-use equipment and medical devices	Surgical blade (10)	2	0.003	99.91
Single-use equipment and medical devices	Marker pen and ruler	2	0.003	99.91
Single-use equipment and medical devices	Pre-operative adhesive glove	2	0.003	99.92
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 1	2	0.003	99.92
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 2	2	0.003	99.92
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 3	2	0.003	99.92
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 4	2	0.003	99.93
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 5	2	0.003	99.93
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 6	2	0.003	99.93
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 7	2	0.003	99.94
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 8	2	0.003	99.94
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 9	2	0.003	99.94
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 10	2	0.003	99.94
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 11	2	0.003	99.95
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 12	2	0.003	99.95
Reusable components from reusable set (patella preparation and trialing set)	Instruments (bottom tray, 13 products) product 13	2	0.003	99.95
Single-use equipment and medical devices	Border dressing (6x8 cm)	2	0.003	99.95
Single-use components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Filter paper	2	0.003	99.96
Single-use components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Tamper proof tags	2	0.002	99.96
Single-use components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Kit list	2	0.002	99.96

Reusable components from reusable set (knee navigation set)	Tray	2	0.002	99.96
Reusable components from reusable set (miscellaneous knee system set)	Pins (long, headless) x4 product 1	2	0.002	99.97
Reusable components from reusable set (miscellaneous knee system set)	Pins (long, headless) x4 product 2	2	0.002	99.97
Reusable components from reusable set (miscellaneous knee system set)	Pins (long, headless) x4 product 3	2	0.002	99.97
Reusable components from reusable set (miscellaneous knee system set)	Pins (long, headless) x4 product 4	2	0.002	99.97
Single-use equipment and medical devices	Diathermy tip	2	0.002	99.97
Single-use components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Filter paper	1	0.002	99.98
Single-use equipment and medical devices	Needle (green)	1	0.002	99.98
Single-use components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Tamper proof tags	1	0.002	99.98
Reusable components from reusable set (miscellaneous knee system set)	Drill bit/ pins x4 product 1	1	0.002	99.98
Reusable components from reusable set (miscellaneous knee system set)	Drill bit/ pins x4 product 2	1	0.002	99.98
Reusable components from reusable set (miscellaneous knee system set)	Drill bit/ pins x4 product 3	1	0.002	99.98
Reusable components from reusable set (miscellaneous knee system set)	Drill bit/ pins x4 product 4	1	0.002	99.99
Single-use components from reusable set (knee navigation set)	Kit list	1	0.001	99.99
Single-use components of individually wrapped instruments (diathermy extras)	Kit list	1	0.001	99.99
Reusable components from reusable set (miscellaneous knee system set)	Nails (short, headed) x4 product 1	1	0.001	99.99
Reusable components from reusable set (miscellaneous knee system set)	Nails (short, headed) x4 product 2	1	0.001	99.99
Reusable components from reusable set (miscellaneous knee system set)	Nails (short, headed) x4 product 3	1	0.001	99.99
Reusable components from reusable set (miscellaneous knee system set)	Nails (short, headed) x4 product 4	1	0.001	99.99
Single-use components from reusable set (knee navigation set)	Filter paper	1	0.001	99.99
Single-use components from reusable set (knee navigation set)	Tamper proof tags	1	0.001	99.99
Single-use equipment and medical devices	Sticky label	1	0.001	99.99
Reusable components of individually wrapped instruments (light handle)	Identification tag	0.43	0.001	100.00
Reusable components from reusable set (basic major orthopaedic set)	Identification tag	0.39	0.00046	100.00
Reusable components from reusable set (miscellaneous knee system set)	Identification tag	0.39	0.00046	100.00
Reusable components from reusable set (femoral and tibial preparation set (size 3-6))	Identification tag	0.39	0.00046	100.00
Reusable components from reusable set (orthopaedic surgical drill)	Identification tag	0.39	0.00046	100.00
Reusable components of individually wrapped instruments (light cover)	Identification tag	0.39	0.00046	100.00
Reusable components from reusable set (cruciate retaining femoral and tibial trialing set (size 3-6))	Identification tag	0.35	0.00041	100.00
Reusable components of individually wrapped instruments (Semb bone holding forceps)	Identification tag	0.31	0.00036	100.00
Reusable components from reusable set (patella preparation and trialing set)	Identification tag	0.27	0.00032	100.00
Reusable components from reusable set (basic major orthopaedic set)	Pin mat	0.21	0.00024	100.00
Reusable components of individually wrapped instruments (Lanes tissue forceps)	Identification tag	0.19	0.00023	100.00
Reusable components from reusable set (posterior stabilised femoral and tibial trialing set (size 3-6))	Identification tag	0.12	0.00014	100.00
Non-set reusable equipment	Shaver base	0.09	0.00010	100.00
Reusable components from reusable set (cruciate retaining femoral and tibial preparation and trialing set (size 1,2,7,8))	Identification tag	0.08	0.00009	100.00
Reusable components of individually wrapped instruments (blunt Hohman bone elevator)	Identification tag	0.08	0.00009	100.00
Reusable components of individually wrapped instruments (non-toothed lamina spreader (large))	Identification tag	0.08	0.00009	100.00
Reusable components from reusable set (knee navigation set)	Pin mat	0.04	0.00005	100.00
Reusable components from reusable set (knee navigation set)	Identification tag	0.04	0.00005	100.00

Reusable components of individually wrapped instruments (diathermy extras)	Identification tag	0.04	0.00005	100.00
Reusable components of individually wrapped instruments (diathermy lead)	Identification tag	0.04	0.00005	100.00
Reusable components of individually wrapped instruments (non-toothed lamina spreader (small))	Identification tag	0.04	0.00005	100.00

Supplementary table 29: Mean average carbon footprint of products used for laparoscopic cholecystectomy
Mean average carbon footprint of products used across six operations (L1-L10), in order of contribution. CO_2e= carbon dioxide equivalents. Mean average across six operations (L1-L6)

Product category	Product	Mean average carbon footprint (g CO_2e)	Percentage of mean average total (%)	Cumulative percentage (%)
Single-use equipment and medical devices	Endoscopic clip applier	1,590	7.83	7.83
Reusable patient or instrument table drape	High fluid drape	1,088	5.36	13.19
Single-use equipment and medical devices	Port (12 mm)	1,077	5.31	18.50
Pharmaceuticals	Levobupivacaine 2.5 mg per 10 ml (10 ml)	756	3.72	22.23
Single-use equipment and medical devices	Suction irrigation	743	3.66	25.89
Single-use patient or instrument table drape	Table drape (instrument)	740	3.65	29.54
Single-use equipment and medical devices	Port (5 mm, dual pack)	655	3.23	32.77
Reusable components from reusable set (general basic set)	Container	643	3.17	35.94
Single-use equipment and medical devices	Insufflating tubing	600	2.96	38.89
Single-use equipment and medical devices	Anti-fog endoscopic demister	565	2.78	41.67
Single-use equipment and medical devices	Laparoscopic scissors	551	2.72	44.39
Reusable components from reusable set (Laparoscope set (10 mm, 0 degree))	Light lead	533	2.63	47.02
Single-use components from reusable set (Laparoscope set (10 mm, 0 degree))	Tray wrap (inner, 100x100 cm)	444	2.19	49.21
Single-use personal protective equipment	Surgical gown (including hand towels)	425	2.09	51.30
Pharmaceuticals	Carbon dioxide (from 3 kg cylinder containing 450 L)	423	2.09	53.39
Reusable components from reusable set (general laparoscopic set)	Container base (deep)	399	1.97	55.36
Reusable personal protective equipment	Reusable scrubs	368	1.81	57.17
Reusable personal protective equipment	Reusable surgical gown (including hand towels)	337	1.66	58.83
Reusable components from reusable set (Laparoscope set (10 mm, 0 degree))	Wire cage with lid	322	1.59	60.42
Single-use personal protective equipment	Sterile gloves (two pairs)	289	1.42	61.84
Reusable personal protective equipment	Reusable surgical gown (including hand towels) double pack	270	1.33	63.17
Single-use equipment and medical devices	Gauze (sterile pack)	256	1.26	64.44
Single-use equipment and medical devices	Needle counter	254	1.25	65.69
Reusable components from reusable set (general laparoscopic set)	Container lid (deep)	247	1.22	66.90
Reusable components from reusable set (Laparoscope set (10 mm, 0 degree))	Hopkins laparoscope (10 mm, 0 degree)	239	1.18	68.08
Reusable components from reusable set (general laparoscopic set)	Kelly crocodile grasping forceps x2	229	1.13	69.21
Single-use components from reusable set (Laparoscope set (10 mm, 0 degree))	Tray wrap (outer, 100x100 cm)	228	1.13	70.34
Reusable components from reusable set (general basic set)	Kidney dish (25 cm) x4	196	0.97	71.30
Single-use personal protective equipment	Sterile gloves (pair)	190	0.94	72.24
Cleaning products, waste bags	Mop head	186	0.91	73.16
Reusable components from reusable set (general laparoscopic set)	Langenbeck retractor (small) x2	172	0.85	74.00
Cleaning products, waste bags	Orange waste bag (infectious waste, large) with cable tie	154	0.76	74.76
Reusable components from reusable set (general laparoscopic set)	Raptor toothed grasping forceps	152	0.75	75.51

Cleaning products, waste bags	Disinfectant wipe	149	0.73	76.24
Pharmaceuticals	Sodium Chloride 0.9% for irrigation (1 L bag)	148	0.73	76.98
Reusable components from reusable set (general laparoscopic set)	Diathermy lead	143	0.71	77.68
Single-use equipment and medical devices	Laparoscope cover	139	0.69	78.37
Reusable components from reusable set (quiver and clip)	Quiver	137	0.68	79.04
Reusable components from reusable set (general basic set)	Rampley sponge holder forceps x4	127	0.63	79.67
Single-use personal protective equipment	Gloves (non-sterile, pair)	124	0.61	80.28
Reusable components from reusable set (general laparoscopic set)	Kocher artery forceps x2	121	0.59	80.87
Reusable components from reusable set (general basic set)	Schnidt artery forceps x6	117	0.58	81.45
Single-use equipment and medical devices	Suction receptacle	117	0.58	82.03
Reusable components from reusable set (general laparoscopic set)	Manhes grasping forceps	116	0.57	82.60
Single-use equipment and medical devices	Pressure saline infusion bag	113	0.56	83.16
Reusable components from reusable set (general laparoscopic set)	Pietlyn dissecting forceps	113	0.56	83.71
Reusable components from reusable set (general laparoscopic set)	Johann grasping forceps	110	0.54	84.26
Reusable components from reusable set (general basic set)	Towel clip x6	105	0.52	84.77
Reusable components from reusable set (general laparoscopic set)	Littlewoods tissue forceps x2	105	0.52	85.29
Cleaning products, waste bags	Black waste bag (domestic waste) with cable tie	105	0.52	85.80
Reusable components from reusable set (general basic set)	Spencer Wells curved artery forceps x4	103	0.51	86.31
Reusable components from reusable set (general laparoscopic set)	Lahey right angle dissecting forceps	102	0.50	86.82
Reusable components from reusable set (general laparoscopic set)	Maryland dissecting forceps	102	0.50	87.32
Single-use equipment and medical devices	Specimen pot (not pre-filled)	92	0.46	87.77
Single-use equipment and medical devices	Syringe (20 ml)	83	0.41	88.18
Single-use equipment and medical devices	Incontinence pad	82	0.40	88.59
Reusable patient or instrument table drape	Huck towel	77	0.38	88.97
Reusable components from reusable set (general basic set)	Spencer Wells straight artery forceps x6	72	0.35	89.32
Single-use components from reusable set (general basic set)	Gallipot x3	71	0.35	89.67
Reusable components from reusable set (general basic set)	Treves toothed dissecting forceps x6	70	0.34	90.02
Cleaning products, waste bags	Orange waste bag (infectious waste, small) with cable tie	68	0.34	90.35
Single-use equipment and medical devices	Diathermy pad	68	0.33	90.68
Reusable components from reusable set (general basic set)	Basket	62	0.31	90.99
Reusable components from reusable set (general basic set)	Czerny retractor x2	61	0.30	91.29
Reusable components from reusable set (general basic set)	Halstead mosquito curved artery forceps x6	60	0.30	91.59
Cleaning products, waste bags	Clear bin bag (quiver diathermy)	60	0.29	91.88
Cleaning products, waste bags	Yellow/ black waste bag (non-infectious offensive waste, large) with cable tie	58	0.29	92.17
Reusable components from reusable set (general basic set)	Diathermy lead	54	0.26	92.43
Pharmaceuticals	Chlorhexidine 1% from 500 ml container (50 ml)	54	0.26	92.70
Reusable components from reusable set (general basic set)	Travers self-retaining retractor	53	0.26	92.96
Reusable components from reusable set (general basic set)	Langenbeck retractor (medium) x2	52	0.25	93.22
Single-use components from reusable set (quiver and clip)	Flexible pouch	51	0.25	93.47
Reusable components from reusable set (general basic set)	Diathermy quiver	47	0.23	93.70
Reusable components from reusable set (general laparoscopic set)	Desjardin forceps	43	0.21	93.92
Single-use equipment and medical devices	Specimen pot (40 ml 4% formaldehyde)	42	0.21	94.12

Reusable components from reusable set (general basic set)	Lanes tissue forceps x2	41	0.20	94.33
Reusable components from reusable set (general laparoscopic set)	Diathermy hook	40	0.20	94.53
Reusable components from reusable set (general basic set)	Bipolar diathermy	40	0.19	94.72
Single-use equipment and medical devices	Laparoscopic tissue retrieval system	39	0.19	94.91
Single-use personal protective equipment	Surgical face mask	39	0.19	95.10
Pharmaceuticals	Sodium Chloride 0.9% from 1 litre bottle (50 ml)	38	0.19	95.29
Cleaning products, waste bags	Yellow/ black waste bag (non-infectious offensive waste, small) with cable tie	37	0.18	95.47
Reusable components from reusable set (general basic set)	Mayo curved scissors	35	0.17	95.64
Cleaning products, waste bags	Disinfectant sachet	34	0.17	95.81
Single-use equipment and medical devices	Nail scrubbing brush	33	0.16	95.97
Cleaning products, waste bags	Clear bin bag (recycling) with cable tie	33	0.16	96.13
Cleaning products, waste bags	Red bag (linen laundering) with cable tie	32	0.16	96.29
Single-use equipment and medical devices	Nonwoven dressing (6x7 cm)	32	0.16	96.45
Single-use equipment and medical devices	Tonsil swab pack	32	0.16	96.61
Reusable components from reusable set (general basic set)	Bonney toothed dissecting forceps	30	0.15	96.75
Reusable components from reusable set (general basic set)	Mayo Hegar needle holder x2	29	0.14	96.90
Reusable components from reusable set (general basic set)	BP scalpel handle (no. 4) x2	29	0.14	97.04
Single-use components from reusable set (general basic set)	Bag plain closure (H)	28	0.14	97.17
Reusable components from reusable set (general basic set)	Allis tissue forceps x2	28	0.14	97.31
Single-use equipment and medical devices	Syringe (10 ml)	27	0.13	97.44
Reusable components from reusable set (diathermy lead)	Diathermy lead	25	0.13	97.57
Reusable components from reusable set (general basic set)	Bulldog clip	25	0.12	97.69
Reusable components from reusable set (general basic set)	BP scalpel handle (no. 3) x2	25	0.12	97.81
Reusable components from reusable set (general basic set)	McIndoe plain diathermy forceps	24	0.12	97.93
Reusable components from reusable set (laparoscopic grasping forceps)	Laparoscopic grasping forceps	24	0.12	98.05
Reusable components from reusable set (general basic set)	Babcock tissue forceps x2	24	0.12	98.17
Single-use equipment and medical devices	Suture (monofilament, absorbable, 1)	24	0.12	98.29
Reusable components from reusable set (general basic set)	Mayo straight scissors	22	0.11	98.39
Single-use personal protective equipment	Surgical hat	20	0.10	98.49
Reusable components from reusable set (general basic set)	Plain dissecting forceps (7")	18	0.09	98.58
Single-use personal protective equipment	Surgical face mask with eye protection	18	0.09	98.67
Cleaning products, waste bags	Green bag (linen laundering) with cable tie	17	0.09	98.76
Single-use personal protective equipment	Sterile gloves (one pair, latex free)	17	0.08	98.84
Reusable components from reusable set (general basic set)	McIndoe scissors	17	0.08	98.93
Reusable components from reusable set (general basic set)	Stitch scissor	16	0.08	99.01
Reusable components from reusable set (general basic set)	Plain dissecting forceps (5")	15	0.07	99.08
Single-use equipment and medical devices	Absorbent towel pack	13	0.06	99.14
Reusable components from reusable set (general laparoscopic set)	Laparoscopic instrument rack	13	0.06	99.20
Reusable components from reusable set (general basic set)	Gillies toothed dissecting forceps	12	0.06	99.26
Single-use components from reusable set (laparoscopic grasping forceps)	Flexible pouch	12	0.06	99.32
Reusable components from reusable set (general basic set)	Debakey dissecting forceps	11	0.05	99.37
Reusable components from reusable set (general basic set)	McIndoe dissecting forceps	10	0.05	99.42

Single-use components from reusable set (general basic set)	Kit list	10	0.05	99.47
Single-use components from reusable set (general laparoscopic set)	Kit list	10	0.05	99.52
Single-use components from reusable set (Laparoscope set (10 mm, 0 degree))	Kit list	10	0.05	99.57
Reusable components from reusable set (quiver and clip)	Clip	9	0.05	99.62
Non-set reusable equipment	Diathermy pad lead	9	0.05	99.66
Single-use components from reusable set (diathermy lead)	Flexible pouch	9	0.04	99.70
Single-use components from reusable set (general basic set)	Filter paper	7	0.04	99.74
Single-use components from reusable set (general laparoscopic set)	Filter paper	7	0.04	99.77
Single-use components from reusable set (general basic set)	Tamper proof tags	7	0.03	99.81
Single-use components from reusable set (general laparoscopic set)	Tamper proof tags	7	0.03	99.84
Single-use equipment and medical devices	Suture (braided, absorbable, 3-0)	7	0.03	99.88
Single-use equipment and medical devices	Light handle	5	0.02	99.90
Single-use equipment and medical devices	Surgical blade (15)	5	0.02	99.92
Single-use equipment and medical devices	Reinforced skin closure strip	4	0.02	99.94
Single-use equipment and medical devices	Needle (green)	3	0.02	99.96
Single-use equipment and medical devices	Suture (monofilament, absorbable, 3-0)	3	0.01	99.97
Reusable personal protective equipment	Reusable surgical hat	2	0.01	99.98
Single-use equipment and medical devices	Surgical blade (11)	1	0.01	99.99
Reusable components from reusable set (Laparoscope set (10 mm, 0 degree))	Identification tag	1	0.0032	99.99
Reusable components from reusable set (general laparoscopic set)	Identification tag	1	0.0028	100.00
Reusable components from reusable set (general basic set)	Identification tag	0.4	0.0019	100.00
Reusable components from reusable set (quiver and clip)	Identification tag	0.4	0.0019	100.00
Reusable components from reusable set (diathermy lead)	Identification tag	0.1	0.0003	100.00
Reusable components from reusable set (laparoscopic grasping forceps)	Identification tag	0.1	0.0003	100.00

Supplementary table 30: Mean average carbon footprint of products used for tonsillectomy
Mean average carbon footprint of products used across ten operations (T1-T10), in order of contribution. Mean is dependent upon number of products used, and number of operations using the product. CO_2e= carbon dioxide equivalents.

Product category	Product	Mean average carbon footprint (g CO_2e)	Percentage of mean average total (%)	Cumulative percentage (%)
Single-use patient or instrument table drape	Table drape (instruments)	840	11.25	11.25
Single-use equipment and medical devices	Suction tubing	539	7.21	18.45
Reusable components from reusable set (tonsillectomy set A)	Container	514	6.88	25.34
Reusable personal protective equipment	Reusable surgical gown (including hand towels)	474	6.34	31.68
Single-use equipment and medical devices	Coblation™ wand	466	6.24	37.92
Single-use equipment and medical devices	Suction receptacle	433	5.79	43.71
Single-use personal protective equipment	Sterile gloves (one pair)	298	3.99	47.69
Reusable personal protective equipment	Reusable scrubs	232	3.11	50.80
Single-use patient or instrument table drape	Patient drape (fenestrated ENT drape)	220	2.94	53.74
Reusable components from reusable set (tonsillectomy set A)	Draffin bipod stand (long) x2	161	2.16	55.90
Cleaning products, waste bags	Mop head	160	2.14	58.04
Pharmaceuticals	Sodium chloride 0.9%, intravenous infusion bag (500 ml)	146	1.95	59.99
Reusable components from reusable set (tonsillectomy set A)	Draffin bipod stand (short) x2	139	1.86	61.85
Reusable components from reusable set (tonsillectomy set B)	Container	129	1.72	63.57
Pharmaceuticals	Chirocaine 2.5mg per ml (10 ml)	126	1.68	65.25
Cleaning products, waste bags	Yellow waste bag (clinical waste) with cable tie	123	1.64	66.89
Pharmaceuticals	Sodium chloride 0.9% from 1 litre bottle (150 ml)	114	1.52	68.41
Single-use equipment and medical devices	Tonsil swab pack	96	1.29	69.70
Reusable patient or instrument table drape	Reusable ENT split head drape (two 42"x42")	94	1.25	70.95
Single-use equipment and medical devices	Yankauer sucker	90	1.20	72.15
Cleaning products, waste bags	Black waste bag (domestic waste) with cable tie	84	1.12	73.27
Cleaning products, waste bags	Clear waste bag (for swab count)	81	1.09	74.36
Cleaning products, waste bags	Clear waste bag (recycling) with cable tie	79	1.05	75.41
Reusable components from reusable set (tonsillectomy set A)	Bipolar diathermy lead	78	1.05	76.46
Cleaning products, waste bags	Disinfectant wipe	75	1.00	77.46
Pharmaceuticals	Bupivacaine 0.5% with 1:200,000 adrenaline (10 ml)	74	0.99	78.45
Reusable components from reusable set (tonsillectomy set A)	Boyle Davis gag	73	0.98	79.43
Reusable components from reusable set (tonsillectomy set A)	Adenoid St Clair Thompson curette	69	0.93	80.36
Cleaning products, waste bags	Orange waste bag (infectious waste) with cable tie	61	0.82	81.18
Reusable components from reusable set (tonsillectomy set A)	Dennis Browne forceps	61	0.82	82.00
Reusable components from reusable set (tonsillectomy set A)	Boyle Davis tongue plate (99 mm)	61	0.81	82.82
Reusable components from reusable set (tonsillectomy set A)	Boyle Davis tongue plate (89 mm)	59	0.79	83.60

Reusable components from reusable set (tonsillectomy set A)	Boyle Davis tongue plate (74 mm)	52	0.70	84.30
Single-use equipment and medical devices	Gallipot	47	0.62	84.92
Reusable components from reusable set (tonsillectomy set A)	Beckman curette	46	0.62	85.54
Reusable components from reusable set (tonsillectomy set A)	Luc forceps (large)	46	0.61	86.16
Reusable components from reusable set (tonsillectomy set A)	Basket	45	0.60	86.76
Single-use personal protective equipment	Gloves (non-sterile, one pair)	44	0.59	87.35
Reusable components from reusable set (tonsillectomy set A)	Hurd dissector/ pillar retractor	43	0.58	87.93
Reusable components from reusable set (tonsillectomy set A)	Kidney dish (20 cm)	40	0.53	88.46
Reusable components from reusable set (tonsillectomy set A)	Bulldog clip	38	0.51	88.97
Reusable components from reusable set (tonsillectomy set A)	Negus knot pusher	36	0.48	89.45
Reusable components from reusable set (tonsillectomy set B)	Draffin bipod stand x 2	35	0.47	89.92
Reusable components from reusable set (tonsillectomy set A)	Negus curved artery forceps(large)	34	0.46	90.38
Reusable components from reusable set (tonsillectomy set A)	Birkett straight tonsil forceps	33	0.44	90.81
Reusable components from reusable set (tonsillectomy set A)	Metzenbaum curved scissors	32	0.43	91.25
Reusable components from reusable set (tonsillectomy set A)	Boyle Davis tongue plate (64 mm)	32	0.43	91.68
Reusable components from reusable set (tonsillectomy set A)	Bipolar diathermy forceps (8")	31	0.42	92.09
Cleaning products, waste bags	Disinfectant sachet	27	0.36	92.45
Reusable components from reusable set (tonsillectomy set A)	Wilson tonsil artery forceps	26	0.35	92.81
Reusable components from reusable set (tonsillectomy set A)	Gwyne Evans tonsil dissector	24	0.33	93.13
Reusable components from reusable set (tonsillectomy set A)	Dissecting forceps (long, toothed)	23	0.31	93.45
Cleaning products, waste bags	Green bag (linen laundering) with cable tie	21	0.28	93.73
Single-use personal protective equipment	Surgical face mask with eye protection	20	0.27	94.00
Reusable components from reusable set (tonsillectomy set B)	Boyle Davis gag (adult)	20	0.26	94.26
Reusable components from reusable set (tonsillectomy set B)	Small receiver x2	19	0.25	94.52
Single-use equipment and medical devices	Braided silk tonsil ties	19	0.25	94.77
Reusable components from reusable set (tonsillectomy set B)	Bipolar diathermy lead	19	0.25	95.02
Reusable components from reusable set (tonsillectomy set B)	Kidney dish (25 cm) x2	18	0.24	95.27
Reusable components from reusable set (tonsillectomy set B)	Diathermy quiver	18	0.24	95.50
Reusable components from reusable set (tonsillectomy set B)	Boyle Davis gag (paediatric)	17	0.23	95.73
Single-use equipment and medical devices	Specimen pot (40 ml 4% formaldehyde)	16	0.21	95.94
Single-use personal protective equipment	Surgical face mask	15	0.20	96.15
Reusable components from reusable set (tonsillectomy set B)	Doughty tongue plate (4")	15	0.20	96.35
Single-use equipment and medical devices	Suction tip	15	0.20	96.55
Reusable components from reusable set (tonsillectomy set B)	Masson needle holder (10")	14	0.19	96.75
Reusable components from reusable set (tonsillectomy set B)	Basket	13	0.18	96.92
Reusable components from reusable set (tonsillectomy set B)	Doughty tongue plate (3.5")	13	0.17	97.09
Single-use equipment and medical devices	Nail scrubbing brush	12	0.16	97.26
Reusable components from reusable set (tonsillectomy set B)	Yankauer sucker	12	0.16	97.41
Reusable components from reusable set (tonsillectomy set B)	Towel clip (ball/socket)	11	0.15	97.56
Reusable components from reusable set (tonsillectomy set B)	Luc forceps (large)	11	0.15	97.71
Reusable components from reusable set (tonsillectomy set B)	Woods ENT scissors	10	0.13	97.84
Single-use personal protective equipment	Surgical hat	9	0.12	97.97
Reusable components from reusable set (tonsillectomy set B)	Bulldog clip	9	0.12	98.09

Single-use components from reusable set (tonsillectomy set B)	Gallipot (60 ml) x2	8	0.11	98.20
Reusable components from reusable set (tonsillectomy set B)	Negus knot pusher	8	0.11	98.32
Reusable components from reusable set (tonsillectomy set B)	Negus curved artery forceps(large)	8	0.11	98.43
Single-use components from reusable set (tonsillectomy set A)	Kit list	8	0.11	98.53
Reusable components from reusable set (tonsillectomy set B)	Birketts straight tonsil forceps	8	0.10	98.64
Single-use equipment and medical devices	Incontinence pad	8	0.10	98.74
Reusable components from reusable set (tonsillectomy set B)	Bipolar forceps (8")	7	0.10	98.84
Single-use equipment and medical devices	Kidney dish	7	0.10	98.93
Reusable components from reusable set (tonsillectomy set B)	Mcindoe curved scissors (7")	7	0.10	99.03
Reusable components from reusable set (tonsillectomy set B)	Waugh toothed dissecting forceps (8")	7	0.10	99.13
Reusable components from reusable set (tonsillectomy set B)	Mollison pillar retractor	7	0.09	99.22
Reusable components from reusable set (tonsillectomy set B)	Wilson tonsil artery forceps	6	0.08	99.30
Reusable personal protective equipment	Reusable surgical hat	6	0.08	99.38
Single-use components from reusable set (tonsillectomy set A)	Filter paper	6	0.08	99.46
Reusable components from reusable set (tonsillectomy set B)	Gwyne Evans tonsil dissector	6	0.08	99.54
Single-use components from reusable set (tonsillectomy set B)	Bag plain closure (H)	6	0.08	99.61
Single-use components from reusable set (tonsillectomy set A)	Tamper proof tags	6	0.07	99.69
Single-use components from reusable set (tonsillectomy set A)	Gag guard	5	0.07	99.75
Reusable components from reusable set (tonsillectomy set B)	Treves plain dissecting forceps (5")	4	0.06	99.81
Single-use equipment and medical devices	Gauze (non-sterile)	3	0.04	99.85
Single-use equipment and medical devices	Syringe (10 ml)	3	0.04	99.89
Single-use components from reusable set (tonsillectomy set B)	Kit list	2	0.03	99.92
Single-use components from reusable set (tonsillectomy set B)	Gag guard	2	0.02	99.94
Single-use components from reusable set (tonsillectomy set B)	Filter paper	1	0.02	99.96
Single-use components from reusable set (tonsillectomy set B)	Tamper proof tags	1	0.02	99.98
Pharmaceuticals	Yellow soft paraffin BP 100% from 15 g tube	1	0.01	99.99
Single-use equipment and medical devices	Filter needle	1	0.01	99.99
Reusable components from reusable set (tonsillectomy set A)	Identification tag	0.3	0.004	100.00
Reusable components from reusable set (tonsillectomy set B)	Identification tag	0.1	0.001	100.00

Supplementary table 31: Carbon footprint of bone cement using process-based approach

The material composition of products were determined based upon product manufacturer data sheets,(235, 236) matching listed materials to available emission factors (Supplementary table 4). A number of materials were omitted due to lack of emission factors; for both types of bone cement N,n-dimethyl-para- toluidine and hydroquinone were omitted; for bone cement mix with gentamicin, gentamicin sulphate and dibenzoyl peroxide were also omitted; for bone cement with tobramycin, tobramycin sulphate was also omitted. Omitted materials were an estimated 4% - 7% of products by weight (excluding packaging), and omitted material weights were allocated across other product materials. The material composition of packaging was based on expert assessment, taking into account available emission factors. Carbon footprint per use equates to a single use of a product in a single operation. CO_2e= carbon dioxide equivalents, ops.= operations

Product	Component	Material(s)	Weight (g)	Number of uses	Number of ops per use	Waste stream	Carbon footprint per use (g CO_2e)		
							Production	Waste stream	Total
Bone cement mix (with gentamicin)	Product	Methyl methacrylate	36.40	1	1	N/A	261.53	N/A	261.53
		Polymethyl methacrylate	16.40				125.67		125.67
		Zirconium oxide	8.20				29.65		29.65
	Packaging	Paper	154.82			Infectious waste	230.68	88.14	318.82
		Polyethylene terephthalate	13.06				52.66	7.44	60.10
		Glass general	11.61			Medicinal contaminated sharps waste	16.72	12.47	29.19
		Polypropylene oriented film	11.42			Infectious waste	39.17	6.50	45.67
		Aluminium foil	9.17				68.50	5.22	73.72
		Low density polyethylene resin	1.18				2.45	0.67	3.13

Bone cement mix (with tobramycin)	Product	Methyl methacrylate	49.93	1	1	N/A	358.74	N/A	358.74
		Polymethyl methacrylate	6.56				50.27		50.27
		Barium Sulfide	4.51				5.34		5.34
	Packaging	Paper	83.65			Infectious waste	124.64	47.62	172.26
		Low density polyethylene film	11.02				28.66	6.28	34.94
		Glass general	9.30			Medicinal contaminated waste	13.39	9.99	23.38
		Polyethylene terephthalate	5.53			Infectious waste	22.30	3.15	25.45
		High density polyethylene resin	2.76				5.32	1.57	6.89
		Low density polyethylene resin	1.18				2.45	0.67	3.13
		Polypropylene oriented film	0.61				2.09	0.35	2.44

Supplementary table 32: Life cycle inventory processes selected from SimaPro databases for CHAPTER 5
Ecoinvent (version 3.6)- allocation, cut-off by classification- unit library was selected for all processes, aside from where unavailable, Industry Data 2.2 library was used.(114)

Material	Process Name	Used for process/ product; comments
Aluminium	Aluminium alloy, metal matrix composite {GLO}| market for | Cut-off, U	Sterile barrier system for reusable instrument decontamination
	Aluminium, cast alloy {GLO}| market for | Cut-off, U	Laparoscopic scissors-hybrid (single-use component)
	Aluminium, wrought alloy {GLO}| market for | Cut-off, U	5 mm port- hybrid (single-use component), 10 mm port- hybrid (single-use component); used for foil
Brass	Brass {RoW}| market for brass | Cut-off, U	5 mm port- hybrid (reusable component)
Chromium	Chromium {GLO}| market for | Cut-off, U	5 mm port- hybrid (reusable component)
Copper	Copper {GLO}| market for | Cut-off, U	Laparoscopic scissors-hybrid (reusable component), laparoscopic scissors- single-use
Cardboard (corrugated)	Corrugated board box {RoW}| market for corrugated board box | Cut-off, U	Clip applier-hybrid (reusable component)
Cardboard (boxboard)	Folding boxboard/chipboard {GLO}| market for | Cut-off, U	Clip applier-single-use, laparoscopic scissors-hybrid (reusable component)
High density polyethylene	Polyethylene, high density, granulate {GLO}| market for | Cut-off, U	Clip applier-hybrid (single-use component), clip applier-single-use, laparoscopic scissors-hybrid (single-use component), laparoscopic scissors- single-use, 5 mm port- hybrid (reusable and single-use component), 5 mm port- single-use, 10 mm port- hybrid (single-use component), 10 mm port- hybrid (reusable components), 11 mm port- single-use, sterile barrier system for reusable instrument decontamination
Liquid resins	Liquid epoxy resins E	Clip applier-hybrid (reusable component); used for liquid-crystal polymer
Low density polyethylene	Polyethylene, low density, granulate {GLO}| market for | Cut-off, U	Clip applier-hybrid (single-use component), 5 mm port- single-use, 11 mm port- single-use; used for polyolefin
	Packaging film, low density polyethylene {GLO}| market for | Cut-off, U	Clip applier decontamination in flexible pouch
Nickel	Nickel, 99.5% {GLO}| market for | Cut-off, U	Laparoscopic scissors-hybrid (reusable component), laparoscopic scissors- single-use, 5 mm port- hybrid (reusable component)

Nylon	Nylon 6-6 {RoW}| market for nylon 6-6 | Cut-off, U	Clip applier-single-use, laparoscopic scissors- single-use, 5 mm port- hybrid (single-use component), 5 mm port- single-use, 10 mm port- hybrid (single-use component), 11 mm port- single-use
Paper	Kraft paper, bleached {GLO}| market for | Cut-off, U	Clip applier-hybrid (reusable and single-use component), clip applier- single-use, laparoscopic scissor-hybrid (reusable component), laparoscopic scissor-single-use, 5 mm port- hybrid (reusable components), 10 mm port- hybrid (reusable components), sterile barrier system for reusable instrument decontamination
Polycarbonate	Polycarbonate {GLO}| market for | Cut-off, U	Clip applier-hybrid (single-use component), clip applier-single-use, laparoscopic scissors- single-use, 5 mm port- single-use, 10 mm port- hybrid (single-use component), 11 mm port- single-use
Polyester	Polyester resin, unsaturated {RoW}| market for polyester resin, unsaturated | Cut-off, U	Laparoscopic scissors- single-use, 10 mm port- hybrid (single-use component)
Polyethylene terephthalate	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Cut-off, U	Clip applier-single-use, 5 mm port- hybrid (single-use component), 10 mm port- hybrid (single-use component)
Polyoxymethylene	Polyoxymethylene (POM)/EU-27	5 mm port- hybrid (reusable component), 10 mm port- hybrid (reusable component)
Polyphenylene sulphide	Polyphenylene sulfide {GLO}| market for | Cut-off, U	Clip applier-hybrid (reusable component), laparoscopic scissors-hybrid (reusable and single-use component), 5 mm port- hybrid (reusable component), 10 mm port- hybrid (reusable component); used as substitute for PEEK (polyether ether ketone); laparoscopic general set container lid
Polypropylene	Polypropylene, granulate {GLO}| market for | Cut-off, U	Clip applier-single-use, laparoscopic scissors- single-use, 5 mm port- single-use, 11 mm port- single-use, sterile barrier system for reusable instrument decontamination
Polyurethane	Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U	Clip applier hybrid-reusable component, 11 mm port- single-use
Polyvinylchloride	Polyvinylchloride, suspension polymerised {GLO}| market for | Cut-off, U	Clip applier-single-use, 5 mm port- hybrid (reusable component),10 mm port- hybrid (reusable components)
Potassium hydroxide	Potassium hydroxide {GLO}| market for | Cut-off, U	Detergent for reusable instrument decontamination
Rubber	Synthetic rubber {GLO}| market for | Cut-off, U	Laparoscopic instrument rack for reusable instrument decontamination
Silicone	Silicone product {RoW}| market for silicone product | Cut-off, U	Laparoscopic scissors-hybrid (single-use component), laparoscopic scissors- single-use, 5 mm port- hybrid (single-use component), 5 mm port- single-use, 10 mm port- hybrid (single-use component), 11 mm port- single-use
Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	Detergent for reusable instrument decontamination
Stainless steel	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	Clip applier-hybrid (reusable and single-use component), clip applier-single-use, laparoscopic scissors-hybrid (reusable and single-use component), laparoscopic scissors- single-use, 5 mm port- hybrid (reusable component), 10 mm port- hybrid (reusable component), 10 mm port- hybrid (reusable component), 11 mm port-

		single-use, sterile barrier system for reusable instrument decontamination, laparoscopic instrument rack for reusable instrument decontamination
Titanium	Titanium, primary {GLO}| market for | Cut-off, U	Clip applier-hybrid (single-use component), clip applier-single-use
Zinc	Zinc {GLO}| market for | Cut-off, U	Laparoscopic scissors-hybrid (reusable component), laparoscopic scissors- single-use
Energy	**Process Name**	**Used for process/ product; comments**
Electricity (UK)	Electricity, medium voltage {GB}| market for | Cut-off, U	Reusable instrument decontamination
Processing	**Process name**	**Used for process/ product; comments**
Plastic product manufacturing	Injection moulding {GLO}| market for | Cut-off, U	Manufacture of all plastics; auxiliaries and energy demand for conversion of plastics via injection moulding
Metal product manufacturing	Metal working, average for metal product manufacturing {GLO}| market for | Cut-off, U	Manufacture of all metals; manufacturing processes to make a semi-manufactured product into a final product, including average values for the processing of metals by machines and factory infrastructure and operation, plus steel input for loss during processing
Production of steam	Process steam from natural gas, heat plant, consumption mix, at plant, MJ GB S	Reusable instrument decontamination
Transportation	**Process Name**	**Used for process/ product; comments**
Air freight	Transport, freight, aircraft, long haul {GLO}| market for transport, freight, aircraft, long haul | Cut-off, U	Transport via air freight
Courier	Transport, freight, light commercial vehicle {RER}| market group for transport, freight, light commercial vehicle | Cut-off, U	Transport via courier
Heavy goods vehicle	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	Transport via heavy goods vehicle
Shipping	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	Alternative transport scenario- shipping
Water	**Process Name**	**Used for process/ product; comments**
Tap water	Tap water {RER}| market group for | Cut-off, U	Reusable instrument decontamination
Wastewater	Wastewater, average {Europe without Switzerland}| market for wastewater, average | Cut-off, U	Reusable instrument decontamination
Waste	**Process Name**	**Used for process/ product; comments**
Hazardous waste	Hazardous waste, for incineration {Europe without Switzerland}| treatment of hazardous waste, hazardous waste incineration | Cut-off, U	All waste streams

Supplementary table 33: Parameters for sterilisation of reusable laparoscopic general set, used to house reusable components of hybrid instruments

Sterilisation material and energy inputs based on data in CHAPTER 6.

Process	Sub-process	Input	Amount (per laparoscopic set decontaminated)		
			Weight (g)	Assumed number of uses	Total per use
Sterile barrier system	Basket	Stainless steel	939.12	116	8.09 g
	Container	Aluminium	2629.88	1000	2.63 g
	Container lid	Polyphenylsulfone	1659.99	1000	1.66 g
	Identification tag	High Density Polyethylene	8.21	46	0.18 g
	Filter paper	Paper	3.55	1	8.4 g
	Kit list		4.85	1	
	Laparoscopic instrument rack	Stainless steel	937.84	500	1.88 g
		Rubber	165.50	500	0.33 g
	Tamper proof tags	Polypropylene granulate	1.78	1	1.78 g
Sterilisation (washing/ disinfection and sterilisation of instrument set)	Detergent	Sodium hydroxide in 50% solution state			1.85 g
		Potassium hydroxide			0.93 g
	Electricity	Electricity (UK)			1.26 kWh
	Fuel	Natural gas (UK)			0.3 m^3 =11.51 MJ =3.2 kWh
	Water	Tap water (UK)			76.2 kg
		Wastewater (UK)			

Supplementary table 34: Parameters for sterilisation of laparoscopic clip applier as individually wrapped product in single-use flexible pouch
Sterilisation material and energy inputs based on data in CHAPTER 6.

Process	**Sub-process**	**Input**	**Amount (per laparoscopic clip applier decontaminated)**
Sterile barrier system	Flexible pouch (single-use double wrap)	Paper	20.92 g
		Polyethylene	30.84 g
	Identification tag (re-used 46 times)	High Density Polyethylene	0.18 g
Sterilisation (washing and disinfection)	Detergent	Sodium hydroxide in 50% solution state	0.46 g
		Potassium hydroxide	0.23 g
	Electricity	Electricity (UK)	0.32 kWh
	Fuel	Natural gas (UK)	0.075 m^3 =2.88 MJ =0.80 kWh
	Water	Tap water (UK)	19 kg
		Wastewater (UK)	

Supplementary table 35: Alternative sterilisation assumptions; environmental impact (midpoint categories) per use of hybrid laparoscopic clip applier, scissors, and ports.

This alternative scenario assumed that the laparoscopic clip applier was individually prepared and housed in a flexible polyethylene pouch (double wrapped), and that the total weight of products contained within the laparoscopic general set was reduced to 1.1 kg, and the sterilisation of the surgical scissors and ports were apportioned accordingly. Environmental impacts (midpoint categories) measured using life cycle assessment and modelled on one use of one laparoscopic clip applier, one laparoscopic scissors, two 5 mm ports, and two 10 mm – 11 mm ports (number required to perform a single laparoscopic cholecystectomy), comparing hybrid with single-use equivalents. 1,4-DCB =dichlorobenzene, CFC11= Trichlorofluoromethane, CO_2e= carbon dioxide equivalents, Cu= copper, eq= equivalents, Bq Co-60 eq = becquerel Cobalt-60, m^2a = square metre years, N= nitrogen, NO_x= nitrous oxides, P=phosphate, PM2.5 = particulate matter <2.5 micrometres, SO_2= sulphur dioxide

Impact category	Unit	Hybrid laparoscopic clip applier	Hybrid laparoscopic scissors	Hybrid ports
Global warming	g CO_2e	1,650	394	999
Stratospheric ozone depletion	g CFC11 eq	0.0006	0.0001	0.0004
Ionizing radiation	Bq Co-60 eq	256	32	92
Ozone formation, Human health	g NO_x eq	2.90	0.81	1.50
Fine particulate matter formation	g PM2.5 eq	1.71	0.79	0.93
Ozone formation, Terrestrial ecosystems	g NO_x eq	3.00	0.83	1.55
Terrestrial acidification	g SO_2 eq	3.50	1.47	2.18
Freshwater eutrophication	g P eq	0.37	0.17	0.18
Marine eutrophication	g N eq	0.38	0.04	0.14
Terrestrial ecotoxicity	g 1,4-DCB	5125	5656	1283
Freshwater ecotoxicity	g 1,4-DCB	59	97	19
Marine ecotoxicity	g 1,4-DCB	78	122	25
Human carcinogenic toxicity	g 1,4-DCB	72	66	45
Human non-carcinogenic toxicity	g 1,4-DCB	1188	960	422
Land use	m^2a crop eq	0.13	0.01	0.03
Mineral resource scarcity	g Cu eq	11	14	3
Fossil resource scarcity	g oil eq	628	106	284
Water consumption	m^3	0.0172	0.0029	0.0086

Supplementary table 36: Alternative energy supply assumptions; environmental impact (midpoint categories) per use of hybrid laparoscopic clip applier, scissors, and ports

This alternative scenario assumed that Australian electricity was used for sterilisation of reusable components. Environmental impacts (midpoint categories) measured using life cycle assessment and modelled on one use of one laparoscopic clip applier, one laparoscopic scissor, two 5 mm ports, and two 10 mm – 11 mm ports (number required to perform a single laparoscopic cholecystectomy), comparing hybrid with single-use equivalents. 1,4-DCB =dichlorobenzene, CFC11= Trichlorofluoromethane, CO_2e= carbon dioxide equivalents, Cu= copper, eq= equivalents, Bq Co-60 eq = becquerel Cobalt-60, m^2a = square metre years, N= nitrogen, NO_x= nitrous oxides, P=phosphate, PM2.5 = particulate matter <2.5 micrometres, SO_2= sulphur dioxide

Impact category	**Unit**	**Hybrid laparoscopic clip applier**	**Hybrid laparoscopic scissors**	**Hybrid ports**
Global warming	g CO_2e	579	421	1,105
Stratospheric ozone depletion	g CFC11 eq	0.0003	0.0002	0.0006
Ionizing radiation	Bq Co-60 eq	11	13	19
Ozone formation, Human health	g NO_x eq	1.16	0.87	1.76
Fine particulate matter formation	g PM2.5 eq	0.78	0.83	1.09
Ozone formation, Terrestrial ecosystems	g NO_x eq	1.18	0.89	1.80
Terrestrial acidification	g SO_2 eq	1.66	1.59	2.69
Freshwater eutrophication	g P eq	0.47	0.28	0.61
Marine eutrophication	g N eq	0.11	0.04	0.14
Terrestrial ecotoxicity	g 1,4-DCB	4,010	5,639	1,215
Freshwater ecotoxicity	g 1,4-DCB	45	100	28
Marine ecotoxicity	g 1,4-DCB	59	126	38
Human carcinogenic toxicity	g 1,4-DCB	62	71	65
Human non-carcinogenic toxicity	g 1,4-DCB	918	1,062	831
Land use	m^2a crop eq	0.01	0.01	0.01
Mineral resource scarcity	g Cu eq	9	14	3
Fossil resource scarcity	g oil eq	162	108	294
Water consumption	m^3	0.003	0.003	0.008

Supplementary table 37: Alternative overseas transportation assumptions; environmental impact (midpoint categories) per use of single-use laparoscopic clip applier, scissors, and ports

Here, shipping was assumed to be used for overseas transportation. Environmental impacts (midpoint categories) measured using life cycle assessment and modelled on one use of one laparoscopic clip applier, one laparoscopic scissors, two 5 mm ports, and two 10 mm – 11 mm ports (number required to perform a single laparoscopic cholecystectomy), comparing hybrid with single-use equivalents. 1,4-DCB =dichlorobenzene, CFC11= Trichlorofluoromethane, CO_2e= carbon dioxide equivalents, Cu= copper, eq= equivalents, Bq Co-60 eq = becquerel Cobalt-60, m^2a = square metre years, N= nitrogen, NO_x= nitrous oxides, P=phosphate, PM2.5 = particulate matter <2.5 micrometres, SO_2= sulphur dioxide

Impact category	**Unit**	**Single-use laparoscopic clip applier**	**Single-use laparoscopic scissors**	**Single-use ports**
Global warming	g CO_2e	1,727	837	2,728
Stratospheric ozone depletion	g CFC11 eq	0.0006	0.0004	0.0011
Ionizing radiation	Bq Co-60 eq	72	22	52
Ozone formation, Human health	g NO_x eq	4.28	1.88	4.91
Fine particulate matter formation	g PM2.5 eq	3.39	1.69	2.96
Ozone formation, Terrestrial ecosystems	g NO_x eq	4.39	1.93	5.07
Terrestrial acidification	g SO_2 eq	6.41	3.81	7.24
Freshwater eutrophication	g P eq	0.61	0.25	0.42
Marine eutrophication	g N eq	0.06	0.05	0.07
Terrestrial ecotoxicity	g 1,4-DCB	19,061	8,342	2,622
Freshwater ecotoxicity	g 1,4-DCB	174	90	37
Marine ecotoxicity	g 1,4-DCB	227	116	49
Human carcinogenic toxicity	g 1,4-DCB	201	90	115
Human non-carcinogenic toxicity	g 1,4-DCB	2,717	1,319	843
Land use	m^2a crop eq	0.16	0.02	0.02
Mineral resource scarcity	g Cu eq	38.78	18.96	3.46
Fossil resource scarcity	g oil eq	514	216	689
Water consumption	m^3	0.014	0.008	0.020

Supplementary table 38: Alternative port set up assumptions; environmental impact (midpoint categories) per use of hybrid versus single-use ports

Hybrid model based upon one use of three 5 mm ports, one 10 mm port; single-use model based upon three 5 mm ports, and one 11 mm port. 1,4-DCB =dichlorobenzene, CFC11= Trichlorofluoromethane, CO_2e= carbon dioxide equivalents, Cu= copper, eq= equivalents, Bq Co-60 eq = becquerel Cobalt-60, m^2a = square metre years, N= nitrogen, NO_x= nitrous oxides, P=phosphate, PM2.5 = particulate matter <2.5 micrometres, SO_2= sulphur dioxide

Impact category	**Unit**	**Hybrid ports**	**Single-use ports**
Global warming	g CO_2e	635	3,613
Stratospheric ozone depletion	g CFC11 eq	0.0003	0.0013
Ionizing radiation	Bq Co-60 eq	65	60
Ozone formation, Human health	g NO_x eq	0.97	8.41
Fine particulate matter formation	g PM2.5 eq	0.59	3.58
Ozone formation, Terrestrial ecosystems	g NO_x eq	0.99	8.60
Terrestrial acidification	g SO_2 eq	1.39	9.13
Freshwater eutrophication	g P eq	0.12	0.45
Marine eutrophication	g N eq	0.10	0.08
Terrestrial ecotoxicity	g 1,4-DCB	900	3,997
Freshwater ecotoxicity	g 1,4-DCB	13	39
Marine ecotoxicity	g 1,4-DCB	17	53
Human carcinogenic toxicity	g 1,4-DCB	29	125
Human non-carcinogenic toxicity	g 1,4-DCB	289	1,032
Land use	m^2a crop eq	0.02	0.03
Mineral resource scarcity	g Cu eq	2	3
Fossil resource scarcity	g oil eq	186	970
Water consumption	m^3	0.0060	0.0220

Supplementary table 39: Emission factors for carbon footprint of decontamination and packaging of reusable surgical instruments

*Polypropylene oriented film chosen as closest fit within ICE database for non-woven polypropylene (SimaPro(114) estimate for non-woven polypropylene=3 kg CO_2e per kg), CO_2e= carbon dioxide equivalents, DEFRA/BEIS= Department for Environment, Food and Rural Affairs/ Department for Business, Energy & Industrial Strategy, ICE=Inventory of Carbon and Energy, v=version.

Process/ product		**Emission factor**		**Emission factor unit**	**Source**
		Component	**Total**		
Aluminium		6.72	6.72	kg CO_2e per kg	ICE version 3(32)
Domestic/ non-infectious offensive hospital waste (low temperature incineration with energy from waste		171.78	171.78	kg CO_2e per t	Rizan et al(8)
Clinical waste		1074.13	1074.13		
General polyethylene		2.54	2.54	kg CO_2e per kg	ICE version 3(32)
General plastic		3.31	3.31	kg CO_2e per kg	ICE version 3(32)
High density polyethylene (HDPE) resin		1.93	1.93	kg CO_2e per kg	ICE version 3(32)
Manufacture of soap and detergent		0.17	0.17	£	Small World Consulting(117)
UK natural gas	Combustion	2.03	2.29	kg CO_2e per m^3	DEFRA /BEIS(116)
	Well to tank	0.26			
Alternative natural gas well to tank (combustion as above)	European	0.40		kg CO_2e per m^3	Ecoinvent version 3.6(114)
	Global average	0.42			
	US	0.51			
Paper		1.49	1.49	kg CO_2e per kg	ICE version 3(32)
Polypropylene oriented film*		3.43	3.43	kg CO_2e per kg	ICE version 3(32)
Stainless steel		6.145	6.145	kg CO_2e per kg	Small World Consulting(117)
UK electricity	Generation	0.26	0.32	kg CO_2e per kWh	DEFRA/ BEIS[4]
	Transmission and distribution	0.02			
	Generation well to tank	0.04			
	Transmission and distribution well to tank	0.003			
Alternative electricity	Australian		0.99	kg CO_2e per kWh	Ecoinvent version 3.6(114)
	European		0.42		
	Global average		0.73		
	Icelandic		0.06		
	US		0.57		
Water	Supply	0.34	1.05	kg CO_2e per m^3	DEFRA/ BEIS(116)
	Treatment	0.71			
Transportation	Heavy goods vehicle (diesel, average laden)	0.11	0.14	kg CO_2e per t.km	DEFRA/ BEIS(116)
	Well to tank	0.02			

Supplementary table 40: Emission factors used within example studies examining carbon footprint of healthcare waste
*/** used to distinguish between sources where studies used >1 source. CO_2e= carbon dioxide equivalents, DEFRA/BEIS= Department for Environment, Food and Rural Affairs (DEFRA) and Department for Business, Energy and Industrial Strategy (BEIS), EfW= energy from waste

Study	**Specified waste stream, emission factor where available (kg CO_2e per t waste)**						**Data sources for estimates**
	Autoclave decontamination	**EfW**	**Incineration**	**Landfill**	**Recycling**	**Other**	
Berner et al.(26)				Everything (199)			DEFRA/BEIS
Chen et al.(190)			Clinical waste (1,800)	Metal (10), plastics (40)	Cardboard/paper (-713), film plastics film (-1,000), dense plastics (-1,500)		DEFRA/BEIS
Connor et al.(191)			Clinical waste (1,800)	Cardboard/paper (550), glass/metal (10), other (91), plastics (40), organic waste: food (231), non-food (230)	Cardboard/paper (-713), glass (-315), metal (-9,000), other (-259), plastics (-1,500)		DEFRA/BEIS
Davis et al.(96)						Solid waste disposal (1,000)	Online reports on disposal of plastic bags, steel and laptops, and publication on rubber production
Duane et al.(193)			Clinical waste (1,800)*			Mercury (3,800)**	*Connor et al.(191), **US government source
Lim et al.(192)			Clinical waste (1,800)*	General waste (1,100)**	Cardboard/paper (-630), plastics (-1,590)**		*Connor et al.(191), **Australian government sources
MacNeill et al.(28)	Biomedical waste, sharps*	Municipal solid waste	Cytotoxic waste (1,833) **	Biomedical waste, sharps	Cardboard (-240); plastic (-282);		*Original data **DEFRA/BEIS

		(1179) **		**	polypropylene (12)**		
McPherson et al.(194)	Biological sharps (125.2)	Chemotherapeutic /pharmacological sharps (1,443)					US government sources, waste company
Morris et al.(27)			Clinical waste (1,833)	Domestic waste: paper (580); plastic (34)			DEFRA/BEIS
Power et al.(131)			Biomedical waste (6,000)				Online sources
Woods et al.(30)				Municipal solid waste (1,000)			Online sources

Supplementary table 41: Emission factors for carbon footprint of healthcare waste Note some emission factors quoted in sources as CO_2e (carbon dioxide equivalents), others as CO_2 (carbon dioxide) depending on emission factor source. DEFRA/BEIS= Department for Environment, Food and Rural Affairs (DEFRA) and Department for Business, Energy and Industrial Strategy (BEIS), HGV= heavy goods vehicle

Process/ product		Emission factor		Emission factor unit	Source
		Component	Total		
Batteries recycling		64.64	64.64	kg CO_2e per t	DEFRA/BEIS(116)
Clothing recycling		21.35	21.35	kg CO_2e per t	DEFRA/BEIS(116)
Gas oil (kg)	Combustion	3.230	3.97	kg CO_2e per kg	DEFRA/BEIS(116)
	Well to tank	0.741			
Gas oil (L)	Combustion	2.758	3.39	kg CO_2e per L	DEFRA/BEIS(116)
	Well to tank	0.633			
HGV rigid 3.5-7.5 t diesel, average laden	Combustion	0.792	0.982	kg CO_2e per mile	DEFRA/BEIS(116)
	Well to tank	0.190			
HGV rigid 7.5-17 t diesel, average laden	Combustion	0.967	1.199	kg CO_2e per mile	DEFRA/BEIS(116)
	Well to tank	0.232			
HGV rigid >17 t diesel, average laden	Combustion	1.538	1.907	kg CO_2e per mile	DEFRA/BEIS(116)
	Well to tank	0.369			
Scrap metal recycling		21.35	21.35	kg CO_2e per t	DEFRA/BEIS(116)
Slag-European ferous metals		1.49	1.49	kg CO_2 per kg	GHG Protocol waste(118)
Thermal treatment-hospital waste		880	880	kg CO_2 per t	GHG Protocol waste(118)
Thermal treatment-household waste		332	332	kg CO_2 per t	GHG Protocol waste(118)
UK electricity	Generation	0.256	0.32	kg CO_2e per kWh	DEFRA/BEIS(116)
	Transmission and distribution	0.022			
	Generation well to tank	0.036			
	Transmission and distribution well to tank	0.003			
Water	Supply	0.343	1.05	kg CO_2e per m^3	DEFRA/BEIS(116)
	Treatment	0.708			

Supplementary table 42: Life cycle inventory processes selected from SimaPro databases(114) for CHAPTER 8

Material	Process Name	Used for process/ product; comments
Cardboard	Corrugated board box {RoW}| market for corrugated board box | Cut-off, U	Reusable scissors packaging
High density polyethylene	Polyethylene, high density, granulate {GLO}| market for | Cut-off, U	Sterile barrier system for scissors decontamination
Low density polyethylene	Packaging film, low density polyethylene {GLO}| market for | Cut-off, U	Reusable scissors packaging, scissors repair (onsite and offsite)
Paper	Kraft paper, bleached {GLO}| market for | Cut-off, U	Sterile barrier system for scissors decontamination
Paraffin	Paraffin {GLO}| market for | Cut-off, U	Scissors repair (onsite and offsite); Oil spray for surgical instruments assumed to be paraffin
Polypropylene	Polypropylene, granulate {GLO}| market for | Cut-off, U	Sterile barrier system for scissors decontamination
Polystyrene	Polystyrene, general purpose {GLO}| market for | Cut-off, U	Reusable scissors packaging
Potassium hydroxide	Potassium hydroxide {GLO}| market for | Cut-off, U	Virudet Eco sterilisation detergent; detergent packaging indicates contains 5% potassium silicate- not available in Ecoinvent, potassium hydroxide used instead
Natural gas (German)	Natural gas, high pressure {DE}| market for | Cut-off, U	Manufacture of steel (German); high pressure is default option
Natural gas (UK)	Natural gas, high pressure {GB}| market for | Cut-off, U	Decontamination reusable scissors; high pressure is default option
Natural gas (for steam production)	Process steam from natural gas, heat plant, consumption mix, at plant, MJ GB S	Production of steam from natural gas; used European Life Cycle Database, as steam processing not available in Ecoinvent
Stainless steel (German)	Steel, chromium steel 18/8 {RER}| steel production, converter, chromium steel 18/8 | Cut-off, U	Reusable scissors manufacture, process copied and adapted for German manufacture (electricity, water, natural gas altered); Chromium steel 18/8 contains 18% chromium and 8% Nickel, so this process chosen as closest match- surgical instruments contain around 11.5-19% chromium, and 0.5-13.5% Nickel(237)
Stainless steel	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	Sterile barrier system for scissors decontamination

Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U			Virudet Eco sterilisation detergent; detergent packaging indicates contains 5% sodium hydroxide
Tissue paper	Tissue paper {GLO}| market for | Cut-off, U			Scissors repair (onsite and offsite)
Energy	**Process Name**			**Used for process/ product; comments**
Electricity (German)	Electricity, medium voltage {DE}| market for | Cut-off, U			Adapting manufacture stainless steel process (German); medium voltage chosen as is this is used for production industry
Electricity (UK)	Electricity, medium voltage {GB}| market for | Cut-off, U			Decontamination reusable scissors, scissors repair (onsite and offsite); as above
Transportation	**Process Name**			**Used for process/ product; comments**
Courier (Europe)	Transport, freight, light commercial vehicle {RER}| market group for transport, freight, light commercial vehicle | Cut-off, U			Transport via courier within Europe, across scenarios
Flight (short haul)	Transport, freight, aircraft, short haul {GLO}| market for transport, freight, aircraft, short haul | Cut-off, U			Transport via flight from Germany to UK
Heavy goods vehicle (Europe)	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U			Transport via heavy goods vehicle within Europe, across scenarios
Train	Transport, freight train {RER}| market group for transport, freight train | Cut-off, U			Transport via train reusable scissors within Germany
Water	**Process Name**			**Used for process/ product; comments**
Tap water (German, UK)	Tap water {RER}| market group for | Cut-off, U			Adapting manufacture stainless steel process (German), decontamination reusable scissors (UK)
Wastewater (German, UK)	Wastewater, average {Europe without Switzerland}| market for wastewater, average | Cut-off, U			Adapting manufacture stainless steel process (German), decontamination reusable scissors (UK)
Processing	**Process 1 Name**	**Process 2 Name (Subprocesses of process 1)**	**Process 3 Name (Subprocesses of process 2)**	**Used for process/ product; comments**
Manufacture stainless steel (German)	Metal working, average for chromium steel product manufacturing {RER}| processing | Cut-off, U	Energy and auxiliary inputs, metal working factory {RER}| market for energy and auxiliary inputs, metal working factory | Cut-off, U	Energy and auxiliary inputs, metal working factory {RER}| with heating from hard coal | Cut-off, U Energy and auxiliary inputs, metal working factory {RER}| with heating from heavy fuel oil | Cut-off, U	Manufacture reusable scissors; adapted for German manufacture through changing electricity source to German supply

			Energy and auxiliary inputs, metal working factory {RER}| with heating from light fuel oil | Cut-off, U	
			Energy and auxiliary inputs, metal working factory {RER}| with heating from natural gas | Cut-off, U	
		Energy and auxiliary inputs, metal working machine {RER}| market for energy and auxiliary inputs, metal working machine | Cut-off, U	Energy and auxiliary inputs, metal working machine {RER}| with process heat from hard coal | Cut-off, U	
			Energy and auxiliary inputs, metal working machine {RER}| with process heat from heavy fuel oil | Cut-off, U	
			Energy and auxiliary inputs, metal working machine {RER}| with process heat from light fuel oil | Cut-off, U	
			Energy and auxiliary inputs, metal working machine {RER}| with process heat from natural gas | Cut-off, U	
		Metal working factory {RER}| construction | Cut-off, U		
		Metal working machine, unspecified {RER}| market for metal working machine, unspecified | Cut-off, U		
		Steel, chromium steel 18/8, hot rolled {GLO}| market for | Cut-off, U		Steel 'wasted' within the manufacturing process

Supplementary table 43: Parameters for sterilisation of reusable surgical scissors
Data based on material and energy flows from CHAPTER 6. The mean weight of instruments across three typical sets used for common operations (tonsillectomy set, minor op set used for carpal tunnel decompression, and basic major orthopaedic set) was 66.7 g. The mean number of instruments per set across sets was 29 (determined using a retrospective audit of instrument decontaminations over one year at RSCH 1/7/18-30/6/19). A typical surgical set was therefore assumed to contain 2 kg instruments, allowing the energy and material inputs to be determined.

Process	**Sub-process**	**Input**	**Amount (per kg of surgical instruments decontaminated)**
Sterile barrier system	Basket	Stainless steel	4.54 g
	Inner wrap	Polypropylene	27.98 g
	Identification tag	High Density Polyethylene	0.09 g
	Outer wrap	Paper	38.39 g
	Label and tape		
	Kit list		
Decontamination (washing and disinfection)	Detergent	Sodium hydroxide in 50% solution state	0.93 g
		Potassium hydroxide	0.46 g
	Electricity	Electricity (UK)	0.63 kWh
	Fuel	Natural gas (UK)	0.15 m^3 =5.76MJ =1.60kWh
	Water	Tap water (UK)	38.1 kg
		Wastewater (UK)	

Supplementary table 44: Alternative waste scenarios

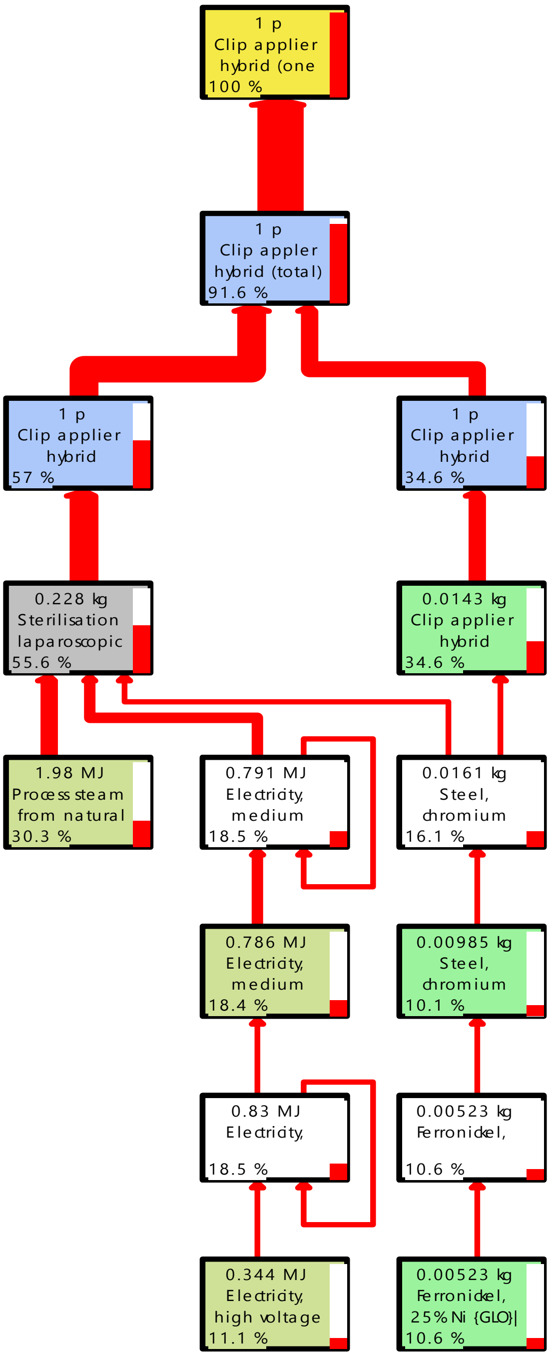
Ecoinvent (version 3.6)- allocation, cut-off by classification- unit library was selected for all processes.(114) 'Waste types' as defined in Ecoinvent (version 3.6)- allocation, cut-off by classification- unit. GLO= global, PE= polyethylene, PET= polyethylene terephthalate, PP= polypropylene, PS= polystyrene.

Waste Scenario	Process Name	Waste type applied to
Hazardous incineration	Hazardous waste, for incineration {Europe without Switzerland}| treatment of hazardous waste, hazardous waste incineration | Cut-off, U	All waste types + waste streams remaining after separation (100%)
Recycling	Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, U	Non-ferro (100%)
	Core board (waste treatment) {GLO}| recycling of core board | Cut-off, U	Cardboard (100%)
	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Cut-off, U	Waste streams remaining after separation (100%)
	Paper (waste treatment) {GLO}| recycling of paper | Cut-off, U	Paper (100%)
	PE (waste treatment) {GLO}| recycling of PE | Cut-off, U	PE (100%)
	PET (waste treatment) {GLO}| recycling of PET | Cut-off, U	PET (100%)
	PP (waste treatment) {GLO}| recycling of PP | Cut-off, U	PP (100%)
	PS (waste treatment) {GLO}| recycling of PS | Cut-off, U	PS (100%)
	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	Steel (100%)
Segregation (landfill)	Core board (waste treatment) {GLO}| recycling of core board | Cut-off, U	Cardboard (100%)
	Hazardous waste, for incineration {Europe without Switzerland}| treatment of hazardous waste, hazardous waste incineration | Cut-off, U	Steel (100%)
	Inert waste {Europe without Switzerland}| treatment of inert waste, sanitary landfill | Cut-off, U	PE (100%), PET (100%), PP (100%), PS (100%), Non-ferro (100%), Waste streams remaining after separation (100%)
	Paper (waste treatment) {GLO}| recycling of paper | Cut-off, U	Paper (100%)
Segregation (municipal incineration)	Core board (waste treatment) {GLO}| recycling of core board | Cut-off, U	Cardboard (100%)
	Hazardous waste, for incineration {Europe without Switzerland}| treatment of hazardous waste, hazardous waste incineration | Cut-off, U	Steel (100%)
	Municipal solid waste {GB}| treatment of incineration | Cut-off, U	PE (100%), PET (100%), PP (100%), PS (100%), Non-ferro (100%), Waste streams remaining after separation (100%)
	Paper (waste treatment) {GLO}| recycling of paper | Cut-off, U	Paper (100%)

Supplementary figures

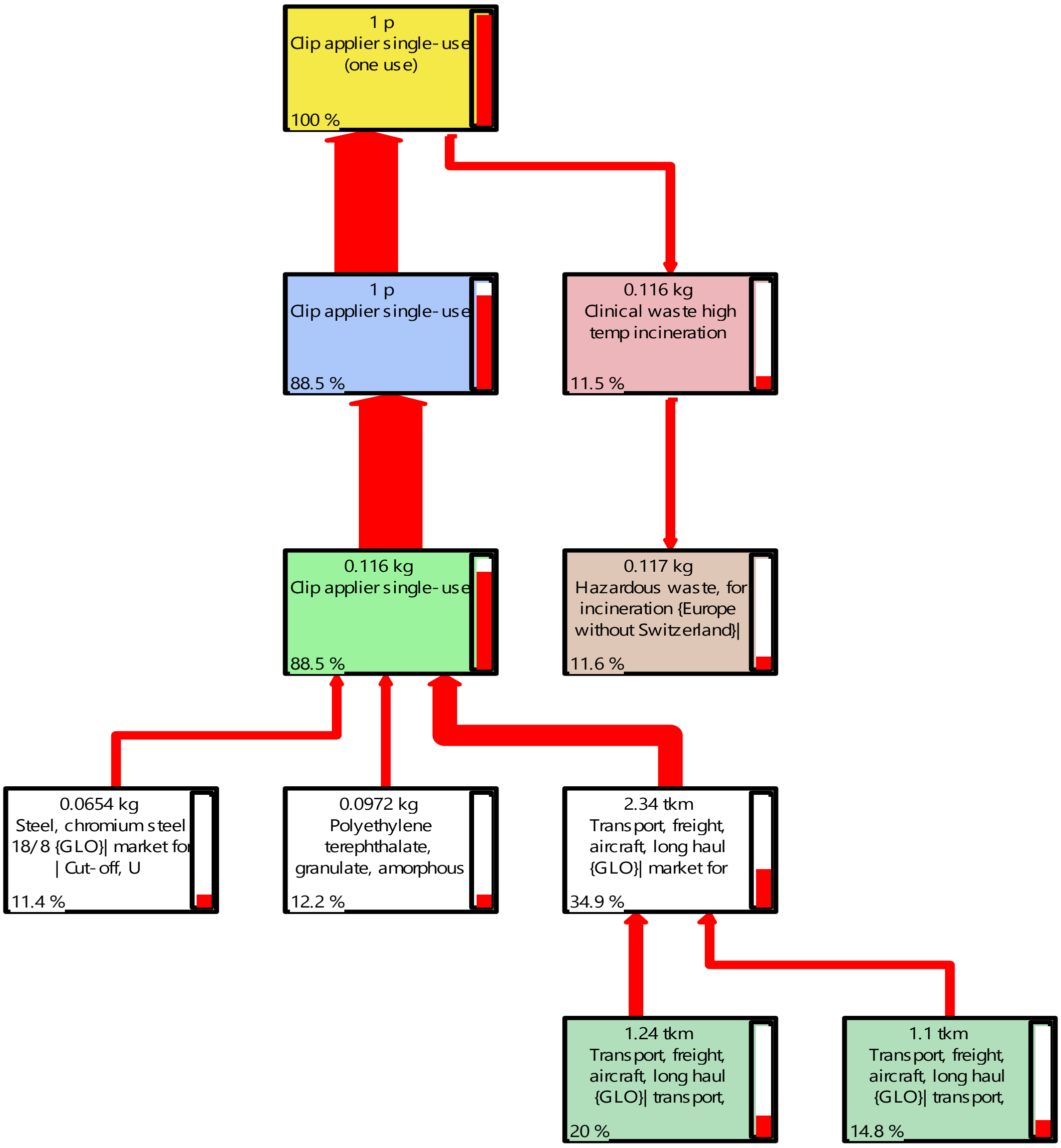
Supplementary figure 1: Network diagram for hybrid laparoscopic clip applier, showing global warming impact drivers (10% cut-off)

Network diagram for LCA of quantity of hybrid laparoscopic clip applier required for a single laparoscopic cholecystectomy (i.e. 1/500 reusable laparoscopic clip applier, one single-use cartridge), showing drivers for the global warming impact category. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.

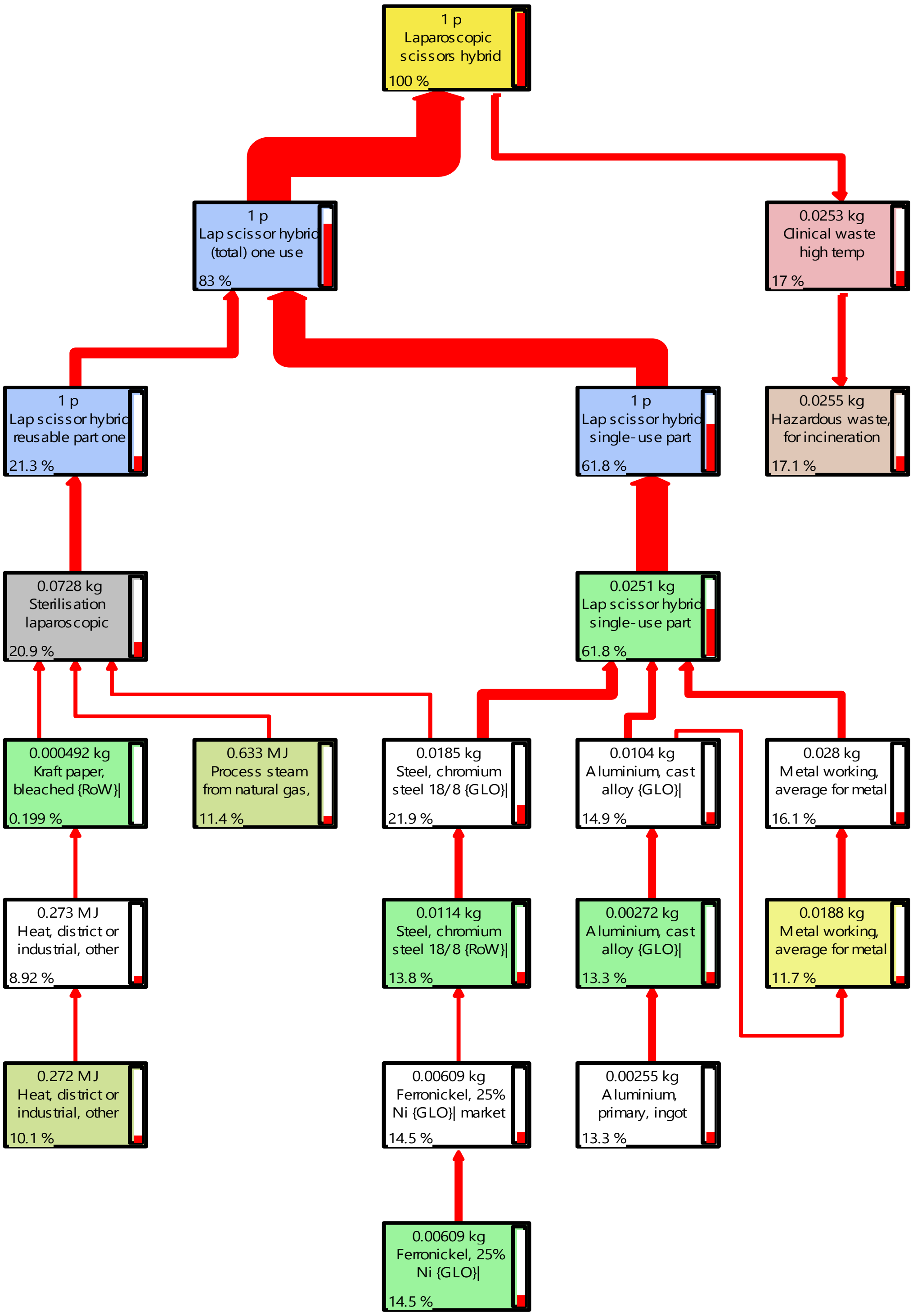


Supplementary figure 2: Network diagram for single-use laparoscopic clip applier, showing global warming impact drivers (10% cut-off)

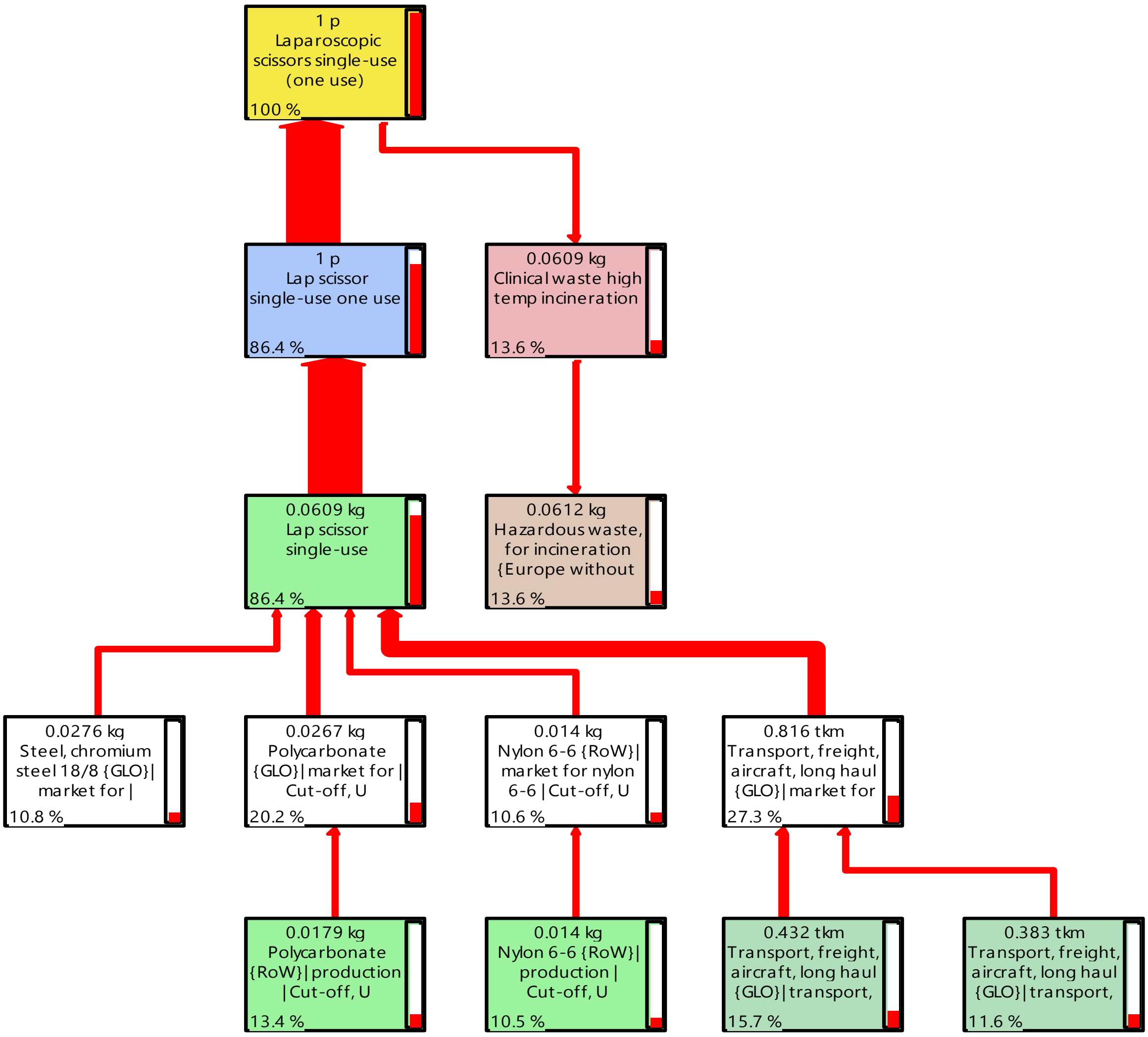
Network diagram for LCA of quantity of single-use laparoscopic clip applier required for a single laparoscopic cholecystectomy (i.e. one single-use laparoscopic clip applier and one single-use cartridge), showing drivers for the global warming impact category. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



Supplementary figure 3: Network diagram for hybrid laparoscopic scissors, showing global warming impact drivers (10% cut-off)
Network diagram for LCA of quantity of hybrid laparoscopic scissors required for a single laparoscopic cholecystectomy (i.e. 1/500 reusable handle, one single-use scissors shaft and blades), showing drivers for the global warming impact category. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.

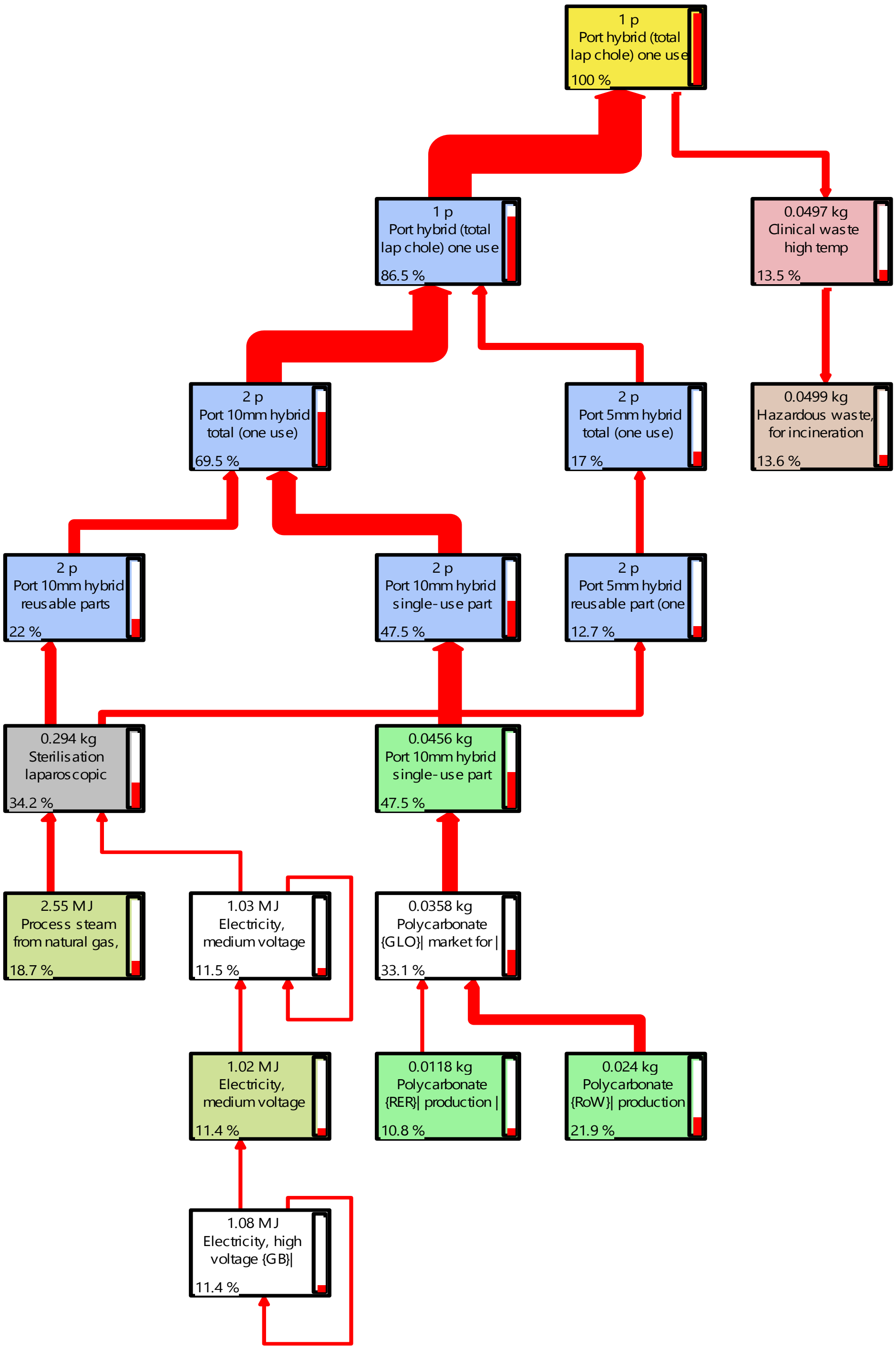


Supplementary figure 4: Network diagram for single-use laparoscopic scissors, showing global warming impact drivers (10% cut-off)
Network diagram for LCA of quantity of single-use laparoscopic scissors required for a single laparoscopic cholecystectomy (i.e. one single-use laparoscopic scissor), showing drivers for the global warming impact category. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



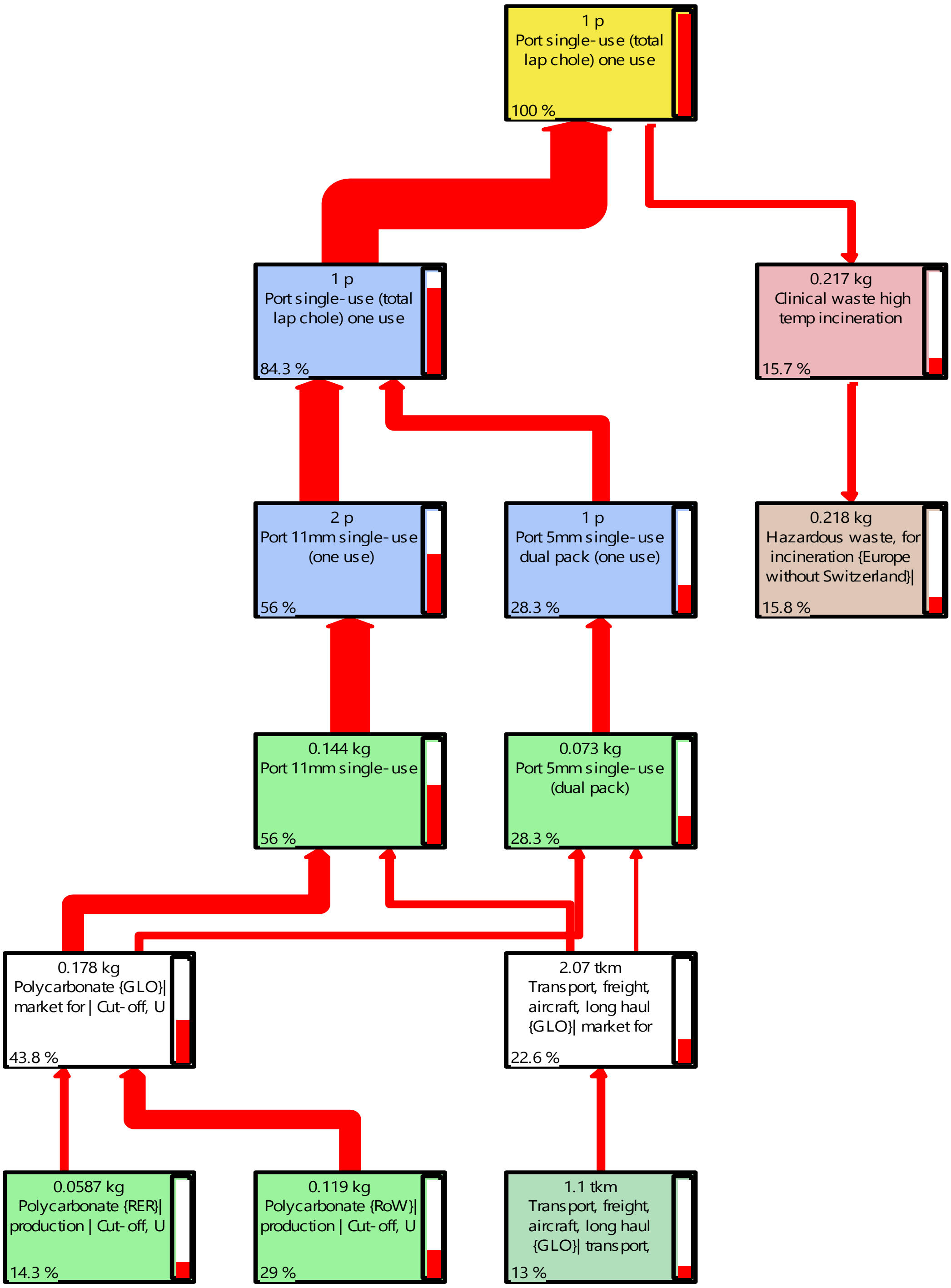
Supplementary figure 5: Network diagram for hybrid ports, showing global warming impact drivers (10% cut-off)

Network diagram for LCA of quantity of hybrid laparoscopic ports required for a single laparoscopic cholecystectomy (i.e. two times 1/500 5 mm and 10 mm cannulas, two times 1/500 5 mm and 10 mm trocars, one single-use 5 mm duckbill valve, one single-use 5-12 mm universal seal), showing drivers for the global warming impact category. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



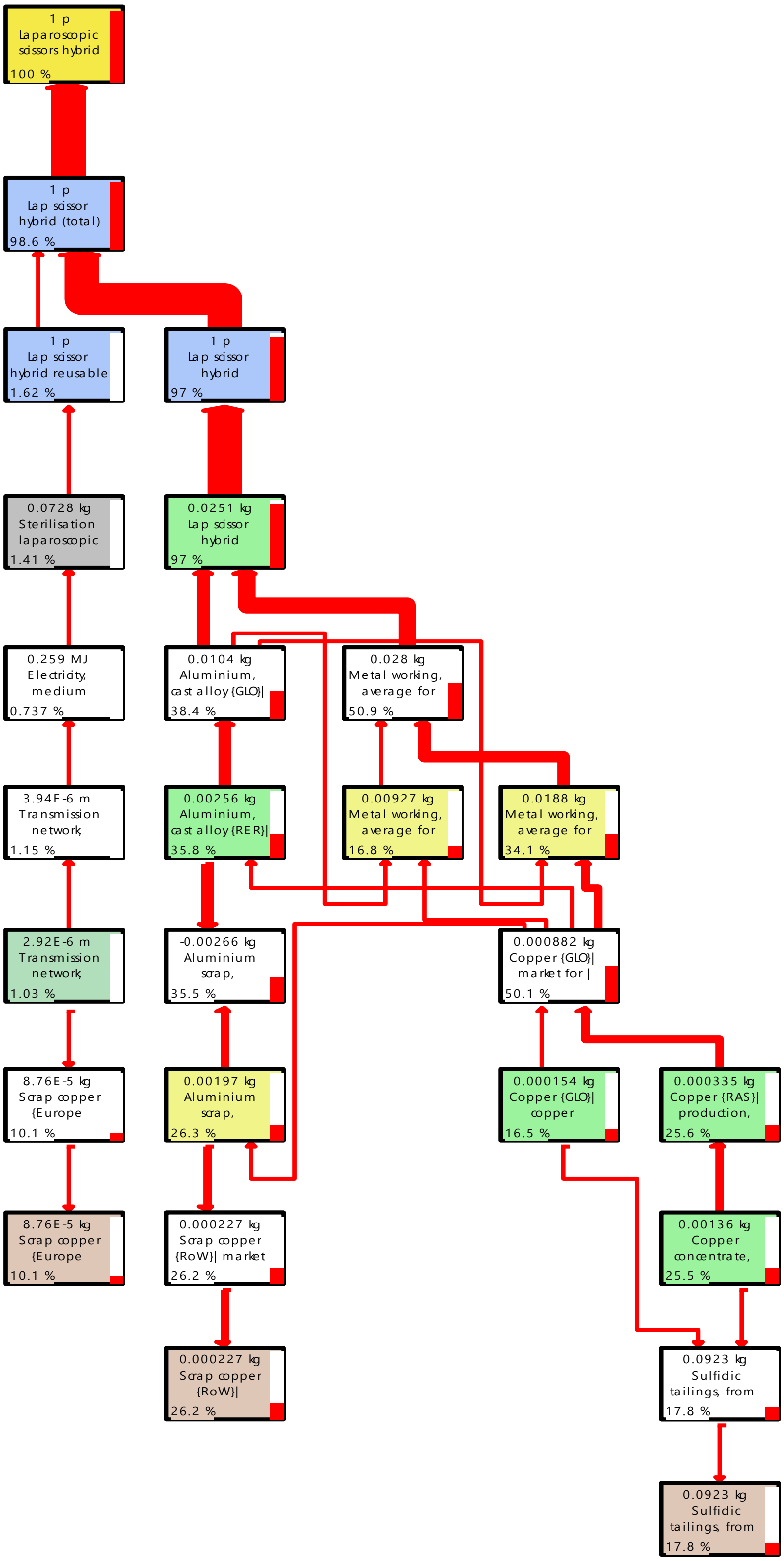
Supplementary figure 6: Network diagram for single-use ports, showing global warming impact drivers (10% cut-off)

Network diagram for LCA of quantity of single-use ports required for a single laparoscopic cholecystectomy (i.e. one single-use 5 mm dual pack port, two single-use 11 mm port), showing drivers for the global warming impact category. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



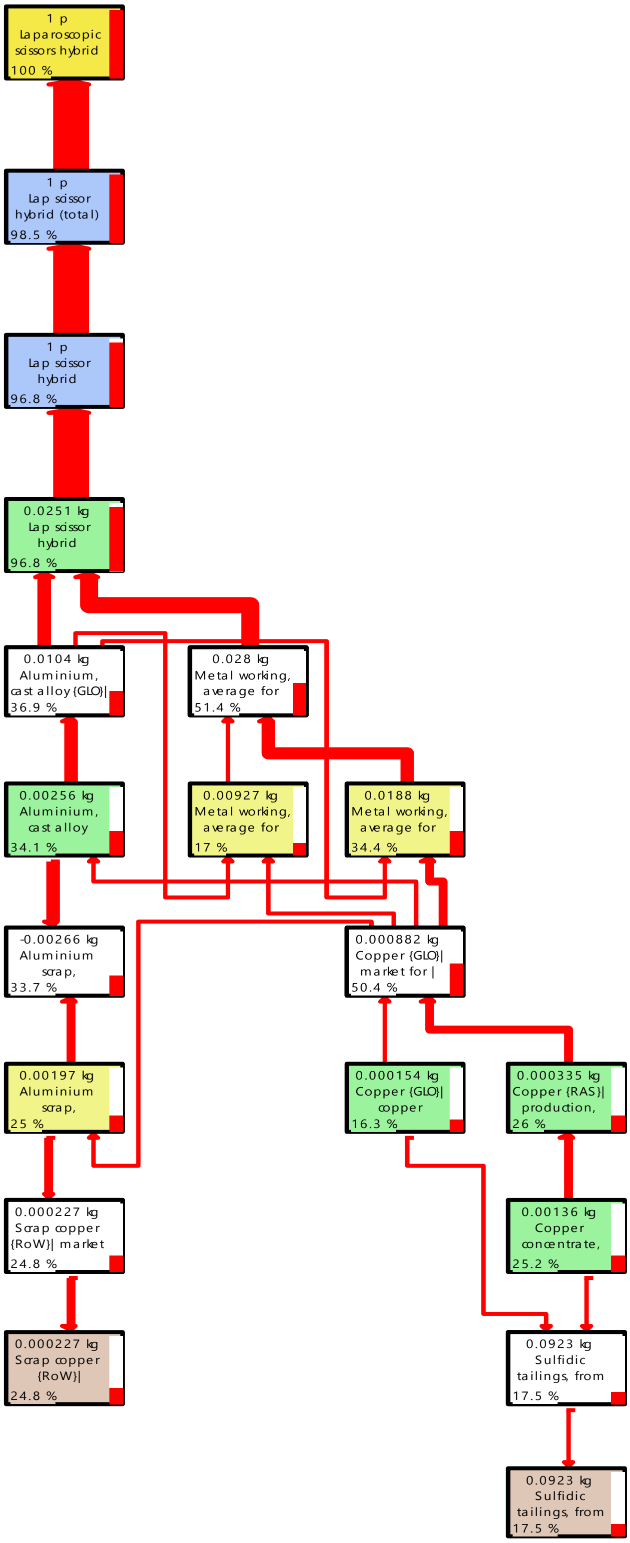
Supplementary figure 7: Network diagram for laparoscopic scissors, showing freshwater ecotoxicity impact drivers (10% cut-off)

Network diagram for LCA of quantity of hybrid laparoscopic scissors required for a single laparoscopic cholecystectomy (i.e. 1/500 reusable handle, one single-use scissors shaft and blades), showing drivers for the freshwater ecotoxicity category. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



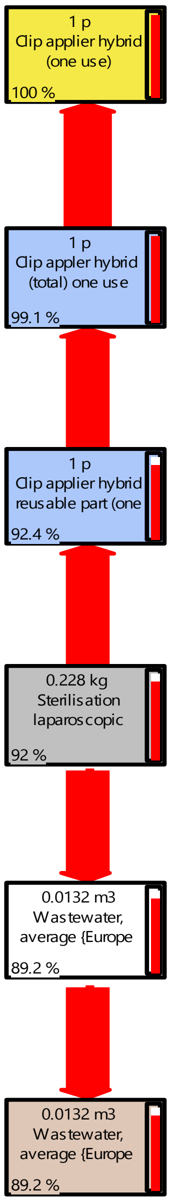
Supplementary figure 8: Network diagram for laparoscopic scissors, showing marine ecotoxicity impact drivers (10% cut-off)

Network diagram for LCA of quantity of hybrid laparoscopic scissors required for a single laparoscopic cholecystectomy (i.e. 1/500 reusable handle, one single-use scissors shaft and blades), showing drivers for the marine ecotoxicity category. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



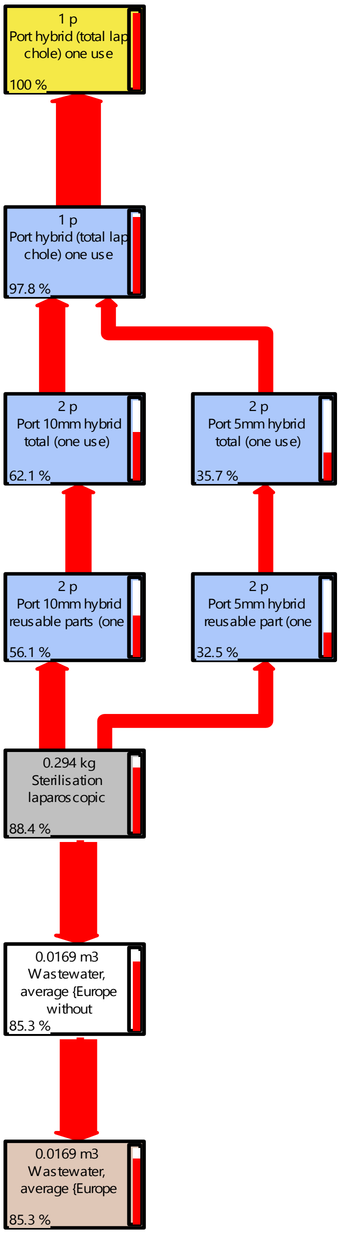
Supplementary figure 9: Network diagram for laparoscopic clip applier, showing marine eutrophication impact drivers (10% cut-off)

Network diagram for LCA of quantity of hybrid laparoscopic clip applier required for a single laparoscopic cholecystectomy i.e. (1/500 reusable laparoscopic clip applier, one single-use cartridge, showing drivers for the marine eutrophication category. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



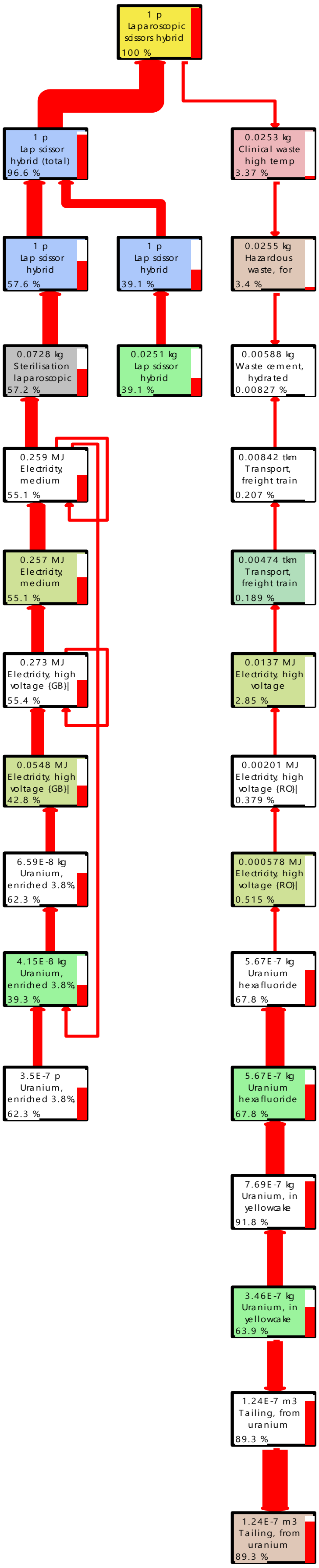
Supplementary figure 10: Network diagram for hybrid ports, showing marine eutrophication impact drivers (10% cut-off)

Network diagram for LCA of quantity of hybrid laparoscopic ports required for a single laparoscopic cholecystectomy (i.e. two times 1/500 5 mm and 10 mm cannulas, two times 1/500 5 mm and 10 mm trocars, one single-use 5 mm duckbill valve, one single-use 5 mm -12 mm universal seal), showing drivers for the marine eutrophication impact category. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



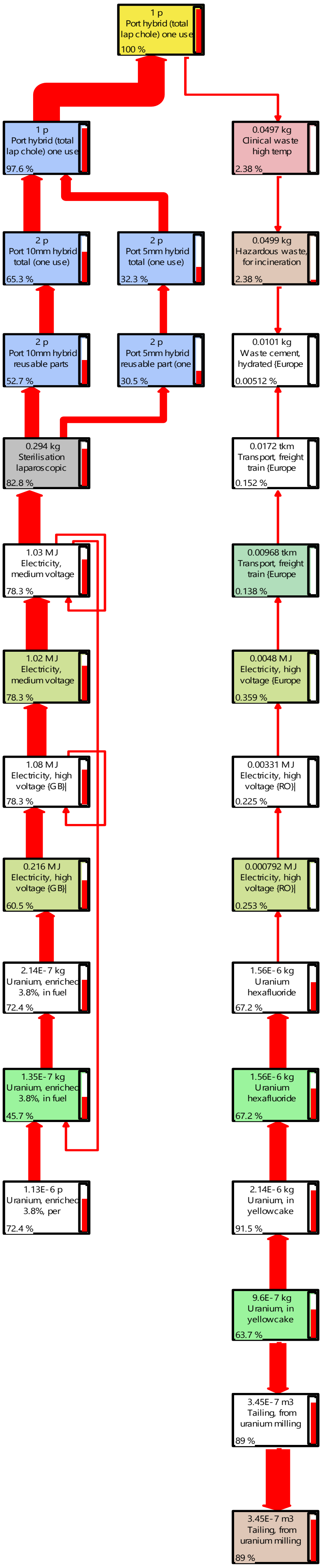
Supplementary figure 11: Network diagram for laparoscopic scissors, showing ionising radiation impact drivers (30% cut-off)

Network diagram for LCA of quantity of hybrid laparoscopic scissors required for a single laparoscopic cholecystectomy (i.e. 1/500 reusable handle, one single-use scissors shaft and blades), showing drivers for the ionising radiation category. Each box represents a unit process (only those >30% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



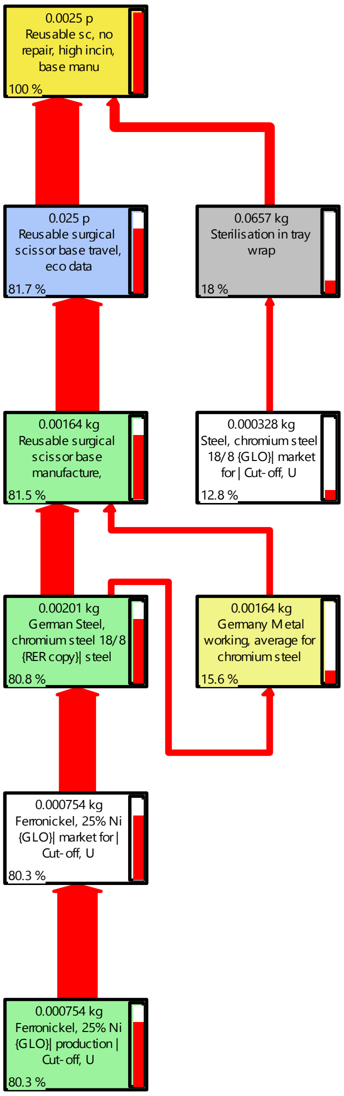
Supplementary figure 12: Network diagram for hybrid ports, showing ionising radiation impact drivers (30% cut-off)

Network diagram for LCA of quantity of hybrid laparoscopic ports required for a single laparoscopic cholecystectomy (i.e. two times 1/500 5 mm and 10 mm cannulas, two times 1/500 5 mm and 10 mm trocars, one single-use 5 mm duckbill valve, one single-use 5 mm - 12 mm universal seal), showing drivers for the marine eutrophication impact category. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.


1 p
Port hybrid (total lap chole) one use
100 %
1 p
Port hybrid (total lap chole) one use
97.6 %
0.0497 kg
Clinical waste high temp
2.38 %
2 p
Port 10mm hybrid total (one use)
65.3 %
2 p
Port 5mm hybrid total (one use)
32.3 %
0.0499 kg
Hazardous waste, for incineration
2.38 %
2 p
Port 10mm hybrid reusable parts
52.7 %
2 p
Port 5mm hybrid reusable part (one
30.5 %
0.0101 kg
Waste cement, hydrated {Europe
0.00512 %
0.294 kg
Sterilisation laparoscopic
82.8 %
0.0172 tkm
Transport, freight train {Europe
0.152 %
1.03 MJ
Electricity, medium voltage
78.3 %
0.00968 tkm
Transport, freight train {Europe
0.138 %
1.02 MJ
Electricity, medium voltage
78.3 %
0.0048 MJ
Electricity, high voltage {Europe
0.359 %
1.08 MJ
Electricity, high voltage {GB}|
78.3 %
0.00331 MJ
Electricity, high voltage {RO}|
0.225 %
0.216 MJ
Electricity, high voltage {GB}|
60.5 %
0.000792 MJ
Electricity, high voltage {RO}|
0.253 %
2.14E-7 kg
Uranium, enriched 3.8%, in fuel
72.4 %
1.56E-6 kg
Uranium hexafluoride
67.2 %
1.35E-7 kg
Uranium, enriched 3.8%, in fuel
45.7 %
1.56E-6 kg
Uranium hexafluoride
67.2 %
1.13E-6 p
Uranium, enriched 3.8%, per
72.4 %
2.14E-6 kg
Uranium, in yellowcake
91.5 %
9.6E-7 kg
Uranium, in yellowcake
63.7 %
3.45E-7 m3
Tailing, from uranium milling
89 %
3.45E-7 m3
Tailing, from uranium milling
89 %

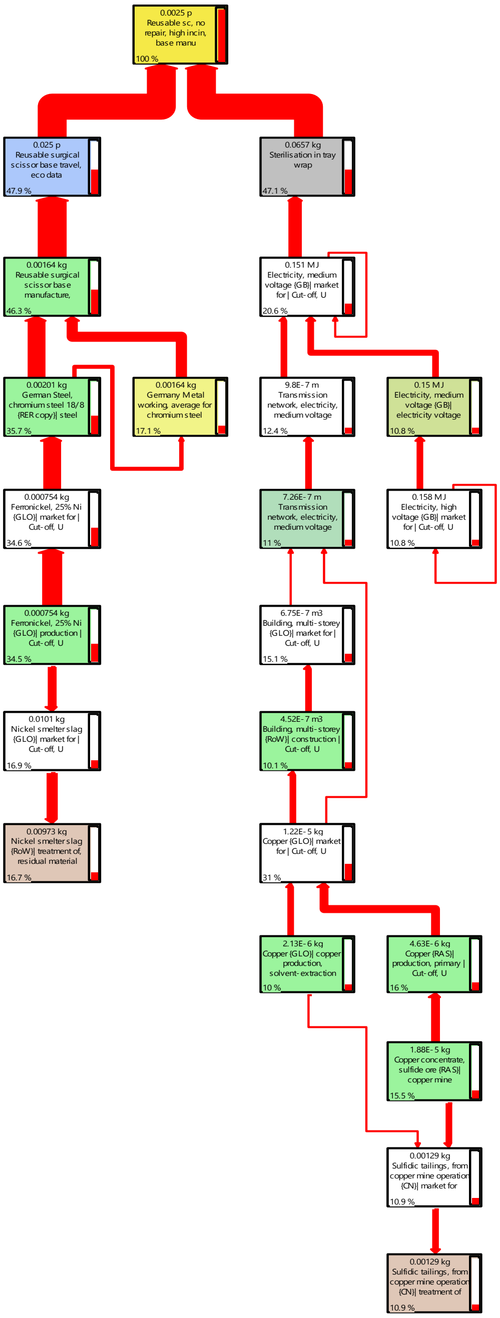
Supplementary figure 13: Network diagram for reusable scissors (no repair) showing mineral resource scarcity drivers (10% cut-off)

Modelled on one use of scissors. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



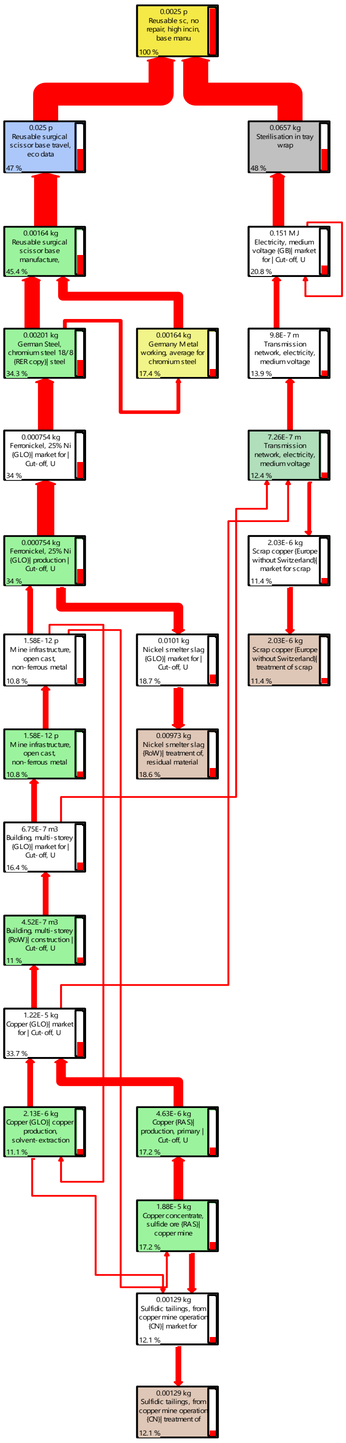
Supplementary figure 14: Network diagram for reusable scissors (no repair) showing marine ecotoxicity drivers (10% cut-off).

Modelled on one use of scissors. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



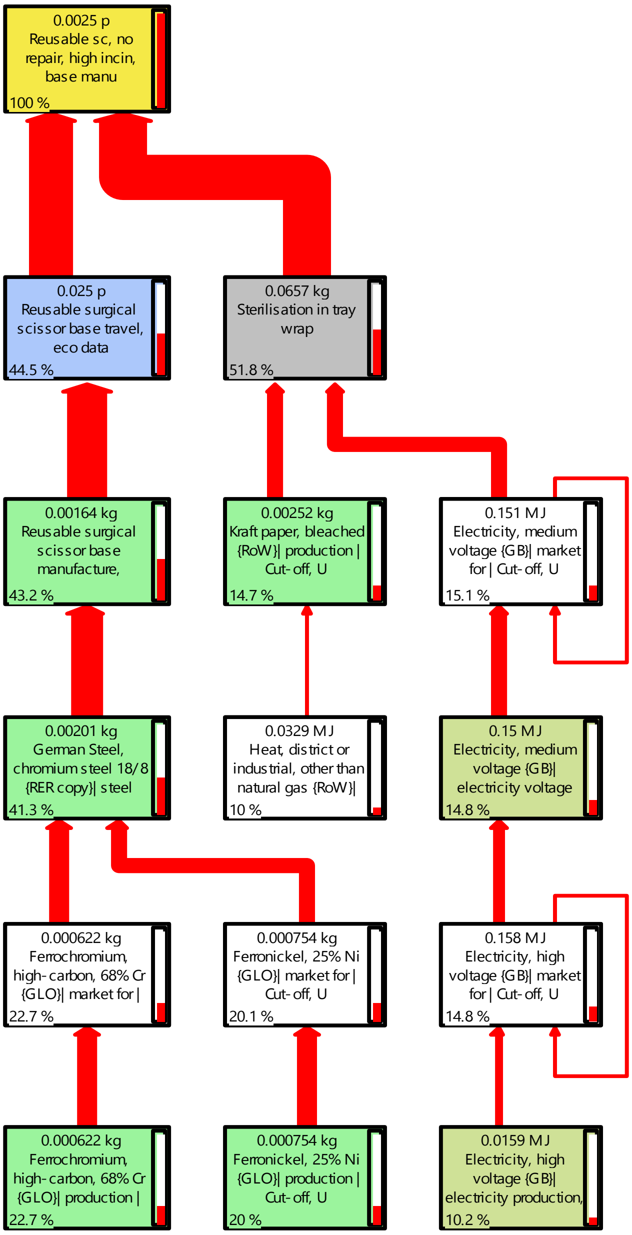
Supplementary figure 15: Network diagram for reusable scissors (no repair) showing freshwater ecotoxicity drivers (10% cut-off).

Modelled on one use of scissors. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



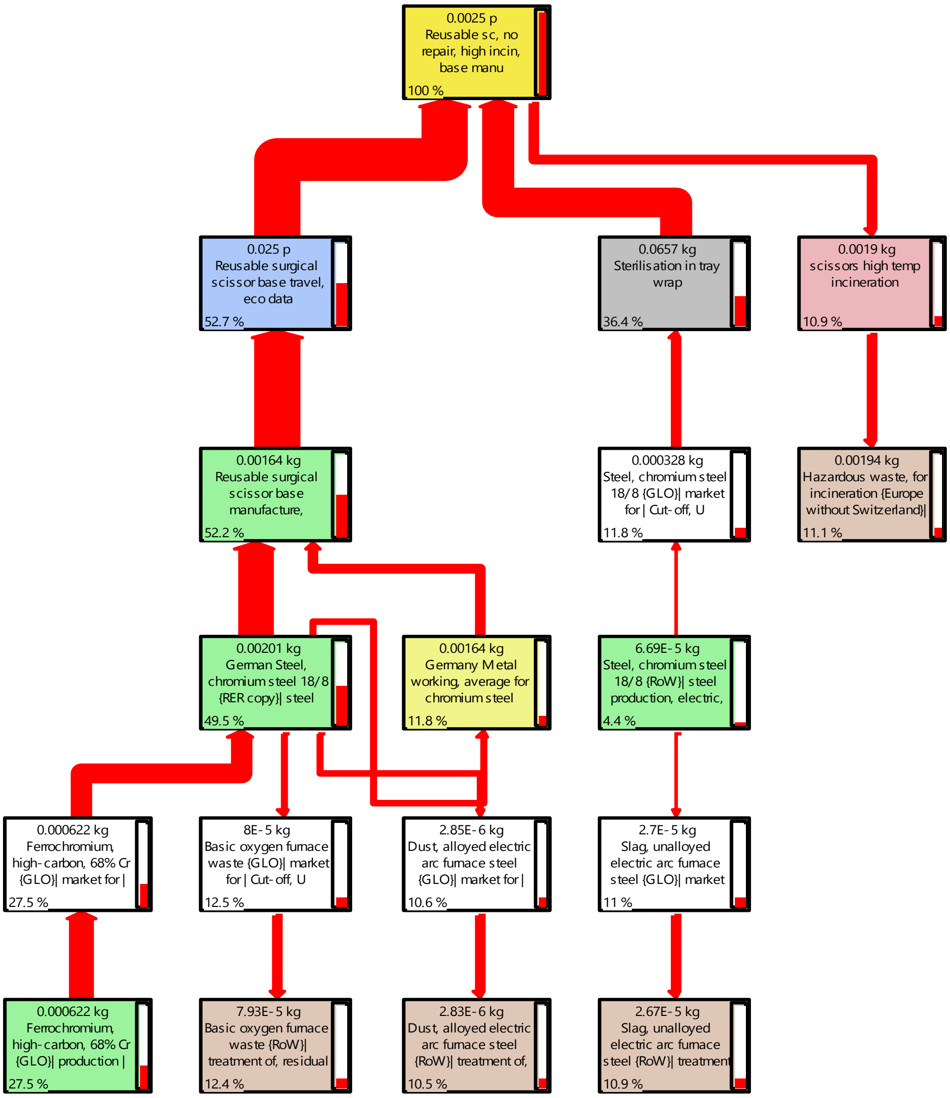
Supplementary figure 16: Network diagram for reusable scissors (no repair) showing fine particulate matter drivers (10% cut-off).

Modelled on one use of scissors. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.

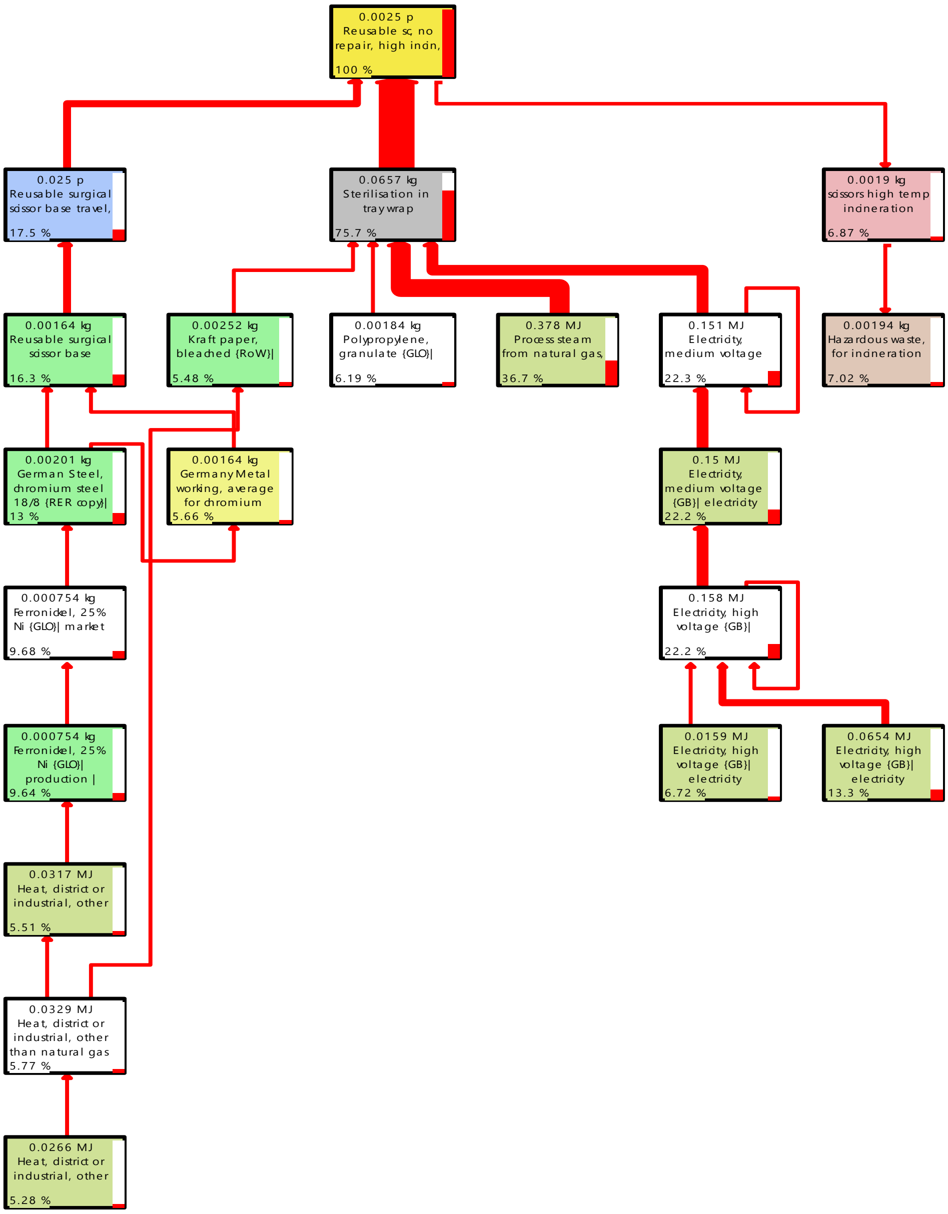


Supplementary figure 17: Network diagram for reusable scissors (no repair) showing human carcinogenic drivers (10% cut-off).

Modelled on one use of scissors. Each box represents a unit process (only those >10% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.

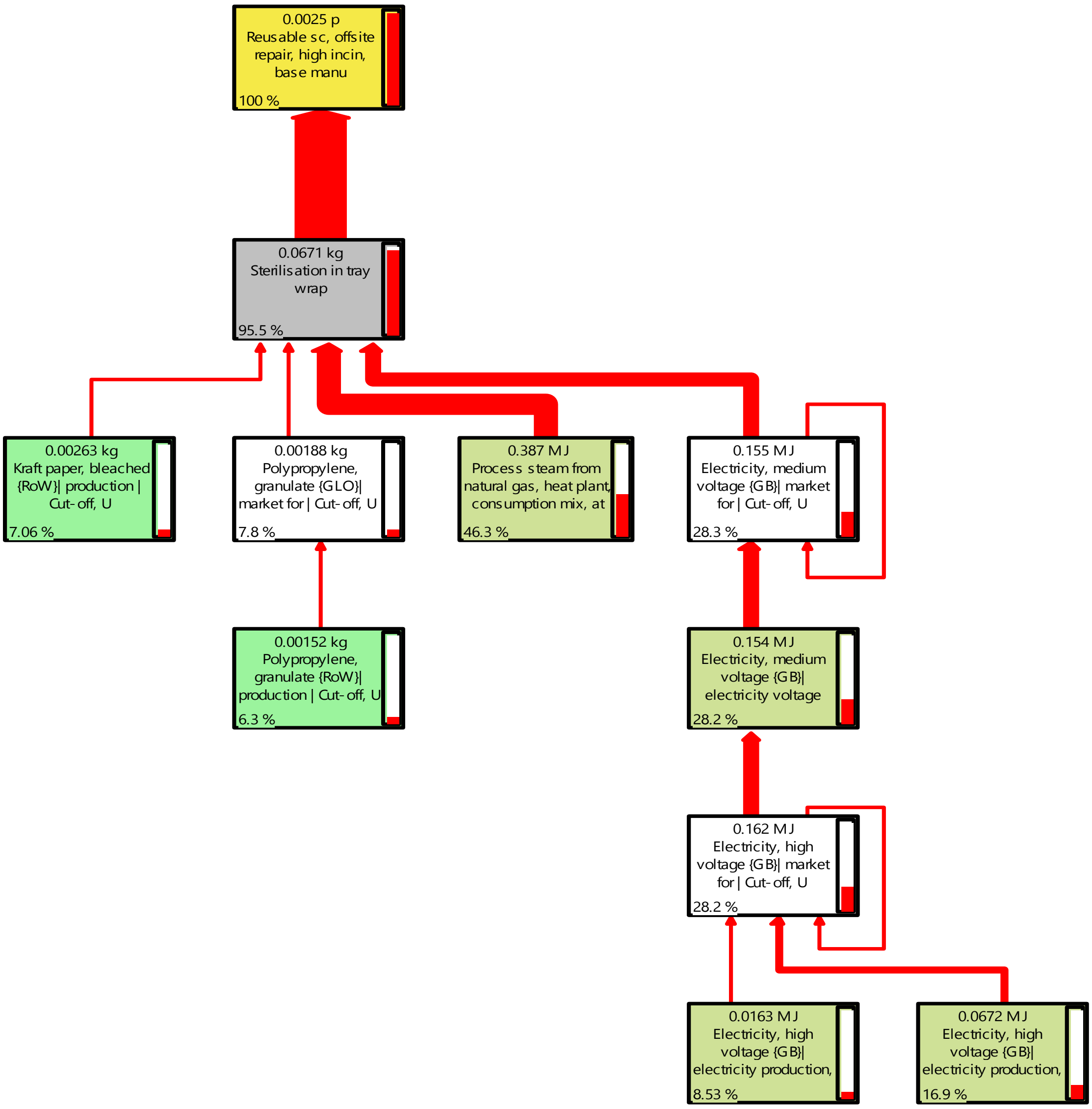


Supplementary figure 18: Network diagram for reusable scissors showing global warming impact drivers (5% cut-off).
Modelled on one use of scissors. Each box represents a unit process (only those >5% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.

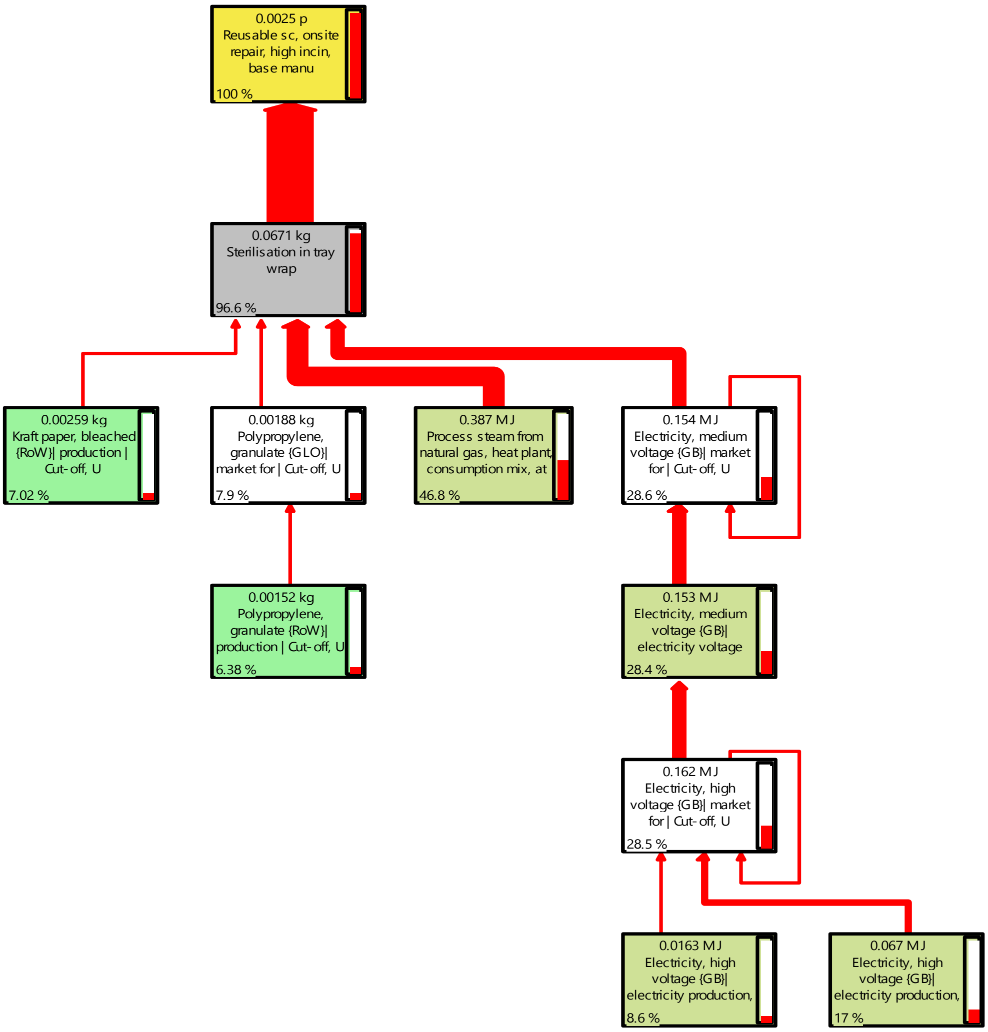


Supplementary figure 19: Network diagram for reusable scissors repaired offsite, showing global warming impact drivers (5% cut-off).

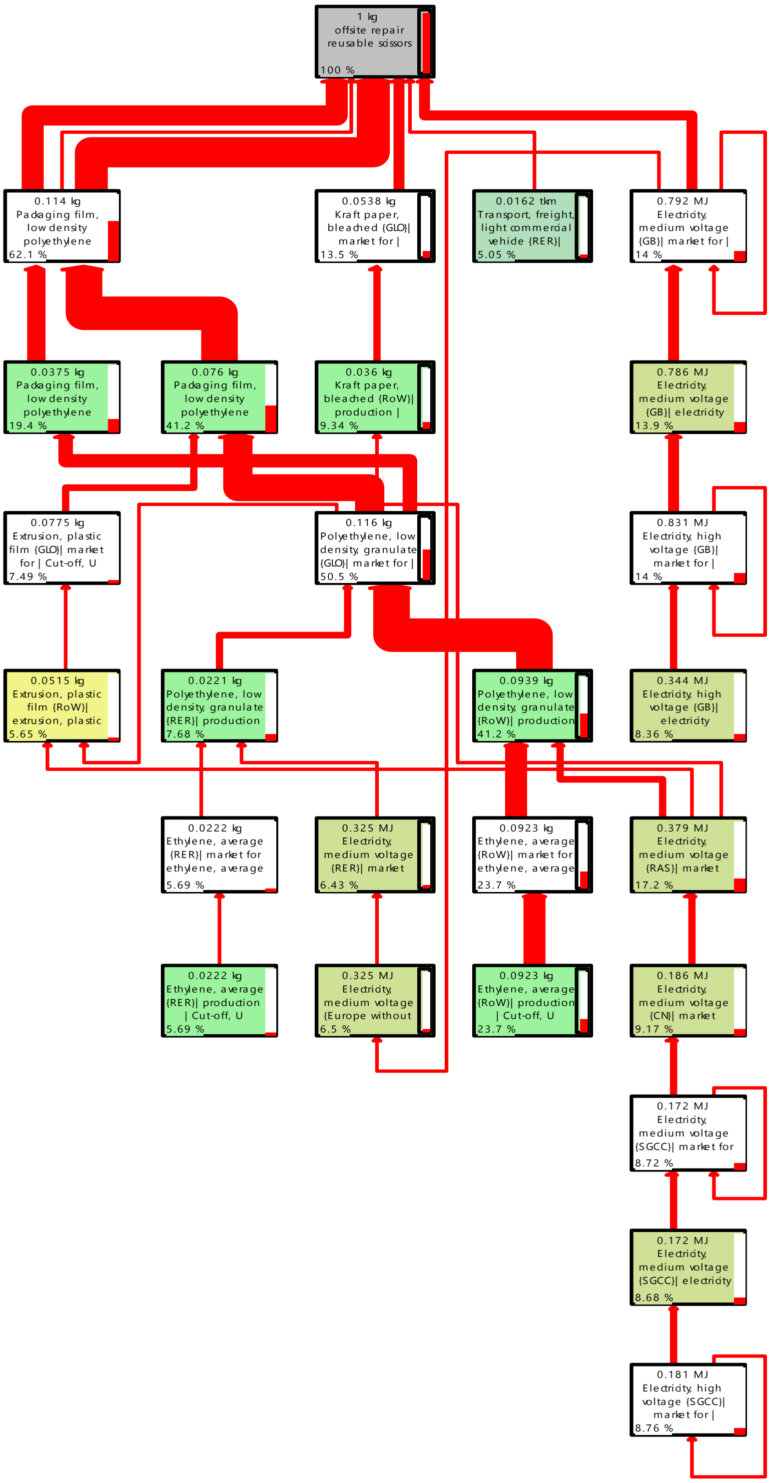
Modelled on one use of scissors. Each box represents a unit process (only those >5% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



Supplementary figure 20: Network diagram for reusable scissors repaired onsite, showing global warming impact drivers (5% cut-off).
Modelled on one use of scissors. Each box represents a unit process (only those >5% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



Supplementary figure 21: Network diagram for offsite repair of reusable scissors, showing global warming impact drivers (5% cut-off).
Modelled on repairing 1 kg reusable scissors. Each box represents a unit process (only those >5% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.



Supplementary figure 22: Network diagram for onsite repair of reusable scissors, showing global warming impact drivers (5% cut-off).

Modelled on repairing 1 kg reusable scissors. Each box represents a unit process (only those >5% contribution to the impact are shown), with percentage contribution shown in bottom left, and quantity of the process for the assembly at the top of each box. The arrows represent the flow of materials between processes, and their thickness reflect the relative contribution.