Advancing Sustainability in Robotic Surgery: A Robust Comparative and Eco-Design Life Cycle Assessment of the Innovative Reusable SATA Instrument Technology

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Preface

This thesis represents the final work of my Master's in Biomedical Engineering at TU Delft, where I applied much of the knowledge gained over years of study, including insights from my Bachelor's in Clinical Technology. This comprehensive project focuses on sustainability in the surgical field, integrating literature review, stakeholder engagement through surveys and interviews, and the practical application of a modified environmental assessment method.

I am especially grateful to my supervisor, Tim Horeman-Franse, for allowing me to work on this unique graduation project that extends beyond typical Biomedical Engineering boundaries. Despite his busy schedule, he always found time to meet, advise, and provide valuable insights from his extensive experience as a MedTech entrepreneur specialising in surgical instruments, implants, and training systems, with a specific focus on sustainability. His support and encouragement motivated me to tackle challenges confidently, strengthening both my skills and independence.

My sincere thanks also go to Bart van Straten, who generously shared his time and expertise, and provided me with a tour of Van Straten Medical. Observing the manufacturing, sterilisation, repair, and recycling processes gave me a deeper understanding of the practical aspects that are central to my research.

I am also grateful to the dedicated teams at TU Delft's workplace and measurement shop for their technical support, assisting me with device disassembly and providing essential information on materials and manufacturing processes. Additionally, I would like to thank the members of the European Association of Endoscopic Surgery (EAES) who participated in my survey, contributing valuable data that informed my analysis.

Finally, I would like to thank my housemates, who supported me throughout this journey, cooking for me and offering encouragement during the long days of study

I hope this research lays a foundation for future advancements in sustainable surgical technology, contributing to a healthcare sector that prioritises both innovation and environmental responsibility.

Anna Gerbens, November 2024

Abstract

Introduction Surgical robotic systems are increasingly valued for their precision and benefits to patients and surgeons, yet traditional designs rely on costly, limited-use, cable-driven instruments that require frequent replacement and specialised cleaning equipment. To address these issues, the Sustainable Surgery & Translational Technology group MI & BITE developed the Advanced Laparoscopy Robotic System (AdLap-RS) with modular shaft-actuated tip articulation (SATA) instruments. Their modular design allows for disassembly, easy cleaning, and part replacement, enhancing reuse potential and lowering operational costs. With the substantial environmental impact of surgical activities, reusable SATA instruments also offer promising sustainability benefits. However, inconsistencies in life cycle assessments (LCAs) applied within the surgical field raise concerns about their reliability, complicating accurate environmental assessments of this innovative technology.

Goal This research aims to assess the environmental impact of the reusable SATA instrument technology for robotic surgery through a robust comparative LCA while simultaneously informing sustainable design choices during the SATA instrument technology's ongoing development.

Method The initial phase of this research included a literature review and a survey among European Association of Endoscopic Surgery (EAES) members to identify reliability challenges in applying LCAs to surgical instruments. Insights from this phase informed a robust comparative LCA, assessing the environmental footprint of one of the reusable SATA instruments against its traditional limited-use counterpart, which also functioned as an eco-design evaluation by applying a circular eco-design approach.

Results Findings from the first part showed a significant gap in LCA usage in surgical decision-making, largely due to limited familiarity and trust in LCA findings. The absence of a standardised, user-friendly LCA methodology tailored to the complexities of surgical instruments further complicates accurate assessments in this specialised domain. Comparative LCA results revealed that the reusable SATA instrument reduces climate change and energy impacts by over 50% compared to its limited-use counterpart. For both instruments, the use phase represented the largest contributor to environmental impact, primarily due to the energy-intensive disinfection and sterilization cycles required before each reuse. The eco-design evaluation recommends prioritising modularity and disassembly improvements to optimise tray load capacity and reduce reprocessing impacts.

Conclusion While this study robustly indicates the sustainability benefits of the innovative reusable SATA instrument technology for robotic surgery, capturing the full complexity of surgical instruments in LCAs remains challenging. Addressing this will require stakeholder engagement, targeted LCA training, refined LCA methodologies, and comprehensive review processes tailored to this specialised field.

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I. Introduction

1.1 Background and Rationale

Surgical robotic systems are becoming increasingly popular in the medical field due to their precision, improved patient outcomes and enhanced surgeon comfort. Traditional systems, however, come with expensive instruments that can only be reused a limited number of times. These instruments often rely on complex, cable-driven designs that make them challenging to inspect, clean, and maintain, leading to their disposal after a few uses to ensure patient safety (1, 2). This forces hospitals to continually purchase costly replacements. Furthermore, these complex designs require specialised cleaning equipment, adding an extra financial burden, particularly for hospitals without advanced central sterile services department (CSSD) facilities (1, 3).

To address these challenges, the Sustainable Surgery & Translational Technology group MI & BITE has developed the Advanced Laparoscopy Robotic System (AdLap-RS), a new robotic platform for advanced laparoscopic procedures. The AdLap-RS incorporates steerable, shaft-actuated tip articulation (SATA) instruments, which use shaft rotations rather than traditional cable mechanisms to transmit movement, and are fully modular. This modular design facilitates disassembly, simplifying cleaning and maintenance, while also enabling the selective replacement of worn or damaged parts. This enhances their potential for increased reuse, presenting a cost-effective alternative to traditional disposable instruments that involve high initial and ongoing costs (1, 3).

By supporting more frequent instrument reuse, the system also offers a valuable opportunity to enhance sustainability within the operating room (OR), which is crucial given the significant contribution of surgical activities to global environmental pollution (3). A recent systematic review on sustainability strategies for surgical instruments (refer to Appendix A) suggests that reusable instruments generally offer environmental advantages over disposable ones, as their production and disposal impacts are spread over multiple uses. In contrast, disposable instruments produce consistently high environmental impacts from manufacturing and contribute significantly to medical waste. However, the review also highlights that these benefits are not always assured, especially due to the high energy and water requirements involved in the disinfection and sterilisation processes necessary for each reuse. Furthermore, the review emphasizes the growing role of Life Cycle Assessments (LCAs) within the surgical field as a tool for assessing the environmental sustainability of surgical instruments. LCAs are valued for their ability to capture the full environmental footprint of products across their entire lifecycle, from raw material extraction to their manufacture, distribution, use, and disposal. This capability to map life cycle stages and quantify environmental impacts makes LCAs a powerful tool for informed decision-making, whether comparing the environmental impacts of existing products for sustainable procurement or guiding eco-design for new products entering the market (4). Despite their recognized value, the review found that LCAs applied in the surgical instrumentation sector often yield inconsistent and occasionally contradictory results, raising concerns about their accurate exectution and reliability in this field.

1.2 Objectives

The primary objective of this research is to provide a comprehensive assessment of the environmental footprint of the innovative reusable SATA instrument technology for robotic surgery through a detailed and robust comparative LCA. This analysis will evaluate the environmental impacts of one of the newly developed SATA instruments compared to its traditional limited-use counterpart, establishing a robust approach that offers stakeholders a reliable basis for comparison and supports informed, sustainable procurement decisions in robotic surgery.

In addition, as the innovative line of reusable instruments for robotic surgery is still under development and has not yet been introduced to the market, a secondary objective is to use insights from the comparative LCA to proactively guide environmentally responsible design decisions during the SATA technology's development process.

To achieve these objectives, this research will address the following questions:

- **How might the reliability of LCA findings be influenced, particularly in the context of surgical instruments, even when following standard LCA methodologies?**
- **How are LCAs perceived and valued within the surgical field?**
- **Can a robust comparative LCA effectively capture the environmental footprint of the innovative reusable robotic instrument technology while simultaneously identifying design modifications to enhance its environmental performance?**

1.3 Structure

To address the research questions and objectives, this research is organised into two main parts, each with a distinct focus and methodology. The first part addresses the first and second research question through a literature research and a survey distributed among members of the European Association for Endoscopic Surgery (EAES). The second part focuses on the third research question by performing a robust LCA that serves both as a comparative analysis and an eco-design evaluation, integrating insights gained from the first part of the research.

II. PART 1: Identifying and Addressing Reliability Challenges in LCAs of Surgical Instruments

2.1 Methods

First, literature research will be performed to develop a deep understanding of the general LCA methodology while recognizing its inherent limitations. Special emphasis will be placed on the surgical field by identifying key risk factors that have contributed or may contribute to inconsistent or even contradictory results in LCAs of surgical instruments, thereby jeopardising the reliability of findings in this area. Additionally, best practices and strategies to mitigate these risk factors will be explored. Next, to further understand the issues impacting the reliability of LCA findings in the surgical field and to investigate potential solutions, stakeholders' perspectives and experiences regarding LCA practices within this field will be examined through a survey targeting members of the EAES. The insights obtained from both literature research and stakeholder feedback will serve as the basis for conducting a reliable LCA of a surgical device.

2.2 Literature Research on LCA Methodology and Reliability Risk Factors

LCAs are one of several environmental management tools, including risk assessments, environmental performance evaluations and environmental audits, all aimed at supporting environmental decision-making (5). Unlike these other methods, which focus on specific aspects related to environmental management, such as risk, performance, or compliance, LCAs provide a comprehensive evaluation of the environmental impacts associated with every stage of a product's life cycle, from raw material extraction to disposal. This 'cradle-to-grave' approach ensures that all environmental burdens are considered and helps prevent the shifting of impacts between different life cycle stages or impact categories. These burdens can include a wide range of issues, including significant energy consumption and the emission of hazardous pollutants (4).

The methodology of LCAs is systematically outlined by the ISO 14040 and 14044 standards and encompasses four main phases: defining the goal and scope, analysing the inventory, assessing impacts, and interpreting the results. This framework assists practitioners through a structured and iterative evaluation process, promoting consistency and transparency while encouraging continuous review and refinement of the LCA process (5). Additional guidance tools, such as the *New Dutch LCA Guide*, which consists of multiple detailed parts (4, 6), and the *International Reference Life Cycle Data System (ILCD) Handbook's General Guide on LCA (7)*, provide further detail aligned with ISO 14040 and 14044 standards to enhance the quality of LCA practices. For an in-depth overview of the general LCA methodology based on these supplementary tools, along with key risk factors for each phase identified in the literature that may affect the reliability of LCAs for surgical instruments and suggested mitigation strategies, please refer to the following sections. A visual representation of the general LCA methodology is provided in Figure 1. Additionally, for a summary of the identified risk factors and corresponding mitigation strategies, please refer to Table 1.

2.2.1 Goal & Scope Definition

The goal and scope definition phase of an LCA is essential for establishing the framework of the study. The goal encompasses defining the study's applications, rationale, and target audience, while the scope involves specifying the product under investigation and establishing the modelling methodologies, quality standards, reporting requirements, and review processes necessary to align the LCA with its intended uses and audience. Early definition of these specifications is vital for maintaining the credibility and reproducibility of results. As the LCA progresses, initial scope definitions may require adjustments based on new data or insights to ensure the LCA remains relevant and accurate. The iterative nature of this process underscores the importance of documenting any changes for transparency throughout the study (6, 7).

2.2.1.1 Application

LCA applications are varied, encompassing product comparisons, improvements in product design, the creation of environmental product declarations, and policy development through impact assessments. Each application comes with specific ISO 14040 and 14044:2006 requirements regarding data sets, reporting, and review, which can result in variations in methodological approaches (6, 7). In the surgical field, LCAs provide a structured framework for evaluating the environmental impacts of various surgical instruments, from reusable instruments that require energy-intensive cleaning processes to disposable options that consume significant materials and generate substantial waste (refer to Appendix A). In this context, LCA applications include comparing the environmental impacts of functionally identical surgical devices, as demonstrated by Donahue et al. (8), who used an LCA to assess the environmental impact of both a disposable and a reusable vaginal speculum. Another example of LCA application in this field is the evaluation of a single surgical device to examine environmental impact differences among various design options, as illustrated by Samenjo et al. (9), who focused on a single syringe extension device.

2.2.1.2 Rationale

Understanding the motivations for conducting the LCA and the specific decision-context helps to shape the LCA to meet its unique needs, ensuring that the results are relevant to the identified target audience (6, 7). In the surgical field, LCA results could assist instrument manufacturers in making eco-design decisions prior to market entry, helping them secure eco-friendly certifications or distinguishing their products. Additionally, LCA results could support healthcare institutions in making informed choices about sustainable procurement practices. It's important to note that not all LCAs are intended for decision support; some are purely descriptive, focusing on documenting the environmental aspects of the product being analysed (7).

However, LCA practitioners themselves may have specific interests in the study outcomes, which can result in biassed decisions during the LCA process, ultimately affecting results and compromising reliability. Therefore, it is essential to clearly document the reasons for undertaking the LCA, particularly within a specific decision-making context, along with the entities commissioning the study from the start. Additionally, since studies are often funded by stakeholders with particular interests, transparency in identifying any co-financing parties is crucial for maintaining the study's credibility. For instance, while reusable surgical instruments typically provide environmental advantages over disposables, Leiden et al. (10) found that a reusable lumbar fusion instrument set was nearly seven times more climate-polluting than its single-use counterpart. It was later revealed that the study was funded by the manufacturer of the single-use set, raising concerns about the reliability of its findings.

2.2.1.3 Target Audience

The target audience, whether internal or external, technical or non-technical, influences the level of detail and confidentiality required in the reporting and should therefore be clearly specified from the start. LCAs involving comparative statements for public disclosure must adhere to additional requirements outlined in ISO 14040 and 14044:2006, due to the potential wider implications of their findings (7).

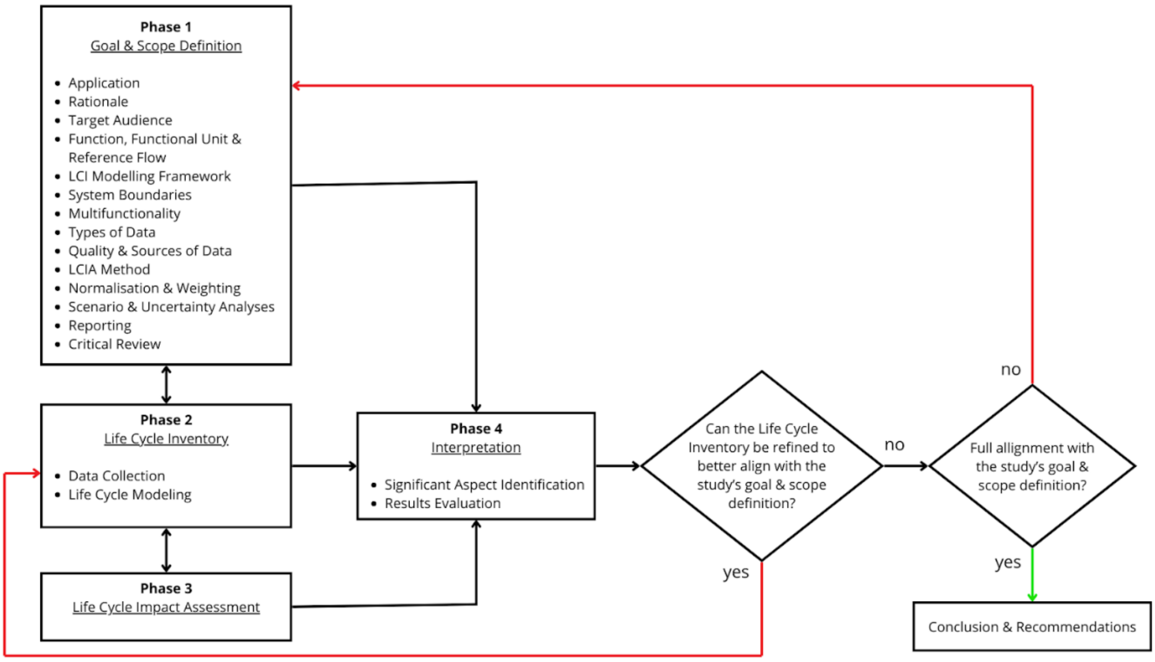

Figure 1: The General LCA Methodology. *Note: The figure is adapted from the ILCD Handbook's General Guide on LCA (7). The arrows represent the flow of data and information. Specifically, the red arrows indicate the iterative refinement process of the LCA, ensuring that the study aligns with the defined goal and scope while maintaining methodological appropriateness and high data quality. In cases where data limitations cannot be adequately resolved, adjustments to the initial goal and scope definition may be required.*

2.2.1.4 Function, Functional Unit & Reference Flow

The function of a product refers to the specific services or performance it offers, while the functional unit quantifies this function in detail, including aspects such as quantity, quality, and duration of use. This unit serves as a standard reference against which impacts are evaluated, ensuring that LCA results are meaningful, comparable, and applicable to real-world decision-making. The reference flow then defines the quantity of the product needed to fulfil the specified functional unit (5-7).

Literature reviews reveal significant variations in functional units across LCAs involving reusable surgical instruments, ranging from 'one use,' which distributes the impacts of reusable instruments over their number of uses in their life cycle, to functional units based on the overall lifespan of these instruments (11) (refer to Appendix A). Since environmental impacts are evaluated based on the defined functional unit, different functional units can lead to varying results among LCA studies examining similar instruments. For instance, Donahue et al. (8) used a functional unit of 20 uses to compare a reusable stainless steel vaginal speculum with an assumed lifespan of 20 uses with 20 single-use acrylic specula. In contrast, Rodriguez and Hicks (12) employed a functional unit of 5,000 uses, comparing 100 stainless steel reusable specula, each with an assumed lifespan of 50 uses, against 5000 single-use acrylic specula. Although both studies reported lower carbon footprints for reusable specula compared to the single-use versions, Rodriguez and Hicks (12) reported significantly higher climate change impacts due to the larger functional unit used, compared to Donahue et al. 's (8) findings.

However, the different assumptions regarding the lifespan of the reusable stainless steel vaginal speculum (50 uses according to Rodriguez and Hicks (12) compared to 20 uses by Donahue et al. (8)) highlight the challenges of standardising functional units in LCAs involving reusable surgical instruments, which may lead to varying LCA results. Although the functional unit is typically based on the overall lifespan of the instruments under study, the actual lifespan of a specific reusable instrument is often not fixed and can vary between facilities due to several factors. These include the complexity of procedures (as instruments employed in more invasive procedures may degrade more quickly), the frequency and quality of maintenance (with poor maintenance leading to premature wear and damage), and storage conditions (instruments should be stored in a dry, clean and well-organised manner to avoid physical damage) (13, 14).

Scenario analyses from various studies illustrate how modifications to functional units, based on different assumptions about an instrument's lifespan, can alter a study's findings. For example, in the baseline scenario by Boberg et al. (15), a functional unit of 500 laparoscopic cholecystectomies was based on an assumed lifespan of 500 uses for a mixed trocar system that includes both single-use and reusable components. In this case, no significant differences were found in resource and ecosystem impacts when comparing the mixed trocar system to 500 single-use counterparts. However, when the functional unit was adjusted to 750 procedures based on an assumed lifespan of 750 uses for the mixed system, the 750 single-use systems displayed a greater impact on both resource use and ecosystem health. Conversely, reducing the mixed system's lifespan and functional unit to 250 procedures made the single-use systems appear more favourable regarding human health impact.

By conducting a break-even analysis, Rodriguez and Hicks (12) further highlight how differences between the assumed lifespan of a reusable instrument and its actual number of uses can lead to misleading conclusions if not carefully considered. They found that the disposable speculum breaks even with the reusable speculum around the 40th use regarding the ecotoxicity impact category which assesses harmful effects on the environment and organisms. With a functional unit of 50 uses, based on an assumed lifespan of 50 uses for the reusable speculum, their findings indicate that the reusable option is more environmentally favourable for this specific impact category. However, if the speculum were actually used only 20 times, as assumed by Donahue et al. (8), and the functional unit was adjusted to 20 uses, the disposable speculum would be preferred based on their ecotoxicity impact results. Therefore, they conclude that, given this uncertainty, no instrument outperforms the other in terms of ecotoxicity impact.

Given these inconsistencies observed in LCA findings due to varying functional units, this research suggests that in order to accurately quantify the functional unit and ensure reliable assessments across instruments that serve similar functions, a deep technical understanding of the analysed instrument, along with LCA expertise, is essential. Functional units should reflect typical or average usage scenarios based on standard practices that are well-supported and agreed upon by stakeholders familiar with the practical application of the instrument. Moreover, performing a break-even analysis is essential to address uncertainties related to an instrument's actual lifespan, preventing incorrect conclusions from being drawn due to potentially inaccurate assumptions. Additionally, providing detailed descriptions, photographs, and technical specifications can enhance clarity regarding the product being studied (7).

2.2.1.5 Life Cycle Inventory Modelling Framework

The choice of life cycle inventory (LCI) modelling framework, either attributional or consequential, affects which processes are included in the product's life cycle, how they are integrated into the LCI model, and the types of inventory data and additional information required (7). Attributional modelling focuses on quantifying the environmental impacts directly linked to a product system, covering all unit processes throughout its lifecycle. This framework is particularly effective for documenting the product supply chain as it stands, specifying the share of global environmental impacts associated with the product without considering broader market or environmental changes resulting from product-related decisions. In contrast, consequential modelling examines how hypothetical product-related decisions can lead to changes in market behaviour and, consequently, alterations in environmental flows. This dynamic approach makes consequential modelling suitable for assessing the broader environmental impacts of new products or policies (7, 16).

2.2.1.6. System Boundaries

Defining system boundaries is crucial for distinguishing the analysed product system from the broader technosphere, as it clearly specifies which life cycle stages and processes are necessary to achieve the system's functional unit. In cradle-to-grave LCAs the entire life cycle is covered, from raw material acquisition to disposal, whereas cradle-to-gate LCAs focus on the initial stages, from raw material acquisition up to the point where the product is ready for distribution, excluding its use and disposal. By establishing precise system boundaries according to the chosen LCI modelling framework, all significant environmental interactions that cross the boundary between the system and the ecosphere are considered, allowing less relevant processes to be excluded or simplified. For transparency, these boundaries should be visually represented in a semi-schematic diagram to show included and excluded life cycle stages and processes (6, 7).

In comparative LCAs of surgical instruments, certain processes are often excluded to simplify the analysis, especially when these processes are not directly related to the product life cycles or are assumed to be comparable for both products. This is particularly common for elements related to the use phase, such as capital goods and hospital infrastructure. Although the impacts associated with the production and disposal of capital goods used for instrument reprocessing, such as washing machines and autoclaves, are typically excluded due to the assumption that these impacts are not directly connected to the instrument's life cycle, their operational use is generally included. While the long lifespan of these machines makes the production and disposal impacts negligible for a single device, their operational use can contribute significantly to the environmental footprint of a reusable instrument primarily due to the energy, water and disinfectants associated with the use of these reprocessing machines (8, 12, 15, 17-21).

Despite efforts to simplify the analysis by excluding less relevant processes, LCA practitioners face difficulties in capturing all relevant processes due to the complexity of the instruments and their life cycles. These instruments, particularly the complexer ones, typically consist of various materials and components and undergo specialised processes, such as component manufacturing, assembly, reprocessing for reuse, and waste treatment. Each of these stages includes variables that can differ based on the location or facility, for which detailed operational data is often unavailable. This forces them to make trade-offs: they can either include additional elements and processes to expand the scope of the assessment, which may risk compromising data quality, or exclude them to preserve data quality, potentially limiting the comprehensiveness of the analysis. Such inconsistencies in defining system boundaries can lead to significant variations in reported environmental impacts and may result in inconsistent findings. This issue is particularly evident in studies where different decisions have been made regarding the inclusion or exclusion of components or processes related to instrument reprocessing, as can be seen in the studies by Donahue et al. (8) and Rodriguez and Hicks (12). After adjusting for functional units, Donahue et al. (8) reported a global warming potential for a stainless-steel reusable vaginal speculum that was more than double that reported by Rodriguez and Hicks (12). This variation was primarily attributed to Donahue et al.'s (8) inclusion of sterilisation pouches, which were excluded in the analysis by Rodriguez and Hicks (12) due to a lack of data.

Furthermore, while many LCAs of surgical instruments aim to cover the full life cycle of the instrument, determining its end-of-life fate can be challenging due to limitations in data and time. As a result, simplified assumptions are often made about the end-of-life phase, which in turn influence decisions on which processes and elements are included or excluded from the system boundaries. For instance, in LCAs that assume recycling, material recovery is typically factored into the system boundaries, leading to reduced waste and decreased demand for virgin materials. This approach is often applied to metal instruments, such as stainless steel scissors or specula, where recycling is feasible because these metals retain their properties and reprocessing them poses minimal biological risks (12, 21). In contrast, in LCAs that assume landfilling as an end-of-life treatment, future material recovery is not accounted for, as waste is buried and no materials are recovered. Since landfilling is generally viewed as a less sustainable option, it is typically only applied to materials that are unsuitable for recycling or incineration, such as certain composites or polymers used in instrument packaging (22).

Even in studies that assume similar end-of-life pathways, system boundaries can still vary. This is particularly evident in LCA studies that consider the disposal of instruments as municipal waste followed by incineration. For instance, single-use instruments made from plastics or composites, such as plastic surgical scissors or laryngeal mask airways, which are often difficult to recycle due to infection risks, are typically treated as municipal waste and incinerated (20, 21). Similarly, complex devices like single-lung ventilation systems, composed of multiple parts and materials, complicate the separation of reusable components, leading to their classification as municipal waste and subsequent incineration (18). Most LCAs include energy recovery from the heat produced during incineration within the system boundaries, subtracting this recovered energy from the device's overall lifecycle energy consumption (15, 18, 23, 24). However, some studies deliberately exclude this factor (19), potentially creating inconsistencies in reported LCA results. Additionally, some studies do not clearly indicate whether energy recovery is accounted for (20, 21), leading to a lack of transparency in the findings .

Extending the lifespan of surgical instruments through repair or remanufacturing processes has significant potential to reduce their environmental footprint, as demonstrated by Rizan et al. (17) and Schulte et al. (25). While Rizan et al. (17) showed that repairing a reusable stainless steel scissor is more environmentally advantageous than producing a new one, Schulte et al. (25) found that remanufacturing a disposable catheter offers greater environmental benefits than manufacturing entirely new devices. Despite these potential benefits, repair and remanufacturing remain underexplored and are not yet widely adopted. The primary challenge lies in the lack of detailed data needed to account for all related processes and impacts, which complicates their inclusion in the system boundaries of LCAs for surgical instruments. This issue is especially prominent for the repair or remanufacturing of more complex instruments, which consist of various materials and components and require specialised equipment and techniques, for which little data is typically available. Additionally, determining which parts can be reused and estimating their potential lifespan demands extensive research, often beyond the scope of standard LCA assessments. Schulte et al. (25) addressed this challenge by incorporating a circularity metric into their LCA, accounting for the reuse of parts and materials over multiple product cycles. While remanufacturing was found to be more advantageous when multiple life cycles were considered, the overall environmental impacts were higher compared to focusing on a single life cycle, underscoring how LCA results can vary based on how end-of-life pathways are integrated into system boundaries.

In some LCA studies, uncertainties about an instrument's actual end-of-life pathway and material recovery rates have led to the decision to omit the end-of-life phase altogether (9). However, while certain processes or entire phases might be deliberately excluded due to data limitations, others might be unintentionally overlooked, despite their potential to contribute significantly to the overall environmental impact.

Therefore, this research highlights the importance of carefully assessing and justifying which processes or elements can be excluded from the system boundaries, based on the study’s goals and the data available. With reprocessing activities playing a major role in the environmental impacts of surgical instruments, particularly for these activities, system boundary decisions should be made carefully. Drawing insights from high-quality studies of similar products is suggested, and any exclusions should be supported by quantitative reasoning rather than based purely on the type of activity or component. Furthermore, to improve understanding and ensure transparency and completeness, a detailed overview of all processes and aspects excluded from the system boundaries, along with their potential environmental contributions, is highly recommended.

2.2.1.7 Multifunctionality

To effectively capture the complexities of a product system, it is essential to already decide during the scope how to manage the multifunctionality of processes that yield multiple products or functions. The ISO 14044:2006 standard provides a hierarchy of approaches to effectively isolate the inventory associated with the specific product or function of interest. Subdivision is the preferred method when possible, as it breaks down multifunctional processes into simpler, single-function processes, thereby eliminating the need for allocation calculations. System expansion and substitution tackle multifunctionality by extending the system to incorporate additional functions or by replacing unnecessary functions with alternatives, which allows for crediting of avoided burdens and adjusting life cycle inputs and outputs accordingly. In contrast, allocation requires careful calculations to quantify total functional output and distribute environmental burdens among the various products or functions based on shared characteristics such as mass, energy content, or economic value (6, 7). The selection of these methods largely depends on the LCI modelling framework adopted and the unique characteristics of the product system being analysed. While attributional modelling typically uses allocation, consequential modelling aims to minimise allocation by utilising system expansion and substitution instead when direct subdivision is not feasible (16).

In the life cycle of reusable surgical instruments, reprocessing practices are a key example of multifunctional processes, as multiple instruments are often reprocessed simultaneously in sterilisation and washing machines. In LCAs that involve reusable instruments and utilise attributional modelling, allocation is typically based on the mass or volume load of instruments in washing or sterilisation machines. However, as these loads can vary between facilities and even between reprocessing cycles, accurately isolating the proportional impact of each instrument per session proves quite challenging (8, 15, 17, 19, 26). Variations in assumptions regarding loading efficiencies have resulted in different environmental outcomes for reprocessing practices, influencing the findings of LCA studies focused on reusable instruments.

For instance, Unger et al. (26) found that their baseline scenario of reusing a dental bur 30 times results in lower environmental impacts across all considered categories compared to using it once, assuming the machines are fully loaded. However, in scenarios with suboptimal loading, the environmental benefits diminish, and when assuming a worst-case scenario where machines are only one-third full, reusing the bur 30 times can even lead to more adverse impacts than using it just once. Additionally, Sørensen (24) observed that reusable bronchoscopes had a higher climate change impact than single-use options in their baseline scenario, where only one bronchoscope was cleaned per operation. However, if more than two bronchoscopes were cleaned simultaneously, the climate change impact significantly decreased, making reusable options more environmentally favourable.

Variations in how reprocessing multifunctionality is managed have even resulted in contradictory findings across different LCA studies in the surgical field. For example, while Friedericy et al. (27) found that using an aluminium rigid sterilisation container (RSC) for sterilising instrument sets was more environmentally beneficial than single-use blue wrap, Rizan et al. (23) reached the opposite conclusion. In their analysis, Rizan et al. (23) assigned the environmental impacts of sterilisation to the instruments themselves rather than the packaging systems. Therefore, they only considered the washing of RSCs, which demands significant energy and water consumption, whereas single-use blue wrap does not suffer such washing impacts.

Considering these examples of how LCA findings can be affected by the management of multifunctionality in reprocessing practices, this research suggests it is crucial that the approach aligns with the selected LCI modelling framework and the unique characteristics of the instrument being studied. In particular, for LCAs employing attributional modelling, allocations should represent typical or average loading scenarios based on standard practices that are recognized and agreed upon by stakeholders familiar with instrument reprocessing. Ideally, a reference hospital should be selected as a basis for gathering accurate data on reprocessing practices, with the chosen loading scenarios then customised to match the conditions at this reference facility.

2.2.1.8 Types of Data

It is advised to already prepare a detailed overview of the types of data and information required for the modelling of the life cycle inventory of the product system, covering for example raw inventory data, use patterns and end-of-life data. Attributional modelling uses historical data to represent the processes as they currently are or are expected to be, preferring specific, directly measured data where possible and only using average data when needed. Consequential modelling, on the other hand, should include marginal data related to the production of inputs, particularly when the product under study only has a relatively small impact on total production volume (6, 7). Marginal data captures the changes in environmental burdens relative to production adjustments as linear approximations, meaning that the environmental impact per unit of production increase remains approximately constant (16).

2.2.1.9 Quality & Sources of Data

The quality of data sets, defined by their accuracy, precision, and completeness, is essential for obtaining reliable LCA results and should therefore already be established during the goal and scope definition phase of the assessment. While accuracy ensures that the data accurately reflects the true characteristics of the system being analysed in terms of technological, geographical, and temporal representativeness, precision measures the uncertainty within the collected or modelled data, and completeness evaluates whether all relevant processes and environmental interventions are included in the inventory. Identifying and selecting reliable data sources early on, such as well-documented and externally verified databases, can improve data quality and significantly simplify the review process (6, 7).

2.2.1.10 Life Cycle Impact Assessment Method

To capture a wide range of potential environmental impacts aligned with the study's objectives, various life cycle impact assessment (LCIA) methodologies have been developed, including 'Revised Continuous Improvement and Progressive Embodiment' (ReCiPe) and the 'Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts' (TRACI). These methodologies focus on different midpoint impact categories, such as global warming potential, ozone depletion, and human toxicity. Some also provide aggregated single-score endpoint indicators to evaluate broader impacts on human health, ecosystems, and natural resources (refer to Appendix A). When using LCA software like SimaPro, inventory data is automatically classified into the impact categories defined by the selected LCIA method. Each contribution is quantified through characterization, for instance, global warming potential is typically measured in 'kg CO_2-equivalents' at the midpoint level. At the endpoint level, impacts reflect more specific damages, such as species loss or human health effects measured in disability-adjusted life years (DALYs). Finally, the quantified individual impacts in each category are ultimately aggregated to provide an overall assessment of the product's environmental footprint (7).

Since the impact categories serve as outcome measures, the choice of LCIA method is crucial in shaping results. Therefore, this research highlights that when selecting these methods, it is essential to ensure they align with the study's objectives and address all relevant environmental issues associated with the analysed system. Any exclusions of impact categories must be justified based on their relevance, while additional identified impacts require appropriate LCIA methods to maintain necessary standards (7). LCAs that model unique conditions or limit impact coverage may restrict the usability and transferability of results, so such limitations should be clearly identified from the start.

2.2.1.11 Normalisation & Weighting

Normalisation and weighting are optional yet crucial for the interpretation of LCA results. Normalisation helps understand the magnitude of the impacts of the product under study relative to a broader context by adjusting the impact assessment data to a common scale or reference such as national averages or per capita impacts. Weighting enhances the decision-making process by assigning different levels of importance to various environmental impact categories based on normative values. To ensure consistency in the application of these measures, they should be planned during the goal and scope definition phase. However, in studies producing comparative assertions intended for public disclosure, weighting is generally avoided to maintain neutrality and transparency in the findings (6, 7).

2.2.1.12 Scenario & Uncertainty Analyses

Scenario analyses play a key role in verifying the robustness of comparative LCA results by evaluating the results under varying conditions, including best case, most likely case, and worst case scenarios. This helps to determine whether the observed differences between systems are substantial enough to support claims of one system's superiority over another. These scenarios adjust for different data and methodological assumptions such as variations in functional unit properties, inventory data values and allocation methods. Additionally, performing uncertainty calculations can enhance the robustness analysis by assessing the overall uncertainty due to natural variations in data values under specific conditions. However, these calculations are only useful when they have not already been used to develop the different scenarios in the scenario analysis (6, 7).

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

2.1.1.13 Reporting

Decisions regarding the format and level of reporting should match the study's goals and the intended audience, ranging from simplified standalone data sets to detailed public comparative analyses. It's important to use standardised reporting formats wherever possible and to keep confidential information separate. The chosen level of reporting, whether for internal use, limited external distribution, or broad public access, should reflect the impact of the findings, ensuring that the presented information is clear and cannot be misinterpreted (6, 7).

2.2.1.14 Critical Review

Conducting a critical review by experts not involved in the LCA is crucial for validating the study's quality and credibility. Given that different data and methodological assumptions in LCA studies on surgical instruments may result from LCA practitioners' specific interests in the study outcomes, the need for external validation by independent experts is emphasised. This process encourages practitioners to clarify their views and assumptions. The type of review, whether being an internal independent review, an external review, or a panel review should be established from the start to ensure that the LCA meets review requirements, thereby optimising the overall data collection, documentation, and reporting process (6, 7).

2.2.2 Life Cycle Inventory

During the Life Cycle Inventory (LCI) phase of an LCA, the actual data collection and modelling of the product system are performed in line with the goals and specifications set in the scope phase. It not only provides the necessary data for the subsequent LCIA phase but also provides insights for refining scope settings based on new insights or data to better reflect actual conditions. The LCI phase typically is the most resource-intensive part of an LCA (6, 7).

2.2.2.1 Data Collection

The data collection process involves gathering quantitative information on all relevant inputs and outputs associated with the product's life cycle, based on the system boundaries defined during the scope phase. This includes product flows, waste flows, and elementary flows, which are obtained through measurements, interviews, literature reviews, and database searches. According to the ILDC Handbook, elementary flows refer to any single substance or energy entering or leaving the analysed system without prior or subsequent human transformation. For processes specific to the product system, primary data, collected directly from product producers or process operators, is preferred. When necessary, this primary data can be supplemented with secondary data from sources like patents, existing databases, literature, or other projects. In instances where data is also lacking from these sources, expert judgement may be applied. For processes not specific to the product system, it is common to rely on secondary data from databases and research groups (6, 7).

One of the primary challenges identified in conducting LCAs on surgical instruments is the lack of primary data on the specialized life cycle processes specific to the instruments being studied. Hospitals and manufacturers often fail to track or report key information related to material flows, energy use, and waste generation, which are essential for assessing environmental impacts. Furthermore, this data gap may be widened by stakeholders' differing priorities and varying willingness to engage in the LCA process, leading to inconsistent and incomplete data quality.

For instance, suppliers of semi-finished products and raw materials, as well as instrument manufacturers themselves, may be reluctant to share data due to fears of competitive disadvantage. Additionally, instrument manufacturers may lack comprehensive information about the composition and manufacturing processes of standard "off-the-shelf" components, such as screws, fasteners, electronic components, and connectors, as these components are typically sourced from external suppliers rather than produced in-house. Furthermore, with the limited number of potential suppliers in the surgical instrument market, it is crucial that relationships between manufacturers and suppliers are maintained, which can further restrict data availability (28). On the healthcare provider side, preferences for specific instruments may result in adjustments to usage data, either being overly optimistic or pessimistic depending on their preferred options, or they may choose not to disclose any usage data at all.

Therefore, this research emphasizes that practitioners must actively encourage stakeholder participation by emphasising the importance and urgency of the study to improve the reliability of LCAs in the surgical field. It is essential for practitioners to secure stakeholders' commitment to the process and uphold any agreements made (28). In cases where variations in the level of detail in primary data are observed, practitioners should consider utilising secondary data to maintain a more consistent data quality.

The data collection process is further constrained by a frequent lack of specific and up-to-date secondary data needed to address the gaps in primary data on an instrument's specialised life cycle processes.

To fill the gaps in primary data concerning the manufacturing phase of an instrument, LCA practitioners often rely on secondary data from comprehensive LCI databases, such as the most commonly used Ecoinvent database, which offers detailed information at the unit process level for various materials and manufacturing processes (refer to Appendix A). The same approach applies to data collection for an instrument's end-of-life phase, where simplified assumptions are often made, relying on secondary data from databases, to fill in the gaps of primary data on its actual end-of-life pathway. However, due to the frequent unavailability or difficulty in obtaining specific data, the secondary data usually relies on averages. For instance, these databases offer insights into common materials and manufacturing processes for standard components, such as off-the-shelf items lacking primary data, or market processes reflecting the average consumption mix of a material (29). While the use of averages helps fill data gaps, it may limit the accuracy of representing the actual conditions for the instruments under study, potentially compromising the quality of the data. Furthermore, there are many different databases available, each varying in content and validity. Some are recognized for their comprehensiveness and transparency, such as the Ecoinvent database which contains over 20,000 datasets (30), while others may provide less complete or outdated information. As a result, the choice of database can significantly affect data quality, and using multiple databases may lead to data quality inconsistencies.

In contrast to the numerous comprehensive databases that provide information on a wide range of materials and manufacturing processes as well as potential end-of-life pathways, detailed databases specifically focusing on the usage practices of surgical instruments are not readily available. As a result, practitioners often have to rely on existing literature or prior studies to obtain secondary data that fill the gaps in primary data concerning the use phase of an instrument. However, usage practices can vary significantly across countries, regions, or even individual hospitals, which affects the usability and transferability of the information and data found in the literature. As a result, secondary data on usage practices sourced from existing literature may not accurately represent the actual conditions of the instruments being examined. This research has previously highlighted how inaccuracies in assumptions related to reprocessing variables, such as reuse frequency and loading efficiencies, can lead to coloured findings, as the environmental impact of an instrument's use phase is heavily influenced by these assumptions. Scenario analyses from various LCA studies have shown that by extending the assumed lifespan of reusable instruments, thereby increasing their reuse frequency, and by improving the assumed loading efficiencies, reusable instruments can become more environmentally favourable than single-use counterparts, even when the baseline scenario initially suggested otherwise (refer to Appendix A).

Moreover, the environmental impact of reprocessing a surgical instrument is greatly influenced by the assumed reprocessing technique. Lalman et al. (31) note that ethylene oxide (ETO) gas sterilisation, a chemical method, consumes substantial energy due to long sterilisation cycles and the need for additional detoxification to handle ETO residue toxicity. For conventional surgical instruments, this generally makes it a much less environmentally favourable technique compared to conventional steam sterilisation, which uses heat. However, as highlighted by Samenjo et al. (9), complex surgical instruments often include heat-sensitive plastics, necessitating chemical sterilisation methods over steam sterilisation to maintain their durability which can result in lower environmental impacts per use of these instruments, as the total impact is distributed over a greater number of uses. Nonetheless, Lalman et al. (31) found that reusing a heat-sensitive electrophysiological catheter five times with ETO had much greater environmental impacts than using five catheters once. Their scenario analysis, however, indicates that hydrogen peroxide sterilisation, another chemical technique, reduces the overall environmental impacts of reusing the catheter by nearly 20 times compared to ETO, though it remains slightly less favourable than single-use. In contrast, Unger and Landis (26) found that reusing seven conventional surgical instruments with ETO gas sterilisation reduced global warming impacts compared to single-use but significantly increased human health impacts. These findings highlight that significant impact differences can be found depending on the specific reprocessing technique used, and the actual impacts vary per instrument based on their complexity. It is not a simple matter of one reprocessing technique being universally the most environmentally favourable for all instruments, highlighting the importance of reflecting the true scenario for the surgical instrument under study.

Studies by Hogan et al. (22) and Kemble et al. (32) illustrate how different assumptions about energy sources for sterilisation can result in conflicting outcomes. Hogan et al. (22) determined that the climate change impact of a reusable flexible cystoscope was greater than its single-use counterpart as they assumed the use of Australian coal-based (high-carbon) energy. In contrast, Kemble et al. (32) concluded that a reusable flexible cystoscope was environmentally beneficial when reprocessing involved lower power consumption. Similarly, McGain et al. (33) showed that reusable anaesthetic equipment had climate change impacts comparable to single-use alternatives when relying on coal-based energy while their scenario analysis indicated that switching to renewable-based electricity or natural gas–based electricity during reprocessing could significantly reduce impacts, making reusable anaesthetic equipment more environmentally favourable compared to single-use options.

Given these inconsistencies, this research emphasizes the need for reprocessing procedure information derived from literature or previous studies to reflect typical or average scenarios based on standard practices, ensuring reasonably reliable results in the absence of primary data. Ideally, this data should be representative of the specific facility conditions, with assumptions validated by experts familiar with instrument reprocessing. To ensure data quality, it is essential that secondary data for the manufacturing and end-of-life phase is sourced from well-documented, externally verified databases, and that it reasonably reflects actual conditions. Moreover, relying on a single database can help practitioners maintain methodological and data quality consistency. Additionally, scenario analyses should be conducted to assess how variations in reprocessing and end-of-life assumptions influence outcomes, ensuring the robustness of LCA findings and broader applicability in practical situations.

2.2.2.2 Life Cycle Modelling

The life cycle model is constructed by connecting and appropriately scaling all data sets to accurately represent the product system's functional unit. This involves managing multifunctionality within the system to ensure precise attribution of processes to their respective inputs and outputs. The final life cycle model should aggregate the correctly scaled inventories of all processes within the defined system boundary, including only the reference flow and elementary flows such as emissions, energy consumption, and material flows. It is advisable to present the inventory results in a table that clearly outlines all inputs and outputs of the product system, enhancing transparency and understanding of the environmental impacts. To protect sensitive information, any confidential or proprietary details should be aggregated (6, 7).

In many cases, LCA software tools like SimaPro, which rely on databases such as Ecoinvent, are used to calculate a product's environmental footprint based on its life cycle model (refer to Appendix A). However, aligning inventoried data with predefined materials and processes from these databases can be challenging, especially for LCAs of complex surgical instruments that involve specialised components and materials not commonly used in other industries. Predefined processes in these databases are often tailored to standard components and may not always be available or expressed in compatible units. For instance, in the LCA of a reusable syringe extension device , when modelling its manufacturing phase in SimaPro, Samenjo et al. (9) faced missing materials and processes from the Ecoinvent database. As a result, they substituted granulated polypropylene (PP) for homopolymer PP, wrought aluminium alloy for aluminium 6061 grade, and chose extrusion techniques instead of injection moulding. While these substitutions might approximate the environmental impacts of the original materials and processes, choosing alternatives that best match the required data is not always straightforward and any inaccuracies could significantly affect the reliability of LCA results. Particularly regarding material selection, practitioners may face challenges in selecting the most appropriate alternatives from an array of suitable options, as databases often provide several variations of certain materials, each with slight differences in treatment or condition.

This research suggests that when specific inventory data is unavailable, practitioners should select alternative materials or predefined processes that best approximate the required data, drawing from common practices for similar applications in the literature. In cases where multiple suitable alternatives exist, it is recommended to assess the environmental differences between potential substitutes. If no significant variation in environmental impact is found, the choice may have minimal influence on the final results. However, if large differences are identified, decisions should be guided by industry standards or expert insights. Alternatively, selecting the process with the highest environmental impact can help ensure results are not underestimated.

2.2.3 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) phase of an LCA evaluates the magnitude and significance of potential environmental impacts associated with the product system by converting the documented elementary flows into environmental impact indicators related to human health, natural resources, and the environment. This phase uses the LCIA method, corresponding category indicators, whether midpoint or endpoint, and any applicable LCA software outlined in the scope phase. The outcomes of this phase provide the basis for the subsequent interpretation phase (6, 7).

However, due to challenges related to data availability, with information frequently being outdated, of uncertain quality, or not comparable, especially when considering specific regions or impact categories, LCIA methodologies tend to calculate environmental impacts as 'potential impacts,' without accounting for local variations, time-specific factors, or rare events. This generalisation, coupled with assumptions about linear relationships between pollutants and impacts and the frequent use of worst-case scenarios, reduces their ability to accurately capture real-world environmental interactions. This inherent limitation can affect the reliability of LCA findings, and practitioners should be aware of it when interpreting results (4).

2.2.4 Interpretation

In the interpretation phase the LCIA results are evaluated against the goal and scope, focusing on the quality of data and methodological choices and assumptions, including completeness, accuracy and precision, as well as their consistency. It guides iterative refinements of the LCI model until alignment with the study's goal and scope definition is achieved, ensuring methodological appropriateness and data quality. This thorough evaluation process of the results aims to derive robust conclusions and recommendations appropriate to the LCA's intended applications. Results should be presented clearly to allow the audience to assess the robustness of conclusions and understand any limitations (6, 7).

2.2.4.1 Significant Aspects Identification

Effective interpretation of LCA results begins with identifying key aspects that significantly influence the outcomes. This includes major life cycle stages, processes, and elementary flows, which are typically highlighted through contribution analyses. These analyses break down the contributions of each element, quantifying their impact and often representing the data visually in formats like pie charts or stacked columns. Additionally, methodological choices and assumptions that may substantially affect the results can be pinpointed through the evaluation of scenario analysis outcomes (6, 7).

2.2.4.2 Results Evaluation

The results are then assessed for completeness, sensitivity, and consistency in relation to the data, methodological choices, and assumptions, with particular attention given to the significant aspects identified earlier. Where completeness checks determine whether all relevant processes and flows are included, sensitivity checks make sure the accuracy and precision of the results meet the study's requirements, enhancing their robustness where possible. Consistency checks ensure that all methodological choices, impact assessment steps, and data quality across processes align with the study's objectives (6, 7).

2.2.4.3 Iterative Approach

The iterative process is guided by the completeness, sensitivity, and consistency evaluations, aimed at refining the life cycle model to meet the quality and consistency standards established during the goal and scope definition. Enhancements may include incorporating more specific primary data for key contributors, improving the quality of data used in methodological decisions, and revising data for life cycle stages or flows that were initially underestimated. If enhancing data quality for certain contributors proves impractical, this should be documented, and those contributors may be excluded. After making these adjustments, the results are recalculated, and completeness, sensitivity, and consistency evaluations are repeated to inform further iterations. It is important to note that insights gained from each iteration may require adjustments to the study's goal and scope definition, especially if data limitations cannot be resolved (6, 7).

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

Based on the findings from the literature search, it is suggested that determining the appropriate level of detailed data to accurately represent the functional unit of a product system, particularly for complex technologies like surgical instruments which have not been as extensively studied in LCAs as other sectors, is challenging. Therefore, the reliability of LCA results heavily depends on practitioners' skills and experience in navigating this complexity and addressing data gaps while defining and modelling the product system. This highlights the importance of having a strong technical understanding of the surgical instrument in question, as well as expertise in LCA methodologies. Adequate training in these areas can significantly enhance the reliability of LCAs for surgical instruments. Furthermore, this underscores the value of repeating LCA studies on surgical instruments to gather insights that could facilitate the collection of the detailed data necessary for accurate evaluations in this field. The initial LCA may utilise average data for processes related to the product system, combined with expert judgement, to identify key processes and elementary flows. Identifying major contributors early on enables a more targeted approach in subsequent LCA studies, which can result in obtaining more detailed data on the most relevant aspects of the system.

2.2.4.5 Conclusions and Recommendations

Once the study's goals and application requirements are met, the results are analysed across the entire system, integrating various scenarios and uncertainty assessments. Conclusions and recommendations are formulated while carefully considering any remaining data gaps, sensitivities, and inconsistencies (6, 7).

Table 1: Summary of Identified Risk Factors and Corresponding Mitigation Strategies

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

Note: These risk factors include the inherent limitations of the LCA methodology that could compromise the reliability of findings in general, along with specific factors that may affect the reliability of conclusions drawn from LCAs of surgical instruments identified in the literature. For a more detailed explanation of each risk factor and further examples, please refer to Section 2.2

2.3 Survey on Stakeholder Perspectives of LCA Practices in the Surgical Field

To enhance understanding of the issues affecting the reliability of LCA findings in the surgical field and to explore considerations for more reliable LCA practices, it is essential to engage key stakeholders in this domain to evaluate the perceptions of LCAs and their usage within this field. This was accomplished by developing and distributing a survey among the approximately 3,500 active members of the European Association for Endoscopic Surgery (EAES), an organisation that plays a leading role in advancing innovation in endoscopic surgery to ensure safe and sustainable surgery for all. Membership in the EAES is open to professionals involved in any form of endoscopic surgery and minimally invasive techniques (34).

2.3.1 Methods

The survey was conducted from May 23rd to Aug 7th, 2024, using the online survey tool Qualtrics (35), with a reminder sent on July 1st to encourage participation. The survey consisted of 29 questions, divided into two sections. The first section examined participants' views on sustainability in the use of surgical instruments within their team and their familiarity with LCAs. The second section delved deeper into their experiences and opinions regarding LCA practices, particularly concerning their reliability in the surgical field. Participants who identified as not familiar at all with LCA practices were automatically directed to the end of the survey after section one, thus skipping the second section. Others were free to skip the second section if they felt not very familiar with LCAs. Participants could choose to skip any questions they preferred not to answer and could withdraw from the survey at any time without providing a reason. All procedures adhered to EAES's ethical guidelines. The consent statement is available in Appendix B. The data was analysed using frequency distribution.

2.3.2 Results

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

2.3.2.1 Survey Section 1

Regarding the roles of the respondents, the largest group were surgeons (83%), followed by surgical residents/trainees (11%). The rest (6%) identified as an anaesthesia assistant, OR nurse or technician (Fig. 2A). About half of the respondents indicated that sustainability concerning the use of surgical instrumentation within their team is rarely or never discussed (combined 51%), while 19% suggested that it is discussed daily (Fig. 2B). When asked if they felt there was sufficient awareness about the impact of using surgical instrumentation within their team, most respondents disagreed (44%), with more than half of them strongly disagreeing, while 25% agreed and the remaining respondents were neutral (Fig. 2C). Regarding sources consulted for information on the environmental impact of using surgical instrumentation, educational programs/workshops were the most frequently used, specifically by 48% of respondents. This was followed by academic or research articles/publications at 43%, and regulatory publications/guidelines at 39%. 15% of respondents admitted to not actively seeking information about the environmental impact of using surgical instrumentation (Fig. 2D). The influence respondents have on decision-making regarding the use of surgical instrumentation in their team varied. Most respondents (30%) contributed to discussions without having the final say, while 15% reported being uninvolved in decision-making. A minority (9%) indicated that they lead the decision-making process (Fig. 2E). When asked if they would consider the environmental impact in their decision-making process if they had full decision freedom, the majority agreed or strongly agreed (combined 80%), while 4% disagreed (Fig. 2F).

Most respondents considered themselves slightly familiar with LCAs (37%), followed by moderately familiar (24%) and not familiar at all (17%). The remaining 22% considered themselves highly or extremely familiar (Fig 2G). Moreover, 37% of respondents indicated that LCAs currently do not influence decision-making about the choice of surgical instrumentation within their teams, while another 37% stated that they do have an influence. Meanwhile, 26% reported that they were uncertain (Fig. 2H). One respondent (2%) indicated not to consider attending training sessions or workshops focused on conducting LCAs specific to surgical instrumentation or utilising their findings if they were available. The rest indicated they would attend these training sessions/workshops or might attend (50% and 48% respectively) (Fig. 2I). Most respondents would prefer online webinars for these training sessions (35%), but in-person workshops, interactive online courses, and hybrid training sessions were also favoured (23%, 19%, and 16% respectively). 7% of respondents preferred recorded video tutorials (Fig. 2J). Preferences for the frequency of these training sessions varied, with once a month being favoured by most respondents (29%). No one preferred weekly sessions (Fig. 2K).

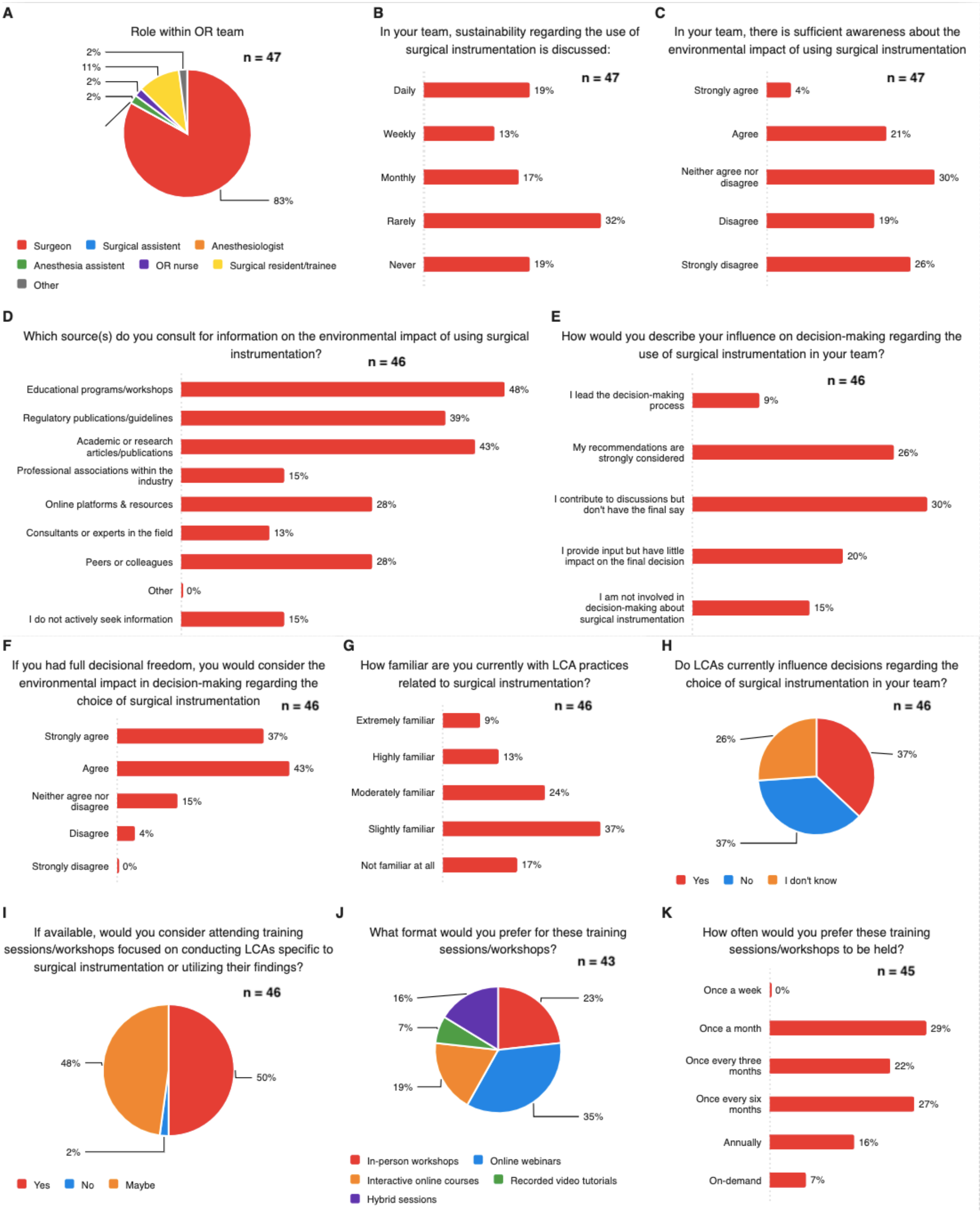

Figure 2: **Survey Data for Questions from Section 1**. *Note: The data is expressed as percentages of all responses, with each subfigure representing a different question. For the question represented in subfigure D, multiple answers could be selected, so the percentages of all answer choices do not add up to 100%.*

2.3.2.2 Survey Section 2

Among the respondents who completed both sections of the survey, a slight majority (52%) indicated they have never used LCA findings to understand the environmental impact of surgical instruments (Fig. 3A). For those who sought information on using LCA findings, the most frequently used sources were academic or research articles/publications (48%), followed by regulatory publications/guidelines (41%) and educational programs/workshops (37%). 15% of respondents admitted to not consulting any sources for information on utilising LCA findings (Fig. 3B).

When asked about their trust in LCA findings related to surgical instrumentation, more than half of the respondents indicated moderate trust (52%). High trust and complete trust were each indicated by 19% of the respondents, while the remaining 11% expressed slight trust. No respondents reported having no trust at all in LCA findings (Fig. 3C). When respondents were asked about the degree to which certain aspects influence their trust in LCA findings, for each aspect most responses indicated a 'somewhat' influence, followed by 'highly' and 'extremely' (Fig. 3D). Specifically, all aspects received an average influence rating between 3 and 4, reflecting a range of 'somewhat" to 'highly.' When asked for any additional aspects that influence their trust in LCA findings, one respondent mentioned the number of variables assessed in LCAs. Additionally, one respondent (4%) indicated having personal experience questioning the findings of an LCA related to surgical instrumentation, as they were unsure of the methodology used in that specific LCA (Fig. 3E). The vast majority (92%) reported not using any tools/methods for evaluating the accuracy and trustworthiness of LCA findings (Fig. 3F). When asked if they considered the existing tools and methods sufficient for this purpose, the majority were neutral (52%), 32% agreed, and 16% disagreed (Fig. 3G).

Among the respondents who completed both sections of the survey, the vast majority (96%) indicated they have never been involved in conducting an LCA related to surgical instrumentation, while one respondent reported involvement (Fig. 3H). For those who sought information on conducting LCAs, the most frequently used sources were regulatory publications/guidelines (52%), followed by academic or research articles/publications (43%) and educational programs/workshops (39%). 26% of respondents admitted to not consulting any sources for information on conducting LCAs (Fig. 3I). When asked if they felt there is sufficient access to the necessary data/tools/methods/guidance to carefully conduct an LCA in the surgical instrumentation sector, the majority were neutral (58%), followed by 25% agreeing, while 17% disagreed (Fig. 3J). Those who disagreed reported challenges such as the presence of too many variables, difficulty finding unbiased information, not knowing where to search for LCA information, and a general lack of awareness about LCAs.

Regarding the degree to which certain aspects contribute to doubts about the trustworthiness of LCA findings, for each aspect most responses indicated a 'somewhat' contribution, followed by 'highly'. Specifically, the average contribution rating for each aspect fell between 3 and 4, reflecting a range from 'somewhat' to 'highly' (Fig. 3K). When asked for additional aspects that contribute to doubts about the trustworthiness of LCA findings, one respondent mentioned that LCAs often leave out important variables, making the results unreliable. Similarly, when evaluating the degree to which certain aspects of surgical instrumentation are inadequately addressed in current LCAs, for each aspect most responses indicated 'somewhat', followed by 'highly', with all aspects receiving an average rating between 'somewhat' and 'highly' (Fig. 3L). When asked for additional inadequately addressed aspects, one respondent mentioned spare parts and transport to and from cleaning and sterilisation.

When asked whether they believed that introducing training sessions or workshops on conducting LCAs and utilising their findings would enhance the quality of LCAs within the surgical instrumentation sector, a majority agreed (72%), with 16% strongly agreeing. 24% expressed neutrality, while one respondent (4%) disagreed (Fig. 3M). Regarding the aspects on which respondents would like these training sessions or workshops to provide guidance, more than half of the respondents selected defining the product or process, establishing system boundaries and functional units, and collecting data (56%, 60%, and 60% respectively). All other given aspects were also indicated by at least a quarter of the respondents as areas where they would like guidance (Fig. 3N).

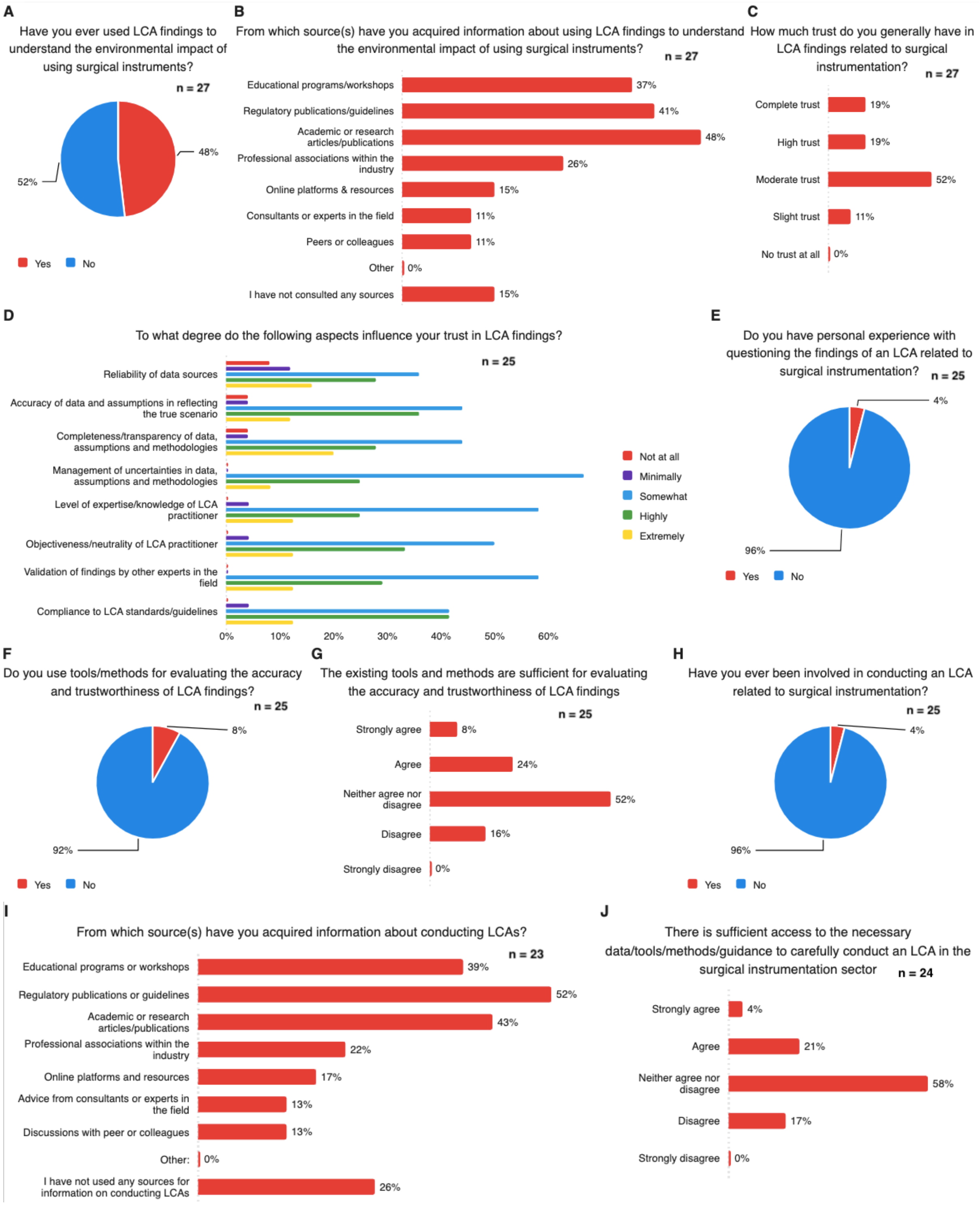

Figure 3 (part 1): Survey Data for Questions from Section 2. *Note: The data is expressed as percentages of all responses, with each subfigure representing a different question. For the questions represented in subfigure B and I, multiple answers could be selected, so for both questions the percentages of all answer choices do not add up to 100%.*

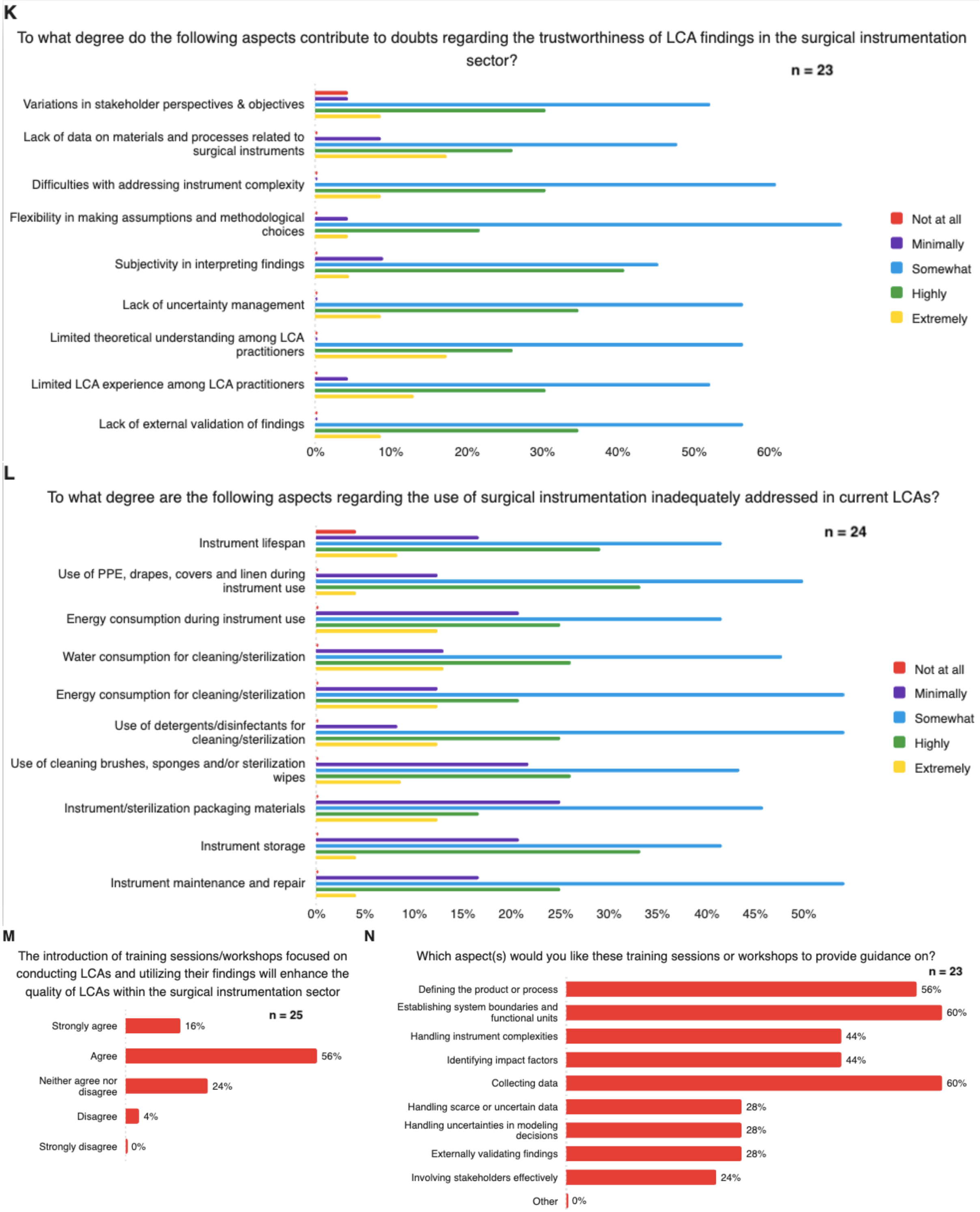

Figure 3 (part 2): Survey Data for Questions Section 2. *Note: The data is expressed as percentages of all responses, with each subfigure representing a different question. For the question represented in subfigure N, multiple answers could be selected, so the percentages of all answer choices do not add up to 100%.*

2.3.3 Discussion

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

2.3.3.1 Sustainability Awareness & Discussion

A noteworthy finding is that sustainability regarding the use of surgical instrumentation is rarely or never discussed within the teams of more than half of the respondents, with only a small percentage reporting daily discussions on this topic within their teams. Despite the increasing formation of green teams focused on developing environmentally conscious practices within the OR and exploring strategies to minimise medical waste and resource consumption (refer to Appendix A), these results indicate a considerable gap in attention and dialogue about the environmental impact of surgical instrumentation use in surgical teams. This is supported by the finding that only a quarter of the respondents agreed there is sufficient awareness about the environmental impact of surgical instrumentation use, while nearly double that number disagreed, indicating that many surgical team members themselves feel that there is inadequate awareness and discussion on this issue.

2.3.3.2 Roles & Influence of Respondents

80% of respondents indicated that they would consider environmental impact when selecting surgical instrumentation if they had full decision-making freedom, highlighting a strong interest in sustainability among surgical teams. The fact that over 80% of the respondents are surgeons is particularly significant, as surgeons are often expected to play a central role in discussions about surgical instrumentation within their teams. This positions them as key advocates for raising awareness and driving sustainability practices in the OR. Indeed, approximately one-third of the respondents contribute to discussions on instrumentation use but do not have the final say, while about a quarter reported that their recommendations are strongly considered. Although these findings suggest that not all surgeons lead the decision-making process, most are involved in some capacity and could therefore take on a greater role in advancing sustainability within their teams, especially since most of them feel there is currently inadequate awareness and discussion around this issue.

2.3.3.3 Familiarity with LCAs

Familiarity with LCAs is generally low, with only a small fraction of respondents considering themselves highly or extremely familiar. This correlates with the finding that within the teams of three-quarters of the respondents, LCAs do not influence decision-making or it is unknown if they do. This suggests a significant opportunity to enhance the impact of LCAs in the OR through education and integration of LCAs into decision-making processes regarding surgical instrumentation. Almost all respondents expressed openness to attending training sessions or workshops on LCAs, except for one, with varied preferences for the format and frequency of these sessions. Online webinars were the most preferred, followed by in-person workshops, with sessions held once a month or once every six months being favoured.

2.3.3.4 Trust in LCA Findings

Among the respondents who completed section 2 of the survey and are therefore at least slightly familiar with LCAs, a slight majority have never used LCA findings to understand the environmental impact of surgical instruments. While LCAs are generally recognized as valuable tools for informed environmental decision-making (4), most respondents express a moderate level of trust in LCA findings related to surgical instrumentation, which may further explain the limited use of LCAs in decision-making in this area. This moderate trust level is reflected in the evaluation of various factors contributing to doubts about the reliability of LCA findings, with all aspects receiving average contribution ratings between 'somewhat' and 'highly.' Similar average ratings were noted regarding the degree to which certain aspects of surgical instrumentation usage are inadequately addressed in current LCAs. This suggests that there is room for improvement in these areas to enhance trust in LCA results for surgical instrumentation, potentially increasing their use in decision-making.

The majority of respondents do not use any tools or methods to evaluate the accuracy and trustworthiness of LCA findings, indicating a need for increased awareness of existing tools and methods, training on how to use them, or even the development of new tools and methods if the existing ones are limited. This lack of use of evaluation tools might explain why most respondents were neutral about whether existing tools and methods are sufficient, as they are likely unfamiliar with what tools and methods exist. Only one respondent reported having personal experience with conducting an LCA related to surgical instrumentation, aligning with the overall low familiarity with LCA practices. This unfamiliarity with conducting LCAs may also explain why most respondents are neutral about whether there is sufficient access to necessary data, tools, methods, and guidance to carefully conduct LCAs in the surgical instrumentation sector.

2.3.3.5 LCA Training & Workshops

Nearly three-quarters of respondents who are at least slightly familiar with LCAs believe that introducing training sessions or workshops on conducting LCAs and utilising their findings would enhance the quality of LCAs in the surgical instrumentation sector. Respondents expressed a particular desire for guidance on defining the product, establishing system boundaries and functional units, and collecting data, indicating these as specific areas where training could be most beneficial.

2.3.4 Limitations

This survey has several limitations that may affect the reliability and generalizability of the results. Firstly, only members of the surgical association were invited to participate, which may not represent the broader population of medical professionals involved in surgical instrumentation. Additionally, the opening statement of the survey mentioned that it is a vital component of a research study in the field of sustainability within the surgical instrumentation sector, potentially attracting a group of active individuals who prioritise sustainability, leading to a biassed view of the results. This might explain why the overwhelming majority agreed that they would consider the environmental impact in their decision-making process regarding the choice of surgical instrumentation if they had full decision freedom. Conversely, individuals who lack knowledge about LCAs might have been discouraged from participating due to the survey's title or introduction, believing they were not qualified, even though the first section was intended for all EAES members regardless of their familiarity with LCAs. Those who still chose to participate despite considering themselves slightly or moderately familiar with LCAs still had the option to answer all questions in the second section, potentially leading to less informed responses.

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

III. PART 2: Life Cycle Assessment of an Innovative Reusable SATA Instrument for Robotic Surgery: A Robust Comparative & Eco-Design Analysis

3.1 Methods

Building on the foundation established in the previous part of this research, this section aims to conduct a robust LCA that functions both as a comparative analysis and an eco-design evaluation. Typically, LCAs for eco-design involve modelling various hypothetical design scenarios, such as adjustments to materials or configurations, and comparing their environmental impacts to identify the most eco-friendly option. In these 'linear' eco-design approaches, each design scenario is treated as an input to the LCA, generating different impact results. The scenario with the lowest environmental impact is then identified as the most sustainable option, thereby guiding design choices (7). However, in this particular LCA, where the environmental impacts of a product in its current design are compared to those of a functionally identical alternative, the focus shifts from creating hypothetical design scenarios to evaluating the product's existing design for both comparative and eco-design purposes.

This will be achieved by using scenario analyses to not only strengthen the robustness of the comparative LCA results but also to identify opportunities for substantial environmental improvements within the product's existing design. By modelling various scenarios for different life cycle aspects of the product's current design, it becomes possible to identify the life cycle aspect that shows the greatest variation in comparative impact results relative to the functionally identical product across the modelled scenarios, theoretically indicating where the largest environmental gains could be achieved. Understanding how life cycle aspects are shaped by design decisions enables targeted design recommendations to realise these environmental enhancements. However, recognizing that limited design flexibility may restrict the practical realisation of these potential gains identified in the scenario analysis, redesign efforts will initially focus on the life cycle aspect with the potential to achieve the most significant environmental improvements through feasible modifications to the product's current design. Due to time constraints, it is not feasible to analyse different scenarios for every life cycle phase aspect. Therefore, the scenario analyses will focus on aspects with uncertain assumptions in this LCA, as well as those identified in the first part of this research as particularly sensitive to changes in assumptions. For an illustration of this adapted 'circular' LCA approach for eco-design alongside the typical 'linear' LCA approach for eco-design, please refer to Figure 4.

3.2 Goal

The goal of this LCA is to accurately assess the environmental footprint of the innovative reusable SATA instrument technology for robotic surgery while identifying potential design modifications to improve its environmental performance. This will be accomplished through a detailed and robust comparative LCA that critically assesses the environmental impacts of one of the newly developed SATA instruments relative to its traditional disposable counterpart, incorporating insights from the initial research phase and following the adapted LCA methodology for eco-design. The findings will support healthcare decision-makers in making environmentally conscious procurement choices and guide the developers of this innovative robotic instrument technology in implementing environmentally responsible design improvements during its ongoing development.

Since the innovative SATA instruments are still in its prototype phase and not yet in regular use, it is important to clarify that the findings from this comparative analysis, intended for public disclosure, are specific to its current design for mass production. Although future design updates are expected to be informed by the insights from this LCA, further studies will be necessary to confirm that these updates indeed align with the environmental performance improvements indicated in the initial findings.

This LCA was commissioned by the Sustainable Surgery & Translational Technology group MI & BITE, part of Delft University of Technology, which focuses on developing innovative technical systems and instruments for minimally invasive surgery, including the newly developed reusable instrument technology for robotic surgery. The research is being conducted by a master's student at Delft University of Technology as part of their thesis project.

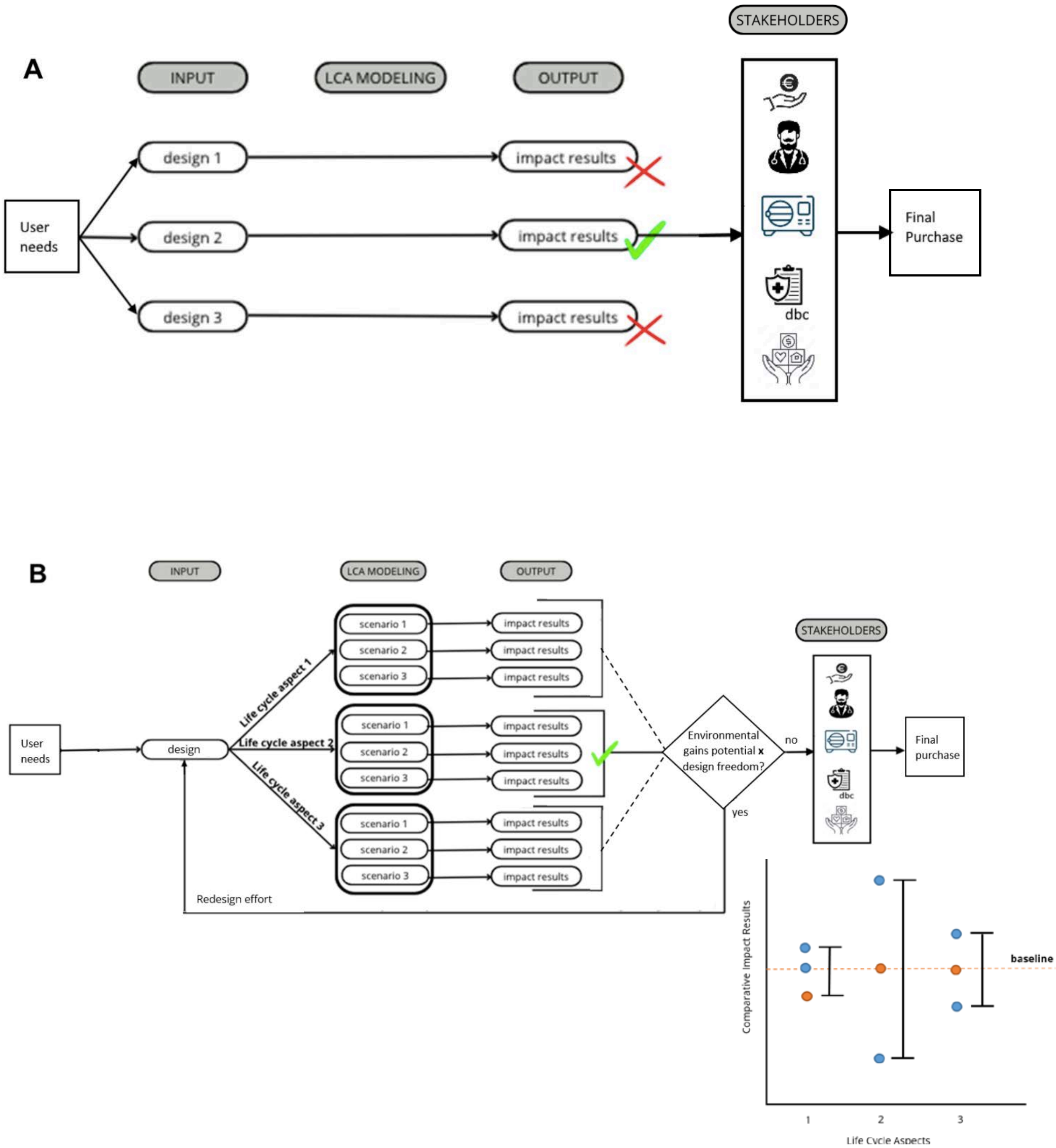

Figure 4: Different LCA Approaches for Eco-Design. *Note: **A**, the typical 'linear' approach; **B**, the adapted 'circular' approach. In the typical LCA approach for eco-design, the green checkmark indicates the design scenario with the lowest environmental impact, marking it as the most environmentally friendly option. In the adapted approach, by analysing comparative impact results for the product's current design relative to a functionally identical product across various modelled life cycle aspect scenarios (illustrated in the bottom-right section of subfigure B) and understanding how design decisions shape life cycle aspects, the life cycle aspect with the potential for the largest environmental gains through feasible modifications to the product's current design can be pinpointed. This aspect, marked with a green check, will serve as the initial focus of redesign efforts. While other life cycle aspects may also show variations in comparative impact results across different scenarios, offering opportunities for environmental improvements, these gains are either smaller or lack feasible design modifications to realise them effectively, and therefore are not prioritised initially. It is important to note that, before investing in an instrument with enhanced environmental performance, hospitals also consider factors such as costs, healthcare providers' preferences, the instrument's capacity for thorough cleaning and sterilisation to ensure patient safety, and reimbursement considerations from the DBC system and insurance providers.*

3.3 Scope

3.3.1 Product Definition

The products compared in this LCA are two steerable laparoscopic devices designed for robotic surgery, specifically intended to grasp, hold and manipulate tissues, organs, or other objects during surgical procedures (36). These include the traditional 8 mm Intuitive Da Vinci Xi Maryland Bipolar Forceps (model 471172) and the innovative shaft-actuated tip articulation (SATA) grasper, developed by the Surgery & Translational Technology group of Bite-ME, which features a modular design. Images of these devices can be found in Figure 5. The Maryland Forceps is compatible with the Da Vinci Xi and X robotic systems, while the SATA grasper is initially designed for use with the newly developed Advanced Laparoscopy (AdLap) robotic system.

Both devices consist of a driver, a shaft, and a tip beak assembly. The driver connects to the robotic system, separated by a drape to maintain the sterility of the robotic system itself. It houses mechanisms that transmit power from the robotic system to the device, converting electrical or mechanical input into the necessary movements. While the electric motors for the Maryland Bipolar Forceps are located in the Da Vinci robotic system, the SATA driver contains its own motors. However, this design poses challenges as the motors, being at risk of contamination due to their exposure to the surgical environment, are difficult to clean and sterilise. The SATA driver's modular design addresses this issue by integrating a sterile barrier (SB) interface, connected via a clip to the drape, which isolates the motor unit (MU) from the potentially contaminated gearbox (GB) that engages the shaft. This design prevents contamination of the MU while allowing the rest of the device to be cleaned and sterilised (37). For both devices, the component that connects the driver to the drape, such as the SB interface clip in the SATA, is excluded from the analysis. Additionally, since the SATA driver's MU remains sterile and functions similarly to the motor component in the Da Vinci system for the Maryland, the MU of the SATA device is also excluded from the product definition.

The shaft ensures that the movements generated by the driver are translated into the rotations and translations of the tip while also providing structural support and access to the surgical site. While the Maryland Bipolar Forceps uses a cable-driven mechanism, the innovative SATA grasper employs a cableless design that transmits movement through shaft rotations. This cable-free approach allows for a modular structure, making the device easier to disassemble for cleaning, inspection, and maintenance at the component level (1).

The tip beak, in this LCA study a grasper, directly interacts with tissue and performs precise surgical tasks. While the Maryland Bipolar Forceps has the added capability to coagulate tissue using electric current due to its bipolarity, this feature is not utilised in every procedure or by every surgeon (36). To ensure a fair comparison with the SATA grasper, which in its current version does not yet include this functionality, the bipolar function of the Maryland, along with the components solely responsible for this feature, are excluded from the analysis.

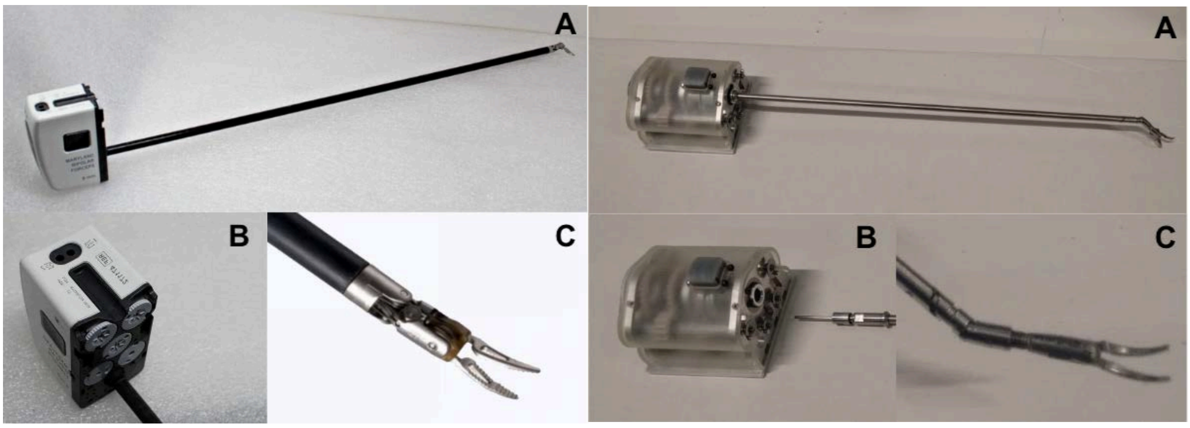

Figure 5: Devices Under Study. *Note:* ***A****, complete devices;* ***B****, driver assembly;* ***C****, tip grasper assembly. The traditional 8 mm Intuitive Da Vinci Xi Maryland Bipolar Forceps (model 471172) is displayed on the left (38), with the innovative SATA grasper on the right (images provided by the Surgery & Translational Technology group of Bite-ME). In Subfigure B, the SATA grasper's cable-free shaft design is highlighted, showcasing its modular structure.*

Due to its innovative nature and lack of current clinical use, the exact number of times the SATA grasper can be reused is difficult to determine. Developers anticipate that, with regular replacements of worn-out parts, the device could be used well over 100 times. However, taking patient safety into account and based on input from experts familiar with the practical application of similar devices, a conservative estimate of 100 uses is assumed for this analysis, with components of the tip grasper assembly being replaced every 50 uses. In contrast, the Maryland Bipolar Forceps, which is designed for limited reuse, has a manufacturer-specified lifespan of 14 uses (38). For the purposes of this analysis, the Maryland Bipolar Forceps will be referred to as the reposable device, while the SATA grasper will be referred to as the reusable device. A specification of both devices is provided in Table 2.

The functional unit is based on a conservative estimate of the reusable device's lifespan and is specifically defined as 100 uses of a steerable laparoscopic device for robotic surgery, designed to grasp, hold, and manipulate tissues, organs, or other objects. Accordingly, the reference flow is set at one reusable device and seven reposable devices to fulfil this functional unit. Although seven reposable devices technically provide only 98 uses instead of 100, this approach allows the LCA to generate more reliable results regarding whether the reusable technology truly offers environmental benefits compared to the disposable alternative. By maintaining a reference flow of seven reposable devices rather than eight, the LCA avoids presenting a biassed outcome in favour of the reusable device.

Recognizing that the actual lifespan of the reusable device may differ significantly from expectations and given that LCA results are highly sensitive to assumptions about the frequency of reuse before disposal, a break-even analysis will be conducted to avoid drawing inaccurate conclusions due to potential misestimations of its lifespan. Additionally, the assumption that the tip grasper assembly is replaced every 50 uses is also based on developer expectations rather than real-world data. Therefore, a scenario analysis will examine how varying the number of uses before tip replacement affects the results. This analysis will include scenarios where the tip grasper assembly is replaced after every 25 uses and another where replacement occurs already after 10 uses.

Table 2: Product Specification

Product	Reference term	Manufacturer	Place of origin	Robotic surgery system	Lifespan (uses)
8 mm Intuitive Da Vinci Maryland Bipolar Forceps (model 471172)	Reposable device	*Intuitive Surgical*	Sunnyvale, California, USA	Da Vinci Xi & X	14
SATA grasper	Reusable device	*Van Straten Medical*	De Meern, The Netherlands	AdLap	100 (incl. 1 tip beak replacement)

Note: AdLap, Advanced Laparoscopy; SATA, Shaft-actuated Tip Articulation; USA, United States of America

3.3.2 System Boundaries

As the LCA aims to compare the environmental impacts directly associated with the devices under study without considering broader market or environmental changes that might result from product-related decisions, an attributional modelling approach will be used. In line with this approach, the system boundaries for this LCA have been defined. This cradle-to-grave comparative LCA covers the complete life cycles of the devices, divided into distinct phases: materials, manufacturing, transport, use, disposal and their end-of-life potential. The reusable device includes an additional phase, the repair phase, situated between its use and disposal. Figure 6 illustrates the product systems for both the reusable and reposable device, clearly outlining the processes included within the system boundaries. Per functional unit, one reusable and seven reposable devices complete the full life cycle. For a detailed overview of the life cycle processes and aspects not included in the comparison, but which may still contribute to the devices' environmental footprint, along with their anticipated impact, refer to Appendix C.

For both devices, the materials phase covers the production of the materials used in the devices. Although this process could theoretically be divided into separate processes such as raw material extraction, processing, and transportation to the manufacturing site, the lack of specific data for these stages introduces uncertainties regarding the precise boundaries of the data. As a result, the material production process is not subdivided further, with the assumption that the impacts of these subprocesses are fully captured within the broader material production process. Similarly, any impacts associated with the collection of material waste after device manufacturing, as well as any potential credits for recovering this waste, are included within the overall material production process. The manufacturing phase addresses the actual production of the devices. While it is assumed that the reposable device is delivered in a sterile condition, the final sterilisation process during manufacturing is excluded from this phase due to a lack of data from the manufacturer. Instead, an initial sterilisation process that occurs when the device is first unpackaged is assigned to the use phase. To maintain consistency and ensure a fair comparison with the reusable device, the same approach is taken for the reusable device’s product system.

Since the transportation impacts related to moving materials from extraction locations to the manufacturing site are already included in the material phase, the transport phase focuses solely on the transport of the finished devices. This includes the journey from the manufacturing site to the hospital where the devices will be used, potentially involving distributors along the way, as well as transportation from the hospital to waste management facilities. Packaging used for transporting the devices has been excluded from the analysis due to data limitations. This exclusion is partly justified by the fact that both devices are similar in size and shape, leading to the assumption that their packaging would be comparable and would therefore result in similar environmental impacts.

In this analysis, the use phase focuses on the reprocessing practices that both devices undergo before each reuse, specifically disinfection and sterilisation, including an initial sterilisation when the device is first unpackaged. The environmental impacts primarily involve those associated with the operational use of disinfecting washing machines and sterilising autoclaves, as well as the impacts of the packaging used for sterilisation, as prior literature in this research has indicated these processes to be a significant contributor to the environmental footprint of reusable instruments. Following the attributional modelling approach used in this LCA, volume-based allocation will be applied to account for the multifunctionality of these processes. Due to data limitations, sterilisation packaging is not subdivided into separate processes. Instead, it is assumed that the impacts related to its material production, manufacturing, transportation to the hospital, and waste treatment are captured within the overall sterilisation packaging process. While operational impacts of washing machines and autoclaves are included, the impacts associated with their production, transport, and disposal are excluded, consistent with common LCA practices that consider these impacts minimal relative to operational use due to the longevity of such equipment (as discussed in the first part of this research). This exclusion also applies to other reprocessing equipment like baskets, trays, and containers. Additional elements of reprocessing, such as manual cleaning and related equipment, are excluded from the analysis due to limited data.

Aspects or processes associated with the operational use of both devices are excluded from the system boundaries, as they are assumed to be consistent across both devices or not directly related to their life cycles. This includes elements such as hospital infrastructure and capital goods like the robotic surgery system. Although the reusable device was originally designed for the AdLap robotic system and the reposable device is currently used with the da Vinci robot, for simplification, it is assumed that the reusable device is also compatible with the da Vinci robot. Therefore, both devices are considered to operate under the same conditions, justifying the exclusion of the robotic systems from the analysis. Furthermore, other surgical instruments and accessories used in robotic procedures are excluded due to their variability, which can depend on factors such as the type of procedure or surgeon preferences. Including these elements could introduce significant uncertainty and potentially colour the comparative impact results of the two devices being evaluated.

The disposal phase encompasses the impacts related to the disposal of the devices, including their collection and sorting at waste treatment facilities in preparation for their intended waste treatment process. Additionally, this analysis will account for the direct environmental impacts of each device's waste treatment process, along with any potential future savings from material recovery through the selected treatment method. The combination of these impacts will be referred to as the devices' end-of-life potential (29).

The key difference between the product systems of the two devices lies in the repair phase, which applies only to the reusable device. Due to its modular design, only simple part replacements are assumed, so the impacts associated with the actual repair process, including the use of instruments, accessories, capital goods, and repair facility infrastructure, are expected to be minimal and are therefore excluded for simplicity. This phase does account for the transportation of the device to and from the offsite repair facility, the material production and manufacturing of replacement parts, as well as the disposal and waste treatment process of the worn components.

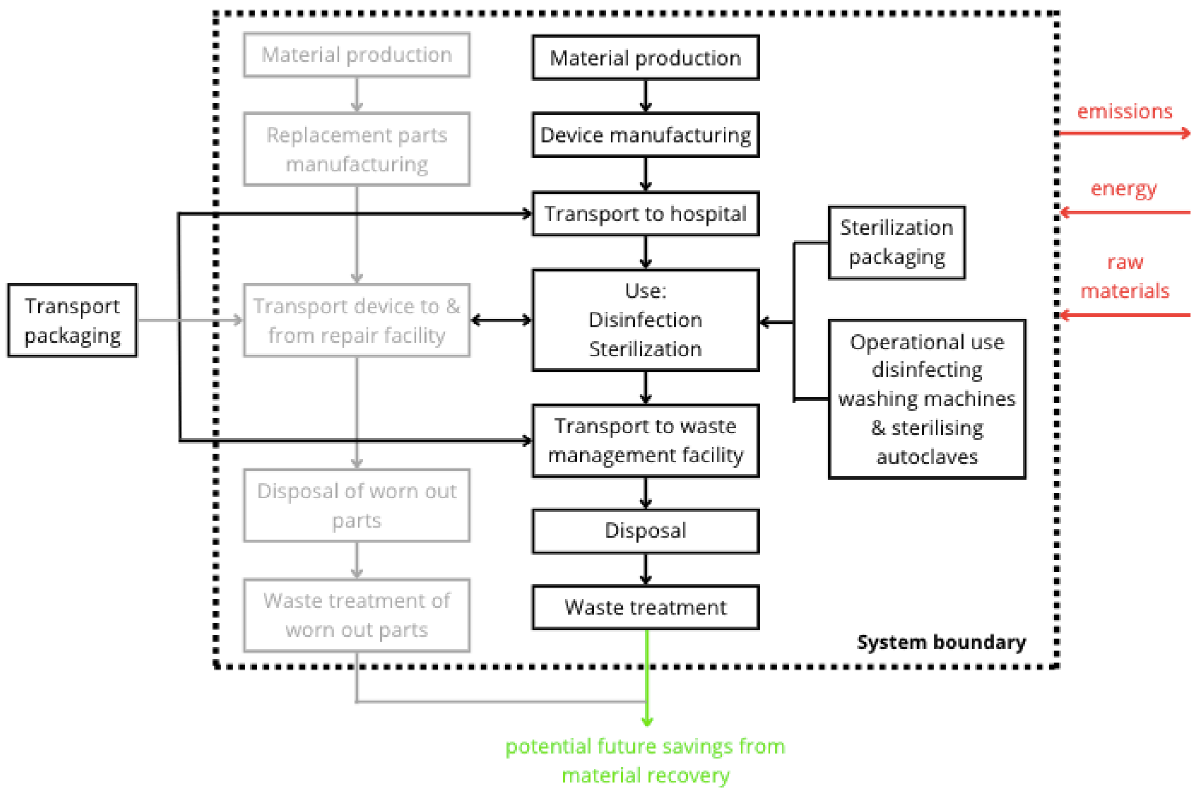

Figure 6: Product System. *Note: Processes enclosed within the dashed lines are included in this analysis. The gray-shaded processes apply exclusively to the reusable device's repair phase. Black arrows indicate intermediate flows within the product system, while green and red arrows represent elementary flows—inputs or outputs of the product system that have not undergone prior or subsequent human transformation (5). Flows crossing the system boundaries correspond to inputs and outputs specific to the processes they connect with. Processes outside the dashed lines are excluded from the analysis. For a more detailed overview of life cycle processes and aspects not included in the comparison, but which may still contribute to the devices' environmental footprint, please refer to Appendix C.*

3.3.3 Data Collection Process

For the reposable device, while certain manufacturing details can be gathered through the direct examination of a physical sample provided for this study, collecting primary data for other device-specific life cycle processes, such as transportation and waste treatment, falls outside the scope of this research. In the case of the reusable device, since it is not yet in clinical use, primary data for most life cycle stages is unavailable, aside from manufacturing data that may be provided directly by the manufacturer. Therefore, assumptions must be made about its life cycle, based on typical practices for similar applications, particularly the reposable device, and drawing on expert opinions and expectations from the reusable device's developers and manufacturers.

To ensure data quality in this LCA, given the limited availability of primary data on the device-specific life cycle processes for both devices, secondary data will be gathered from well-documented and verified databases and literature, supplemented by expert insights. This approach aims to achieve a reasonable balance of data completeness and precision. Whenever possible, device-specific information will be prioritised to improve data accuracy, while average data reflecting typical practices for similar applications will only be used when necessary. To further enhance data accuracy, a reference hospital will be selected for data collection on device transportation and reprocessing practices specific to the devices under study. In cases where uncertainty arises during the data collection process about which data best reflects real-world scenarios, a 'worst-case scenario' approach will be applied to avoid underestimating environmental impacts.

3.3.4 Impact Assessment Method

The analysis focuses on two key environmental impact categories: climate change (measured in carbon dioxide equivalents (CO2-eq) to capture the total impact of greenhouse gas emissions) and energy demand (expressed in megajoules (MJ) to reflect total energy consumption). These categories were chosen because they are widely recognized and frequently used as critical environmental indicators (29). While they do not encompass the full range of environmental effects, other impact categories were excluded due to time constraints and limited data availability.

Due to licensing restrictions, commonly used LCA software, which models life cycle processes based on inventoried data and automatically generates a detailed environmental footprint, were not accessible for this study. Instead, the EcoAudit tool within the Granta Edupack software package was utilised, as it was available to the practitioner. This tool draws data from the 'Level 3 Eco-Design' database and primarily focuses on the environmental impact indicators of climate change (using the Intergovernmental Panel on Climate Change (IPCC) LCIA method) and energy demand (using the Cumulative Energy Demand (CED) LCIA method) (29), limiting the inclusion of other impact categories in the analysis. Processes not directly handled by EcoAudit will be modelled using a custom Excel file.

Since this LCA study offers a comparative assessment for public disclosure, normalisation and weighting of results were avoided to ensure neutral and transparent findings. Multiple scenario analyses were conducted to strengthen result robustness and ensure their applicability in practical contexts. However, a comprehensive uncertainty analysis to assess potential variability in environmental impacts from alternative life cycle assumptions beyond those covered in the planned scenarios and to account for natural data fluctuations to further enhance result robustness was beyond the study's scope.

3.4 Life Cycle Inventory

The data collection and modelling process for each phase of the devices' life cycles is outlined below. For information on the quality of the inventory data, please refer to Appendix D.

3.4.1 Materials & Manufacturing

For the reusable device, the manufacturer provided SolidWorks files detailing the exact dimensions of each component, along with information on material types and manufacturing processes for most parts, assuming mass production conditions. However, data was not available for off-the-shelf components like screws, clips, and washers, which are sourced as pre-manufactured items rather than produced in-house. However, this information was unavailable for off-the-shelf components like screws, clips, and washers which are sourced as pre-made items rather than produced in-house. For these components, material types were inferred from common practices found in the literature, considering the harsh conditions of surgical environments and the reprocessing practices they must withstand. Once material types were assigned to each component in the SolidWorks file, the software automatically calculated the weight of each part according to its material and dimensions. In order to account for the lack of primary data on manufacturing processes for the off-the-shelf components, common practices for similar materials and shapes were derived from the literature, ensuring consistency with the processes applied to the other parts of the reusable device.

For the reposable device, information about its composition was gathered by physically disassembling and examining a provided sample, specifically an 8 mm Intuitive Da Vinci Maryland Bipolar Forceps (470172-T), designed for 30 training uses. While this model is not identical to the one assessed in the LCA, its manufacturing is assumed to closely resemble that of the model under review. Following disassembly and with the guidance of instrument manufacturing experts, components related to the device's bipolar function were identified and excluded from the comparison. Given the small size and number of components related to the reposable device's bipolar function, their exclusion is unlikely to significantly affect the overall results. The material type of each remaining part was determined with expert assistance, further supported by standard practices documented in the literature. Each component's weight was measured using a scale with a 100 grams capacity and 0.001 grams resolution. Similar to the off-the-shelf components of the reusable device, to address the lack of primary data on the manufacturing processes of the reposable device's components, common manufacturing practices for similar materials and shapes were derived from the literature, ensuring consistency with the processes applied to the reusable device's components.

To model material production, corresponding materials from the EcoAudit tool were selected for each component based on their closest match to the available inventory data. These selections were guided by standard industry practices described in the literature and supported by insights from manufacturing experts. A worst-case scenario was applied, assuming that all materials for both devices are virgin, with no recycled content, and that all feedstock is sourced from raw materials. The same approach was used for modelling the manufacturing process, with predefined processes from the EcoAudit tool for the selected materials serving as inputs, aligned with the best available inventory data.

Additionally, to accurately capture the impact of both material production and device manufacturing, the EcoAudit tool requires specifying the percentage of material removed during production for each component. EcoAudit assumes that all this waste material is either recycled or, if recycling is not feasible, downcycled and reintegrated into the material supply chain. For processes where components are shaped from a solid block of material, a fixed waste removal percentage is applied based on an instrument manufacturer's expertise. Although processes in which components are shaped in moulds are generally more efficient with minimal material loss, there can still be some waste, typically in the form of support structures (29). Operating under a worst-case scenario, a small fixed waste percentage is applied to account for this potential material loss.

For a summary of the composition of both devices, their respective manufacturing processes, and the input data used in EcoAudit, refer to Table 3. For a detailed breakdown of the inventory results for each device component, along with the input data selected to represent these inventory items, please refer to Appendix E.

Table 3: Overview of Device Composition, Manufacturing & Waste Treatment Processes

Device (weight *)	Material type	Material *(Input EcoAudit)*	Weight (% of total device)	Manufacturing process *(input EcoAudit)*	Waste treatment process *(input EcoAudit)*
Reposable (180 grams)	Metal	SS *(Stainless steel, austenitic, AISI 304, annealed)*	22.5	CNC machining *(forging, fine machining, 50% removed)*	Incineration *(landfill, 0% recovered)*
		Alu *(Aluminium, 7075, T73)*	2.2		
		Ti *(Titanium, alpha-beta alloy, Ti6Al-4V, annealed)*	0.4		
		Brass *(Brass, CuZn36Pb3, C36000, soft (free-cutting brass))*	0.1		
	Plastic	PTFE *(PTFE (15% glass fibre))*	1.8	CNC machining *(polymer extrusion, fine machining, 50% removed)*	
		ABS (ABS (high-impact, injection molding))	55.5	Injection molding *(polymer molding, fine machining, 2% removed)*	Incineration *(combust, 95% recovered)*
		PMMA *(PMMA (moulding and extrusion))*	0.7		
	Composite	CFRP *(Epoxy/HS carbon fibre, UD prepreg, QI lay-up)*	17.2	Injection molding *(compression moulding, cutting and trimming, 2% removed)*	Incineration *(combust, 70% recovered)*
Reusable (270 grams)	Metal	SS 316 (Stainless steel, austenitic, AISI 316, annealed)	42.3	CNC machining / laser cutting *(forging, fine machining, 50% removed)*	Recycling *(recycle, 75% recoverd)*
				Injection molding *(metal powder forming, fine machining, 2% removed)*	
		Alu 7075 (Aluminium, 7075, T73)	34.9	CNC machining *(forging, fine machining, 50% removed)*	
	Plastic	PEEK (PEEK (30% carbon fibre))	4.0	CNC machining *(polymer extrusion, fine machining, 50% removed)*	Landfill *(landfill, 0% recovered)*
		ABS *(ABS (high-impact, injection molding))*	17.8	Injection molding *(polymer molding, fine machining, 2% removed)*	Downcycling *(downcycle, 75% recovered)*

Note: -, unspecified; ABS, Acrylonitrile Butadiene Styrene; Alu, Aluminium; CFRP, Carbon Filled Reinforced Polymer; ; CNC, Computer Numerical Control; PEEK, Polyetheretherketone; PMMA, Polymethyl Methacrylate; PTFE, Polytetrafluoroethylene; SS, Stainless Steel; Ti, Titanium; *****, The weight of components not included in the device's product system is excluded from the total weight calculation.

3.4.2 Transport

According to procurement experts in medical instruments, the reposable device is most likely transported by truck from its manufacturing site at Intuitive Surgical in Sunnyvale, California, to the Port of Los Angeles, and then shipped via container ship across the ocean to the Port of Amsterdam. Here, the device is temporarily stored in a warehouse before being distributed by truck to hospitals. In contrast, upon its market introduction, the reusable device would be distributed directly from its manufacturing facility at Van Straten Medical in De Meern to hospitals using a smaller van, as indicated by the manufacturer. For this LCA study, the Leiden University Medical Center (LUMC) has been selected as the reference hospital, as it is situated at a relatively similar distance from distribution points, being neither the closest nor the furthest hospital. It is therefore assumed that both devices are delivered to the LUMC from their respective distribution locations.

After reaching its manufacturer-specified lifespan of 14 uses, the reposable device is assumed to be transported by truck, along with other medical waste from LUMC, to ZAVIN, a waste management facility in Dordrecht where medical waste from hospitals across the Netherlands, including LUMC, is typically processed and incinerated (39). Meanwhile, as intended by its manufacturer's, the reusable device will be transported by a smaller van to Green Cycle in De Meern once it reaches the end of its lifecycle. Green Cycle, co-founded by Van Straten Medical, specialises in the collection and reprocessing of hospital waste, allowing Van Straten Medical to reuse the recovered materials for the production and distribution of recycled medical products (40).

All road transport distances were estimated in kilometres using Google Maps, while sea distances were calculated with sea-distances.org (with nautical miles converted to kilometres via a Google converter), both assuming the fastest route. In line with the manufacturing phase, the EcoAudit tool was used to model this phase, with input data selected to best match the available inventory data, guided by common practices for similar applications found in the literature and expert insights.

For an overview of all transport routes, including distances covered, modes of transportation used, and the corresponding input data for EcoAudit, please refer to Table 4.

Table 4: Overview of Transport Routes

Device	From	To	Mode	Distance (km)	Input EcoAudit
Reposable	*Intuitive Surgical*, Sunnyvale (USA)	Port of Los Angeles	Truck	598	Truck 16-32t, EURO 5 - 598
	Port of Los Angeles	Port of Amsterdam (NL)	Container ship	14409	Sea, container ship - 14409
	Port of Amsterdam	*LUMC*, Leiden	Truck	43.6	Truck 7.5-16t, EURO 5 - 43.6
	LUMC, Leiden	*ZAVIN*, Dordrecht	Truck	67.7	Truck 16-32t, EURO 5 - 67.7
Reusable	*Van Straten Medical*, de Meern (NL)	*LUMC*, Leiden	Van	53.8	Light commercial vehicles - 53.8
	LUMC, Leiden	*Green Cycle*, de Meern	Van	54.1	Light commercial vehicles - 54.1

Note: EURO, refers to the European emission standards for vehicles; LUMC, Leiden Universitair Medisch Centrum; NL, Netherlands; t, metric tons (1,000 kilograms); USA, United States of America. For example, a 16-32t, EURO 5 truck signifies a truck with a weight capacity between 16 metric tons (16,000 kg) and 32 metric tons (32,000 kg) that complies with Euro 5 emission standards. While Euro 6 is the most current emission regulation in Europe, a significant portion of the transportation fleet still operates using Euro 5 engines (41). To account for this and operate under a worst-case scenario, Euro 5 trucks are chosen for this analysis. Given that many trucks in the U.S. meet emission standards comparable to Euro 5 (41), this standard is also used for truck transport in the USA.

3.4.3 Use

For both devices, one reprocessing cycle (disinfection followed by sterilisation) is conducted before each reuse. The reposable device, with a lifespan of 14 uses, undergoes 13 reuses during its lifecycle, while the reusable device, with an assumed lifespan of 100 uses, goes through 99 reuses. After 50 uses, the reusable device requires a repair process, which involves one disinfection cycle before and one sterilisation cycle after. This accounts for one reprocessing cycle, meaning it does not add to the total number of disinfection or sterilisation cycles across the reusable device's lifecycle. To ensure consistency and allow a fair comparison with the reposable device, the repair-related disinfection and sterilisation cycles are assumed to occur at the healthcare facility, with the associated impacts assigned to the reusable device's use phase. Additionally, after 100 uses, the reusable device requires one more disinfection cycle before it can be reprocessed at Green Cycle. For consistency this process is also assumed to take place at the hospital. Including the initial sterilisation prior to first use, this results in a total of 13 disinfection and 14 sterilisation cycles per lifecycle for the reposable device and 100 disinfection and sterilisation cycles for the reusable device.

As outlined in the scope, for the use phase of both devices, this analysis focuses specifically on the operational use of disinfecting washing machines and sterilising autoclaves, as well as the full lifecycle of the packaging used for sterilisation. Due to the lack of primary data specific to LUMC and the EcoAudit tool's inability to directly model these processes, energy demand and climate change impacts were sourced from literature.

Friedericy et al. (27) evaluated the environmental impacts of two sterilisation packaging methods at LUMC, comparing the carbon footprint of 5,000 single-use blue wraps with one reusable rigid sterilisation container. They considered material production, manufacturing, transport, energy use for heating the packaging during sterilisation, and waste incineration. Since Friedericy et al. (27) identified blue wrap as LUMC's standard, the total carbon footprint for 5,000 blue wraps was divided by 5,000 to estimate the climate change impact per unit of sterilisation packaging. As detailed CO_2 emissions data for each process were not provided, the EU-27 average electricity mix emission factor was applied to convert the overall carbon footprint into energy demand. Although this approach might misrepresent processes like transport and incineration, which typically involve higher emission factors from fuel combustion, the use of the lower electricity emission factor ensures the energy demand is not underestimated.

In contrast to sterilisation packaging, for which detailed data about its impact at LUMC was available from literature, no specific information was found regarding the reprocessing machines used at LUMC or their operational impact. To fill this gap, data was taken from Rizan et al. (23), who evaluated the carbon footprint of a typical cycle for a disinfecting washer (Steelco TW300/3, 12-slot capacity) and a steam steriliser (BMM Weston V9934, 18-slot capacity) in a UK hospital. Their evaluation was based on typical loading patterns observed during an audit and accounted for the machines' consumption of energy, water, and disinfectants. Although these machines may not perfectly match those used at LUMC, selecting models that are neither the largest nor the smallest, with energy- and water-saving systems though not the most advanced, provides a conservative estimate of environmental impact. Based on expert insights into medical instrument reprocessing, this estimate is assumed to be reasonable for LUMC's scale and efficiency of sterilisation processes. To align more accurately with LUMC practices, the emission factor for the Dutch average electricity mix was applied, replacing the UK factors used by Rizan et al.(23), recalculating the carbon footprint for the washer and steriliser's energy use.

To allocate the estimated impacts of a single reprocessing machine cycle and one unit of sterilisation packaging to an individual device, assumptions were made due to data limitations. Mean machine-loading efficiencies used by Rizan et al. (23) were applied, with each slot accommodating one instrument tray. Based on feedback from reprocessing professionals, it was assumed that six reposable devices fit into a specialized laparoscopic tray, which is wrapped in a single blue wrap. According to these experts, the tray also accommodates components of a flushing system necessary for directing disinfectant fluid and steam through the shaft of the device. This system ensures effective cleaning and sterilization by eliminating biological debris, contaminants, and fluids from the shaft's internal channels. Additionally, the devices are positioned at an angle within the tray to optimize the flushing and drying process.

Since the reusable device is slightly smaller than the reposable device, it is anticipated that at least an equal number of units could fit into an instrument tray. However, its modular design, which allows the shaft to be detached from both the driver and tip assemblies, is expected to enable a more space-efficient arrangement. This modularity, combined with the cableless, hollow design of the shaft, enhances cleaning efficiency by providing direct access to the shaft interior. As this design allows for effective fluid and steam access even in more horizontal positions, placing the reusable device at a steep angle may no longer be necessary, potentially enabling the stacking of multiple shaft layers within the tray. Furthermore, the open and accessible shaft likely eliminates the need for a flushing system to push disinfectant and steam through complex channels. With the modular design facilitating efficient separation of the shaft from the driver and tip assemblies, improving tray arrangement and allowing for multiple stacked layers while likely eliminating the need for a flushing system, it is expected that a significantly higher number of reusable devices could fit in a tray compared to the reposable devices. Using a conservative estimate, it is assumed that twice as many reusable devices, specifically 12 units, could be accommodated in a single instrument tray.

Given the uncertainties regarding how well these assumptions represent actual conditions at LUMC, and the sensitivity of reprocessing impacts to loading efficiency, scenario analyses will explore variations in impact allocation. This includes examining environmental outcomes under different machine-loading efficiencies, such as using half the mean loading efficiency from Rizan et al. (23) and assuming maximal machine loading. Additionally, alternative scenarios will assess the assumption that an instrument tray can hold twice as many reusable devices as reposable devices, allocating the reusable device half of the impacts per reprocessing cycle allocated to the reposable device. These scenarios will consider the effect of assuming equal capacity for both device types in a tray, therefore matching the reusable device's allocation with that of the reposable device, and of assuming three times the tray capacity for reusable devices, allocating one-third of the reposable device's reprocessing impact per cycle.

For a comprehensive overview of the sourced data on the operational use of disinfecting washers, sterilising autoclaves, and the full lifecycle of sterilisation packaging, along with the estimated impacts of each process per cycle/unit, please refer to Table 5.

Table 5: Estimated Impact Data on Disinfecting Washers, Sterilising Autoclaves, and Sterilisation Packaging

	Sourced data				Estimations per cycle/unit	
Product (model/type)	Machine loading efficiency (occupied slots)	Inputs	Quanitity	Carbon footprint (kg CO2e)	Climate change (kg CO2e)	Energy demand (MJ)
Disinfecting washer (Steelco TW300/3, 12-slot capacity)	67.5% (8.1)	Detergent	150 mL	0.05	0.05	-
		Electricity	8.17 kWh	2.58	2.68	29.41
		Natural gas	0.36 m3 (3.86 kWh)	0.83	1.27 *	13.90
		Water supply & treatment	255 L	0.27	0.27 *	-
		Total (1 cycle)	-	3.74	4.27	43.31
Sterilising autoclave (BMM Weston V9934, 18-slot capacity)	62.9% (11.33)	Electricity	4.27 kWh	1.35	1.40 *	15.37
		Natural gas	4.35 m3 (46.28 kWh)	9.98	15.18 *	166.61
		Water supply & treatment	760 L	0.80	0.80	-
		Total (1 cycle)	-	12.13	17.38	181.98
Sterilisation packaging (blue wrap)	-	Total (5000 units)	-	1869	0.374	4.81 **

*Note: All estimations are based on one cycle/unit per product. The conversion from power to energy is calculated using the formula 1 kWh = 3.6 MJ. * This data is estimated using the emission factor for the Dutch average electricity mix, which is 0.328 kg CO_2eq/kWh (42); ** This data is estimated using the emission factor for the EU-27 average electricity mix, which is 0.280 kg CO_2eq/kWh (43).*

3.4.4 Disposal & End-of-life Potential

Typically, contaminated hospital waste, including surgical instruments at the end of their lifespan, is transported to incineration facilities to ensure safe disposal and prevent the spread of infections (39). While there is a growing trend to recycle metals from simpler instruments like stainless steel scissors, the complexity of disassembling more advanced devices, which are composed of numerous permanently attached components made from various materials, makes recovering recyclable materials more challenging (as identified in the first part of this research). Therefore, in this LCA, the reposable device is treated as contaminated hospital waste and is assumed to undergo incineration with heat recovery.

In contrast, the modular design of the reusable device allows for easier manual disassembly after it is collected by Green Cycle and disinfected, making material recovery feasible. While recycling efforts for plastics are expanding, many processes remain unavailable for certain types of plastics due to complexity and degradation issues (44). Therefore, plastics that Green Cycle can process are assumed to be downcycled, while those not commonly handled there are assumed to be sent to landfill. All metal components of the reusable device are assumed to be recycled.

To model the disposal and waste treatment processes for each device, the end-of-life pathways provided by the EcoAudit tool for the selected materials were used as inputs, aligned with the intended waste treatment methods for those materials. If a matching end-of-life pathway was not available in the tool, the field was left blank, and the default assumption of landfill as the final route was applied, except in the case of toxic materials, which were automatically set to downcycling. Additionally, the EcoAudit tool required specifying the percentage of material expected to be recovered through the chosen waste treatment process, with unrecovered materials assumed to be sent to landfill. Since determining exact recovery percentages would require extensive research beyond the scope of this study, these percentages were estimated using expert insights from a surgical instrument reprocessing professional, considering worst-case scenarios. To explore the impacts of optimised recovery, a scenario analysis will be conducted, assuming 100% material recovery to assess the potential effects if recycling processes were fully efficient.

Please refer to Table 3 for an overview of the assumed waste treatment processes and the corresponding end-of-life input data used in EcoAudit for each material in both devices.

Given uncertainties around the exact end-of-life pathways for both devices, the end-of-life potential will be shown separately as a distinct life cycle phase. This allows for a comparison of both devices without this phase, evaluating environmental impacts over one lifecycle, and with this phase, where potential future savings are considered.

3.4.5 Repair

Instead of being discarded after 50 uses, the reusable device is assumed to be returned to its manufacturer, Van Straten Medical, which specialises in both surgical instrument manufacturing and repair. At this facility, the reusable device undergoes a simple repair process, specifically replacing the tip grasper assembly, after which it can be used for an additional 50 cycles before final disposal.

Since the transportation impact of the reusable device from Van Straten Medical to the LUMC after manufacturing has already been assessed in the transportation phase, it can be directly applied and doubled to account for the round-trip transportation to and from the offsite repair facility. As only the tip grasper assembly is being replaced, and the material production, manufacturing processes, disposal, and end-of-life potential for the corresponding components have already been modelled in the manufacturing and end-of-life phases, these impacts will be combined and used to represent the material production and manufacturing of replacement parts, as well as the disposal and end-of-life potential of discarded components. The transportation impact to and from the repair facility will then be added to give the total impact of the repair phase.

In the scenario analysis, which includes scenarios where the tip beak is replaced after every 25 uses and another where replacement occurs after 10 uses, the impact of the repair phase will be multiplied by 3 and 9, respectively.

3.5 Life Cycle Impact Assessment

While use-phase impacts were directly estimated from literature, impacts from other life cycle phases, including materials, manufacturing, transport, disposal, end-of-life potential, and repair of the reusable device, were modelled using the EcoAudit tool's capabilities. The input data, closely aligned with the inventory, were automatically processed within EcoAudit to calculate climate change and energy demand impacts, following IPCC and CED LCIA methods. To align with the functional unit, which accounts for one reusable device and seven reposable devices, the impacts calculated for the reposable device using the EcoAudit tool were scaled by a factor of seven. Detailed calculations for allocating estimated use-phase impacts to match the functional unit are provided in Appendix F.

Figure 7 provides a visual comparison of life cycle impacts for both devices based on a functional unit of 100 uses. In both the climate change and energy demand categories, the reusable device shows less than half the environmental impact of the reposable device, with values of 24.13 kg CO_2-eq versus 58.01 kg CO_2-eq and 272.74 MJ versus 716.93 MJ, resulting in reductions of 58.4% CO_2-eq and 62.0% MJ.

Figure 8 presents a break-even analysis for the climate change impact category, indicating the number of uses at which the climate change impacts of both devices equalise. Due to the high similarity, the break-even analysis for energy demand is not included here but is available in Appendix G.

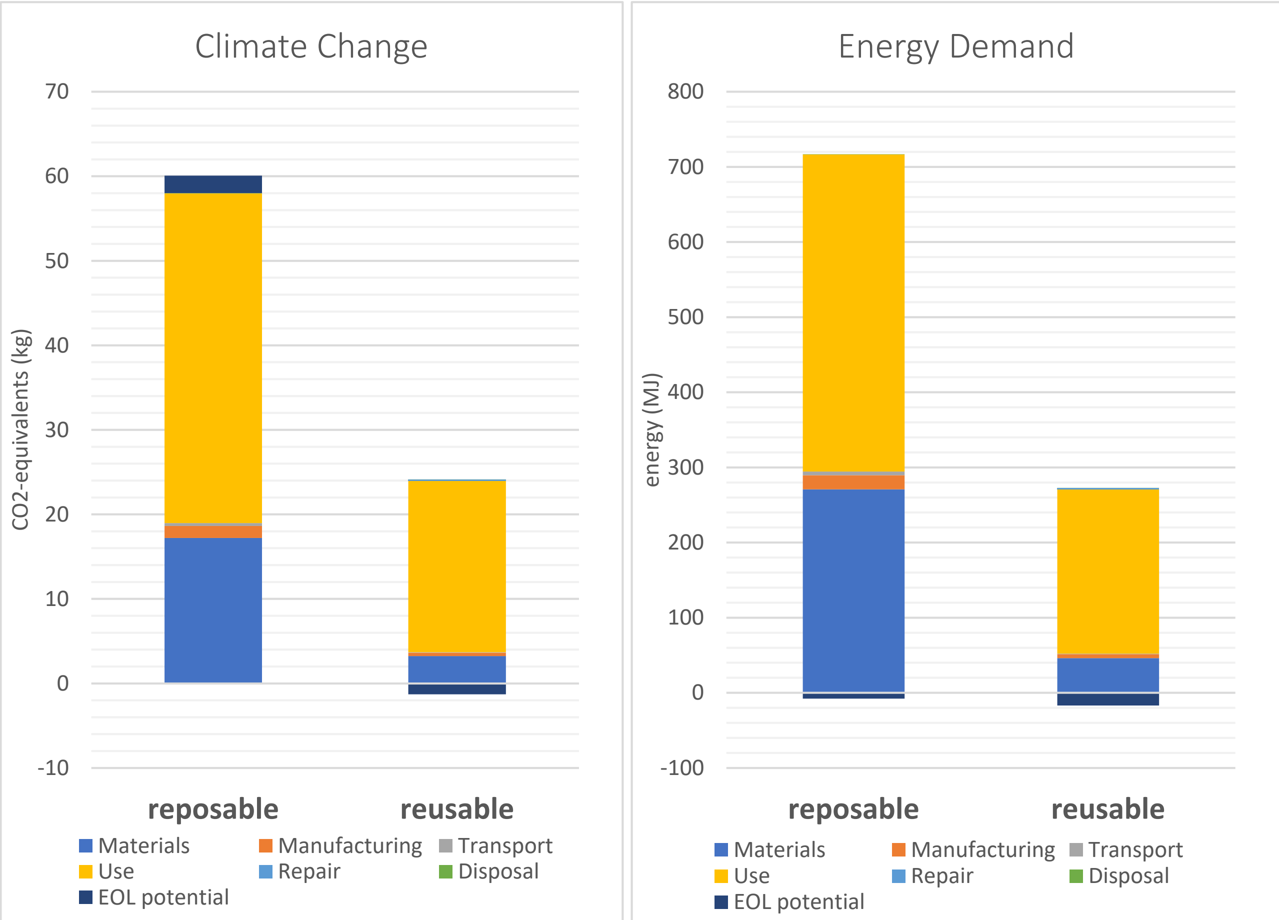

Figure 7: LCIA Results. *Note*: *The left side illustrates the impact results for both devices in terms of climate change (measured in kg CO2 equivalents) for the defined functional unit of 100 uses, while the right side shows the impact results related to energy demand (measured in MJ). Negative values indicate impact savings.*

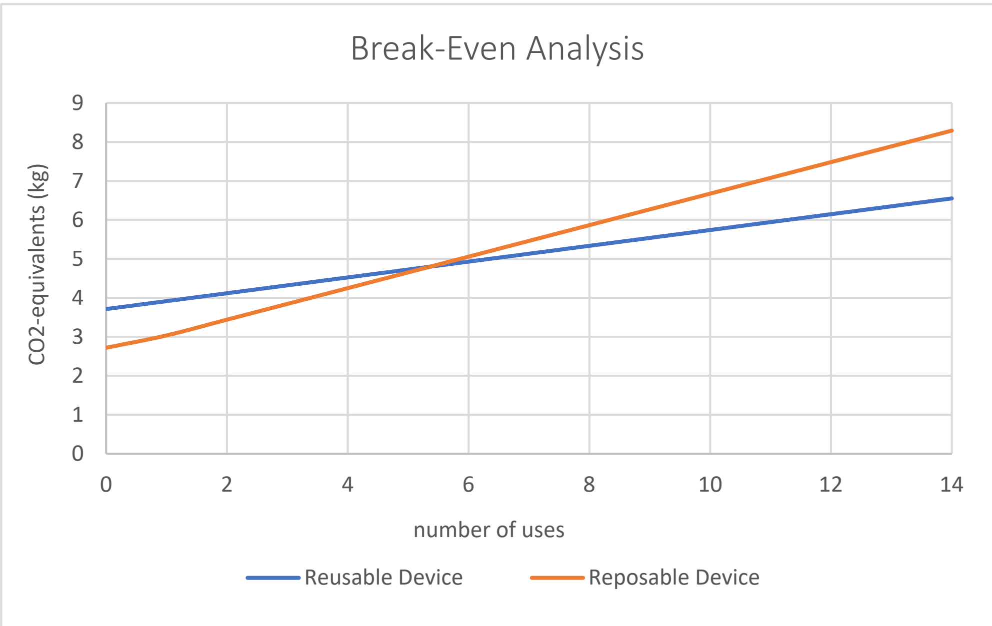

Figure 8: Break-Even Analysis. *Note: This figure illustrates the break-even point for the climate change impact category, defined as the number of device uses at which climate change impacts are equal for both devices.*

All comparative results under alternative assumptions modelled in scenario analyses are detailed in Appendix H, with an illustrative summary for the climate change impact category presented in Figure 9 and for the energy demand impact category in Appendix G. Adjusting machine-loading assumptions shows that reducing machine-loading to half of the baseline (mean efficiencies of 67.5% for the disinfecting washer and 62.9% for the sterilising autoclave per Rizan et al.) slightly decreases impact reduction percentages, while optimal machine-loading slightly increases them. When the tray capacity of the reusable device is matched to that of the reposable device, the reusable device still achieves overall reductions, though these are considerably smaller than under the baseline assumption of double capacity. Conversely, a scenario with a tray capacity three times larger than the reposable device results in the highest reduction percentages. Additional analysis shows that even if the reusable device's tip grasper assembly needs more frequent replacements, every 25 or 10 uses instead of 50, its environmental impact remains less than half that of the reposable device. Furthermore, including end-of-life potential in both the baseline and alternative scenarios leads to somewhat higher reduction percentages compared to excluding this phase. A scenario assuming fully efficient recycling and downcycling of the reusable device's recoverable materials, achieving a 100% material recovery rate, offers minimal additional reductions over the baseline 75% recovery rate.

For a visual representation of how these results are subsequently applied in the adapted 'circular' LCA approach for eco-design, guiding design recommendations to further improve the reusable device's environmental footprint, please refer to Figure 10. A complete breakdown of impacts per life cycle phase for both devices, across baseline and alternative scenarios, can be found in Appendix I.

3.6 Interpretation

3.6.1 Comparative Analysis

The main finding of this LCA is that for a functional unit of 100 uses based on the reusable device's expected lifespan, within the LUMC context, the reusable device achieves climate change and energy demand impact reductions of 58.4% in CO_2-eq and 62.0% in MJ, respectively, compared to the reposable device. These comparable percentages across both impact categories are largely due to the use phase's dominance, where the energy-intensive disinfection and sterilisation cycles before each reuse are the biggest contributors to climate change and energy demand impacts for both devices. While the materials phase also contributes somewhat to their overall impact, all other phases together account for less than 5%. This outcome aligns with findings from other LCAs on reusable instruments, highlighting the importance of energy-efficient reprocessing equipment and renewable energy sources to reduce impacts for devices intended for multiple uses.

Some uncertainties remain regarding how accurately the use-phase impacts reflect actual conditions at LUMC, due to data limitations about how the devices are specifically reprocessed within the hospital. This is particularly relevant for loading efficiencies, for which assumptions had to be made to determine the share of reprocessing machine and sterilisation packaging impacts allocated to each device. While the baseline assumption of approximately two-thirds machine-loading efficiency aligns with other LCAs on reusable surgical instruments and is likely reasonable, scenario analysis shows that even when machine-loading efficiencies are maximised for both the disinfecting washer and sterilising autoclave, thereby reducing use-phase impacts for both devices, the use phase remains the dominant contributor. Moreover, given that reprocessing conditions are expected to be relatively consistent for both devices, these uncertainties are unlikely to alter the conclusion that the reusable device offers significant impact reductions compared to the reposable device.

The primary distinction is that the modular design of the reusable device likely allows more units per instrument tray than the reposable device. This analysis assumes double the tray capacity for the reusable device, thereby applying only half the reprocessing machine and sterilisation packaging impacts compared to the reposable device. However, even in a 'worst-case' scenario, where the reusable device's tray capacity matches that of the reposable device, the reusable device still demonstrates lower overall environmental impacts. Although this scenario leads to slightly higher use-phase impacts for the reusable device than the reposable device, due to a few additional reprocessing cycles needed to fulfil the 100-use functional unit, these are outweighed by reduced impacts in other life cycle phases due to the reusable device's extended lifespan. While materials, manufacturing, transport, and disposal impacts are individually higher for a single reusable device than for a single reposable device, fulfilling the 100-use functional unit requires only one reusable device compared to multiple reposable devices, resulting in a cumulative impact advantage for the reusable option.

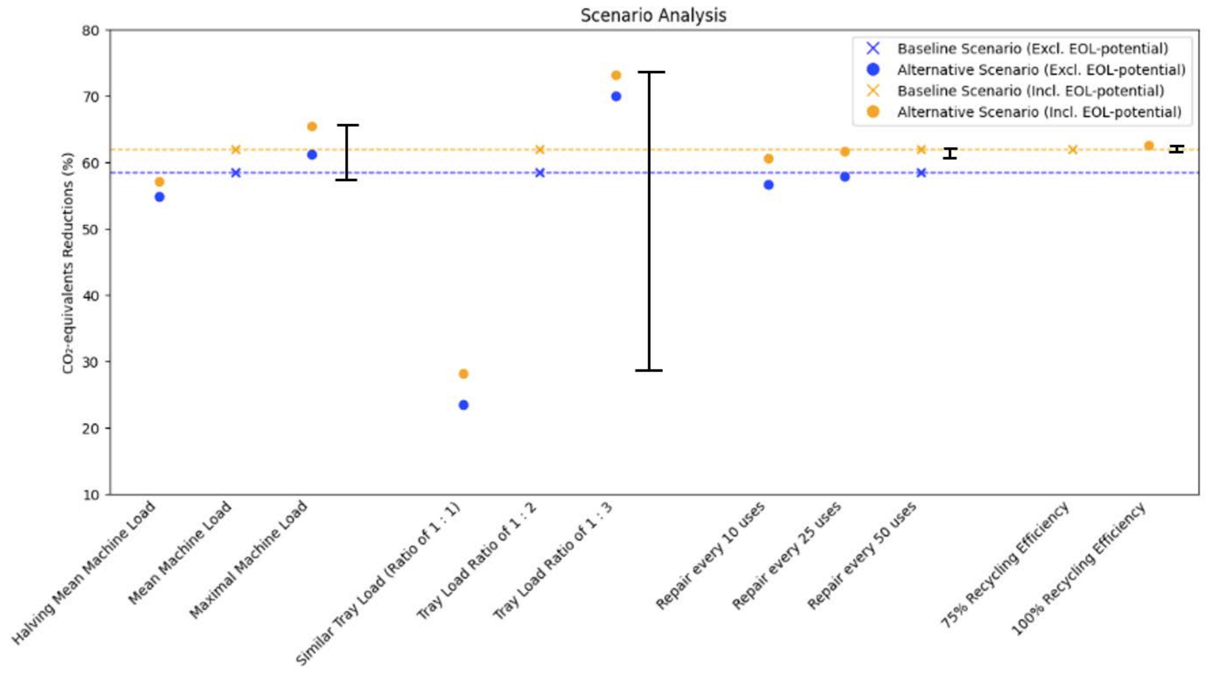

Figure 9: Scenario Analysis. *Note: This figure presents the comparative impact results for the climate change category between the two devices across baseline and alternative scenarios, with crosses representing baseline scenarios and dots representing alternative scenarios for both excluding and including end-of-life (EOL) potential. The scenario analysis assesses life cycle aspects including machine load efficiency, tray load capacity, repair frequency, and recycling efficiency. Results are shown as climate change impact reduction percentages for the reusable device relative to the disposable device, with variations across scenarios, including EOL potential, for each life cycle aspect marked by a distance indicator. Dashed lines highlight the baseline scenarios, clearly differentiating the one that excludes EOL potential from the one that includes it.*

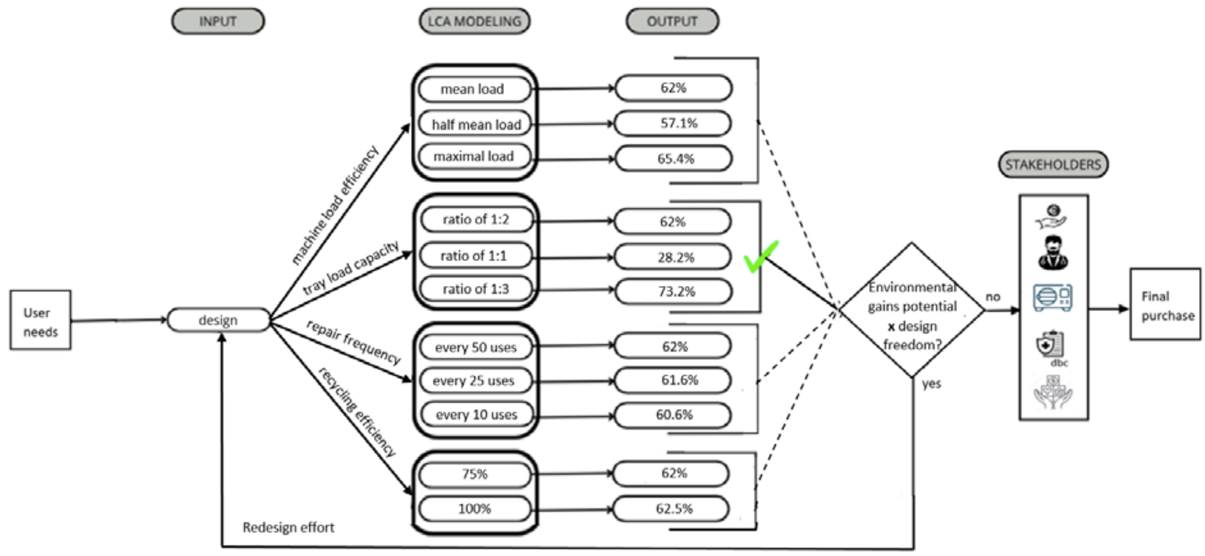

Figure 10: Circular Eco-Design Approach. *Note: In the scenario analyses, various scenarios are modelled for life cycle aspects, including machine load efficiency, tray load capacity, repair frequency, and recycling efficiency, with the top scenario for each aspect indicating the baseline. While different scenarios for machine load efficiency are applied to both devices, affecting the impacts of both, adjustments for the other life cycle aspects are made solely to the reusable device, influencing its impacts alone. The outputs represent the climate change impact reduction percentages of the reusable device relative to the reposable device across the modelled scenarios where end-of-life potential is included. The green checkmark highlights the life cycle aspect identified in this analysis as having the potential for the greatest additional environmental gains for the reusable device achievable through feasible modifications to its current design, thereby serving as the initial focus of redesign efforts. Although other life cycle aspects also might show variations in outputs across different scenarios, the additional environmental gains that could be achieved in these areas are either smaller or lack feasible design modification options to effectively realise them, and are therefore not prioritised initially.*

Additionally, although not included in this LCA, the disassembly capability of the reusable device likely improves reprocessing efficiency relative to the reposable device by making surfaces more accessible, potentially reducing the need for aggressive disinfectants, lower temperatures, and shorter processing times. In practice, this improvement may result in lower environmental impacts during the use phase. Furthermore, while not accounted for in this analysis, the reposable device requires a complex flushing process, likely increasing its reprocessing impact, whereas this requirement is probably unnecessary for the reusable device due to its hollow, easily accessible shaft enabled by its modular and cableless design. This distinction further underscores the reusable device's environmental advantages.

While inventory data quality across most life cycle phases was comparable between devices, as secondary data sources were consistent, notable differences arose in the materials and manufacturing phase. For the reposable device, material types and manufacturing processes were gathered through disassembly and observation rather than relying on direct manufacturing data as was done for the reusable device. This approach introduces some uncertainty in data quality for the reposable device, in contrast to the more precise data available for the reusable device. Additionally, certain permanently bonded components in the reposable device could not be fully separated, limiting accuracy in assessing their weight and material composition. To address these data quality differences, materials and manufacturing processes from similar components of the reusable device were applied to the reposable device, ensuring consistency and reducing the likelihood that these uncertainties would significantly impact the comparative findings.

Further uncertainty arises from selecting predefined processes in the EcoAudit tool to represent inventoried life cycle data. This was especially relevant for manufacturing processes, as the EcoAudit tool requires distinctions between primary and secondary processes and specifications of removed material percentages, while direct data for the reusable device consisted of only a single manufacturing process. To ensure consistency, similar secondary processes were chosen for all components of both devices wherever feasible within the EcoAudit tool for the selected materials. Because the removed material percentage is specific to the selected material type, similar values for plastic injection moulding were used for metal part injection, even though metal part injection likely involves higher impacts due to binder extraction and additional energy for sintering. Additionally, while most components undergo finishing processes such as anodizing or surface polishing in practice, these steps were not captured by the EcoAudit tool. Although these exclusions may slightly underestimate manufacturing-related impacts, the consistent application of metal part injection to similar components in both devices and the expectation of minimal differences in finishing processes suggest these exclusions are unlikely to significantly impact comparative results. Furthermore, as the manufacturing phase contributes only a small percentage to total environmental impacts, uncertainties in EcoAudit process selection are unlikely to meaningfully impact findings. Similarly, while data limitations raise questions about transport and disposal phase accuracy, as these phases contribute less than 1% to total impacts, such uncertainties are also unlikely to affect overall results.

The minimal environmental impact of the reusable device's repair phase, which contributes less than 1% to its total impacts while extending its lifespan significantly, highlights the advantages of its modular design that enables straightforward replacements of the tip grasper assembly. Even if more frequent replacements are needed than the single replacement assumed to extend its lifespan to 100 uses, the relatively low impact of these simple repairs is greatly outweighed by the benefits of avoiding early device disposal. If other components beyond the tip grasper assembly require repair, the fully modular design is expected to allow for easy replacement of these parts as well. This approach would help keep the repair phase's impact minimal while reducing early disposal.

Acknowledging some uncertainty around the reusable device's anticipated 100-use lifespan, as it has not yet been clinically implemented, break-even analyses show that the reusable device offers environmental benefits over the reposable device after just six uses. This implies that even if the reusable device's lifespan were limited to the 14 uses typical of the reposable device, it would still present environmental advantages. However, with its durable materials and modular design supporting efficient reprocessing and repairs, the reusable device is expected to last well beyond 14 uses, providing greater sustainability benefits in practice.

In terms of end-of-life pathways, the modular design of the reusable device facilitates efficient recycling or downcycling, enabling the recovery of most materials except for PEEK, which is assumed to be landfilled in this analysis due to current recycling limitations of PEEK at GreenCycle. As shown in Figure 7, this material recovery offers potential end-of-life savings in future life cycles of the reusable device for both climate change and energy demand impact categories. In contrast, the reposable device achieves only minimal energy savings from heat recovery during incineration, which are insufficient to compensate for the significant emissions associated with this process, resulting in no net climate change benefit. Notably, while the EcoAudit tool doesn't account for metal incineration, in practice, the reposable device's metals are incinerated before being landfilled as slag (45). This additional energy demand without generating heat likely reduces energy savings and further increases the climate change impacts associated with the reposable device.

While this analysis considers potential end-of-life savings from material recovery, it evaluates each device's impact over a single life cycle under a conservative "worst-case" scenario by assuming all materials are virgin. In practice, many materials already contain recycled content as a standard industry practice, which is especially anticipated for the reusable device, whose manufacturer prioritises recycled materials in medical products. This could create a closed-loop system, where recovered metals and plastics from one device are reused in producing new ones, thereby reducing impacts across multiple life cycles. Additionally, the modular design of the device allows for the reuse of intact parts, creating a potential for remanufacturing that could further reduce impacts over extended cycles. While this analysis did not investigate these pathways, future research into component reuse and material recovery rates could support integrating circularity metrics, as demonstrated by Schulte et al. (25), to provide a more comprehensive view of the reusable device's long-term environmental advantages.

It is important to note that uncertainties regarding the accuracy of the calculated impacts in representing the actual impacts of the devices arise not only from limited primary data for both devices but also from inherent limitations within the LCIA methodologies themselves. Although using a single database within the EcoAudit tool ensured consistent data quality across all processes modelled via this tool for both devices, the database's reliance on global averages from diverse sources means the resulting impacts may not perfectly align with the specific input data used. Similarly, while impact data for use-phase processes were directly sourced from reasonably high-quality studies, as confirmed by a literature review's critical appraisal (refer to Appendix A), uncertainties remain as to whether these data fully reflect real-world conditions for the devices under study. Selecting LUMC as the reference hospital improved data accuracy for sterilisation packaging, though this benefit did not extend to the operational use of reprocessing machines. Given the substantial differences in life cycle impacts between the reposable and reusable device and the use of consistent LCIA methodologies for both, it is unlikely these uncertainties would change the overall conclusion that the reusable device has environmental advantages over the reposable device. However, for a more precise evaluation of the reusable device's environmental benefits, future research could incorporate a detailed uncertainty analysis, such as a Monte Carlo analysis, which is commonly used in LCA studies on surgical instruments to address these types of uncertainties (refer to Appendix A).

Finally, it is recognized that, as this LCA was commissioned by the developers of the reusable device for robotic surgery, specifically the Sustainable Surgery & Translational Technology group MI & BITE at Delft University of Technology, and was conducted by a master's student at the same institution as part of a thesis project, questions may arise regarding the independence of the research and, consequently, the reliability of the comparative findings. Although conducting external review processes proved challenging due to limited familiarity with LCA methodologies in the specialised field of surgical instruments, incorporating such reviews in future research will be essential to strengthen the reliability of the findings.

3.6.2 Eco-Design Analysis

Following the circular eco-design approach, this analysis recommends prioritising initial redesign efforts on modifications that maximise the reusable device's tray load capacity (as illustrated in Figure 10). Figure 9 highlights tray load capacity as the life cycle aspect with the potential for the most substantial additional environmental gains for the reusable device, demonstrating the greatest variation in impact reduction percentages relative to the reposable device across modelled scenarios. Additionally, increasing the number of reusable devices per instrument tray, beyond the baseline assumption of twice as many reusable devices as reposable devices, is expected to be achievable through targeted design changes. These adjustments could involve enhancing the device's disassembly capability, for example, by avoiding permanent adhesives or fasteners that complicate disassembly, and incorporating additional modular features. Such improvements would significantly reduce the reprocessing impacts of the reusable device, thereby further enhancing its environmental benefits over the reposable device, particularly since the use phase is the largest contributor to its overall environmental footprint.

While machine load efficiency also shows some variation in impact reduction percentages across modelled scenarios, these variations are smaller than those observed for tray load capacity, indicating that additional environmental gains are possible but more limited in this area. Importantly, while adjustments for most life cycle aspects are applied solely to the reusable device, affecting its impacts alone, scenarios for machine load efficiency are applied to both devices, influencing the impacts of each. Because differences in machine load efficiency affect the environmental impact of the use phase for both devices similarly (as shown in Appendix I), this accounts for the relatively small variations in impact reduction percentages across different machine load scenarios. If these scenarios were applied exclusively to the reusable device, the impact reduction percentages would show much greater variation across different scenarios, suggesting the potential for larger additional environmental gains. However, since machine load efficiency relates to the number of instrument trays processed per machine cycle, an aspect not directly influenced by the reusable device's design, these gains cannot be directly achieved through modifications to the device itself and are therefore not prioritised in redesign efforts.

While scenario analysis results indicate that optimising tray load capacity would offer the greatest environmental gains, redesign efforts could also focus on reducing the repair frequency of the reusable device, potentially by incorporating more durable materials or applying specialised coatings to enhance durability, reduce material degradation, and extend component life, thereby decreasing the need for repairs. Similarly, small additional environmental gains could be achieved by improving recycling efficiency, for instance, by further optimising the disassembly capability of the reusable device to enable efficient recycling and downcycling of recoverable materials, minimising material loss and maximising material recovery. Additionally, incorporating more standardised, interchangeable components could facilitate the reuse of intact parts, offering potential for even greater end-of-life savings in future life cycles of the reusable device.

It's important to note that since the scenario analyses focus on specific life cycle aspects, including machine load efficiency, tray load capacity, repair frequency, and recycling efficiency, the circular eco-design approach is limited to evaluating potential additional environmental gains within these areas for the reusable device. While other life cycle aspects not included in the analyses might also present opportunities for environmental improvements, the chosen aspects were selected due to high uncertainties surrounding the assumptions made about them in this analysis, or because the initial phase of this research indicated that their impact results are particularly sensitive to changes in assumptions. This careful selection reduces the likelihood that more impactful aspects were overlooked as priorities for redesign. Moreover, defining baseline, worst-case, and optimal scenarios for each evaluated aspect was not always straightforward, which could affect the scenario analysis results and the prioritisation of life cycle aspects for redesign efforts. Nevertheless, baseline scenarios were based on conservative estimates informed by expert guidance, and where minimum or maximum values were unclear, expert insights were also used. Given this approach, along with the substantial impact reduction percentages observed for tray load capacity compared to other evaluated aspects, it is unlikely that any other evaluated aspect would surpass tray load capacity in terms of potential additional environmental gains for the reusable device.

Beyond insights derived from the scenario analyses in this study, other findings from the life cycle impact assessment suggest further design recommendations to enhance the reusable device's environmental performance. Notably, the relatively low impact of simple tip grasper replacements, compared to the significant benefits of avoiding early device disposal, underscores the importance of further enhancing the device's modularity and disassembly capability. Enhancing these aspects would allow all components, and not just the tip grasper, to be easily replaced when damaged or worn. This approach could extend the device's lifespan well beyond 100 uses, with only minimal additional impacts associated with such simple replacements, thereby significantly enhancing its environmental benefits. If complete component replacement proves unfeasible, repairs could offer a viable alternative, although further research is needed to determine whether the environmental benefits of lifespan extension outweigh the impacts of more intensive repair processes. To facilitate easier, quicker and more effective repair processes, and thereby minimising their environmental footprint, design modifications could focus on reducing hard-to-reach areas and creating smoother surfaces, alongside increasing disassembly capability and modularity. Additionally, these design improvements could enable more effective reprocessing practices, potentially reducing the need for aggressive disinfectants, lower temperatures, and shorter processing times, further reducing the environmental impact of these activities.

Furthermore, as PEEK is currently the only material in the reusable device that is not recoverable, substituting it with a recyclable material with similar mechanical properties, such as polyetherimide (PEI), could slightly improve the device's environmental performance. PEI offers comparable strength, rigidity, and chemical resistance to PEEK, and is generally more recyclable and easier to reprocess. Although PEI has a slightly lower heat resistance than PEEK, it should perform well at the standard 134 °C autoclave sterilisation temperature, maintaining durability without rapid degradation (46). Alternatively, exploring advanced chemical recycling methods for PEEK, such as pyrolysis, could facilitate downcycling of this plastic (44). However, further research would be needed to evaluate whether the benefits of material recovery outweigh the environmental impacts of these advanced recycling methods and to identify any design modifications that would support these processes. It is important to note that, given that PEEK accounts for only a small portion of the reusable device's weight (4%, as determined in this analysis), these design changes are not expected to yield the most substantial additional environmental gains for the reusable device.

For an illustrative summary of the design change recommendations arising from this analysis to further enhance the reusable device's environmental footprint, please refer to Figure 11. Importantly, each of these recommended design modifications should undergo thorough evaluation to confirm that they indeed enhance the reusable device's environmental performance without compromising surgical outcomes or patient safety.

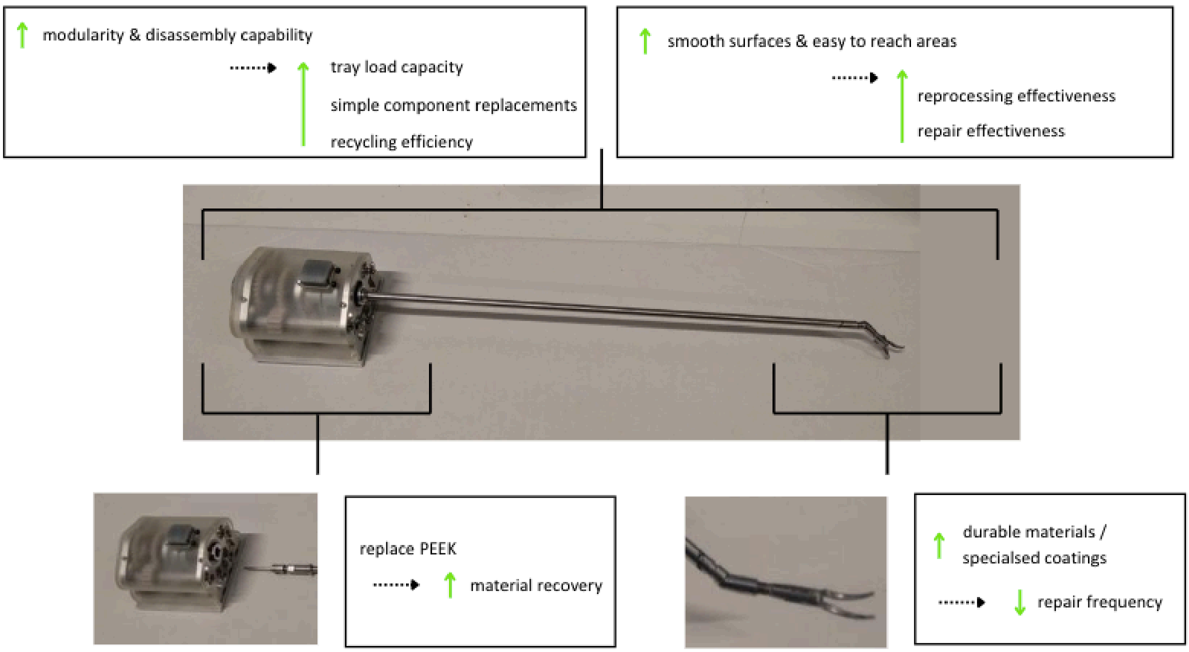

Figure 11: Recommendations for Design Modifications. *Note: Upward arrows indicate increases, while downward arrows indicate decreases. Enhancing the modularity and disassembly capability of the overall device would provide several key benefits. First, it would maximise tray load capacity, thereby significantly reducing reprocessing impacts per device. Second, it would enable straightforward replacement of damaged or worn components, thereby extending the device's lifespan with minimal additional impacts from such replacements. Third, it would improve recycling efficiency,* optimising the recovery of the device's recyclable materials at end-of-life*. Additionally, incorporating smoother surfaces and more accessible design features would support more effective reprocessing and repair, thereby lowering the environmental impact associated with these activities. For specific components, substituting PEEK in the driver assembly with recyclable materials would enhance material recovery at end-of-life. Similarly, using more durable materials or applying specialised coatings to the tip grasper assembly would extend its lifespan, decreasing the need for repairs.*

IV. Conclusions & Recommendations

This research reveals a significant gap in sustainability awareness and the use of LCAs in surgical instrument decision-making, primarily due to unfamiliarity and limited trust in LCA findings, as suggested by survey responses and the low response rate. The lack of a standardised, user-friendly LCA methodology suited to the complexity of surgical instruments further complicates reliable environmental assessments in this field. However, there is strong interest in sustainability and a willingness to learn more about LCAs. Targeted LCA training and addressing key risk factors as outlined in Table 1 could improve both familiarity with LCAs and trust in their findings, encouraging their adoption in decision-making and promoting more sustainable practices within the surgical sector. Political measures, such as mandating LCA use in surgical decisions, could further support these efforts.

The second part of this research conducted a robust LCA on an innovative reusable SATA instrument for robotic surgery, serving as both a comparative assessment and an eco-design evaluation using an adapted circular approach. Results indicate that the reusable SATA instruments offer substantial environmental benefits over traditional limited-use designs, particularly in reducing climate change and energy impacts. Their modular design enables efficient reprocessing and straightforward part replacements, which allows for frequent reuse and considerably extends the instrument's lifespan. By contrast, the complex design of traditional cable-driven instruments limits reusability due to reprocessing challenges and few repair options, resulting in a much shorter lifespan and a significantly larger environmental footprint. This research emphasizes that reprocessing impacts are among the primary environmental contributors for reusable instruments, largely due to the energy-intensive disinfection and sterilization required before each use. The circular eco-design evaluation recommends prioritising initial redesign efforts on further optimising modularity and disassembly of the SATA instruments to increase tray load capacity, which would effectively minimize their reprocessing impacts.

Despite efforts to enhance the reliability of this LCA, resulting in robust findings that highlight the sustainability benefits of the innovative reusable SATA instrument technology for robotic surgery, this research underscores ongoing challenges in fully capturing the complexities of surgical instruments, largely due to limited primary data, reliance on assumptions, and challenges in accurately representing data in LCA software. These findings emphasise the importance of stakeholder engagement and the need for refined, user-friendly LCA methodologies specifically tailored to complex surgical instruments like those used in robotic surgery, along with robust review processes to ensure LCA reliability in this field.

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Appendix A

Note: This systematic review, authored by the same Master's student conducting this research, was previously assessed as part of a separate Master's course (BM51010) and received a score of 9 out of 10.

Identifying the Environmental Effects of Sustainability Strategies for Surgical Instruments and Mitigation Potentials: A Systematic Review

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Abstract

Introduction - Recognizing the significant environmental impact of surgical procedures, current research focuses on environmentally conscious practices within the operating room (OR), seeking to minimize medical waste and resource consumption. While the shift to reusable healthcare products in the OR is considered a promising solution, it is acknowledged that transitioning to reusable surgical instruments raises concerns due toextensive energy and water consumption during decontamination processes required for each reuse. Guided by frameworks like Potting's, various strategies beyond the reusable approach could potentially mitigate the environmental impact of surgical instruments.

Aim - This review aims to identify the environmental effects associated with sustainability strategies applied to surgical instruments and explore mitigation potentials, offering valuable insights for enhancing environmental sustainability in the context of surgical instruments.

Methods - Definitions of existing sustainability strategies for products were refined, specifically tailored to the product category of surgical instruments. Subsequently, employing an iterative approach, a search string was constructed, and a scientific literature search was performed across three databases - Scopus, PubMed and MEDLINE - to identify records within the scope of this research. During the full-text analysis, records that presented primary data and reported quantitative results associated with environmental effects of sustainability strategies for surgical instruments were ultimately included.

Results - The 27 studies included provide thorough assessments of the environmental impacts linked to various sustainability strategies for a wide range of surgical instruments by employing life cycle analysis (LCA), with variations in methodology across each study. Studies were categorized according to their sustainability strategy focus. Utilizing reusable surgical instruments instead of single-use/disposable counterparts generally reduced environmental impacts (median climate change effect: reduction of 42%), with the reprocessing phase identified as a primary hotspot. However, outcomes varied for switching to hybrid instruments, and opting for metal single-use instruments was suggested to increase environmental impacts compared to plastic equivalents. There was consensus that optimizing reprocessing practices, as well as increasing the number of reuse cycles, effectively mitigates environmental impacts associated with reusable instruments. Furthermore, redesigning plastic disposable instruments with alternative polymeric materials, incorporating durable metalsin reusable instrument manufacturing, sterilizing reusable instruments as part of a set and using appropriately sized sterilization containers for packaging, were proposed to significantly reduce their environmental footprint. While there was broad agreement on the benefits of reusing instruments through steam sterilization, one study highlighted increased environmental impact with reusing complex disposable instruments through ethylene oxide (ETO) reprocessing due to its toxicity. Finally, repairing reusable instruments and remanufacturing disposables to extend their functional life were claimed to reduce their overall environmental footprint.

Discussion - Due to the inclusion of diverse types of instruments and the significant diversity in LCA methodological choices, the assessment of environmental impacts yields highly variable absolute results amongst studies, occasionally leading to contradictory outcomes. Recognizing that the environmental effects of refusing or reusing disposables depend on reprocessing practices, the need for careful consideration is emphasized, especially for complex instruments. Future research should concentrate on developing practical guidelines for conducting LCAs specifically in the field of surgical instrumentation to ensure the delivery of reliable conclusions.

Conclusion - Literature favors switching to reusable surgical instruments with additional strategies like metal integration, optimized reprocessing, increased reuse cycles, and repairs to reduce their environmental impacts. Redesigning plastic disposables with alternative polymeric materials and remanufacturing prove environmentallybeneficial.

Keywords: Sustainability Strategies, Circularity, Reuse, Repair, Remanufacture, Environmental Impact, Surgical Instruments

1. Introduction

1.1. Background and Rationale

The rapid growth of the healthcare industry, while designed to promote health, has become a significant source of global environmental pollution. The operating room (OR) plays a crucial role in this context, contributing substantially to the waste generation and resource consumption due to surgical procedures that heavily rely on disposable supplies and involve high energy consumption (Kampman & Sperna Weiland).

Recognizing the environmental consequences of surgical procedures, researchers have turned their focus toward developing environmentally conscious practices within the OR and exploring strategies to minimize medical waste and resource consumption. For instance, Kampman & Sperna Weiland found that the set-back of unoccupied air-treatment systems can save up to 70% of energy, and Pradere et al.'s findings indicate that improving education and awareness on proper waste segregation among medical staff significantly reduces waste. Only a subset of research specifically focuses on transitioning from disposable healthcare products to reusable alternatives in the OR, ranging from personal protective equipment (PPE) to anesthetic gasses, as a way to reduce environmental impacts, as evident in the works of Adisa et al., Keil et al., Drew et al., and Hiloidhari & Bandyopadhyay. These works emphasize that switching to reusables presents a promising solution to reduce the environmental impact associated with healthcare products used in the OR and that thisshift may extend to surgical instruments specifically. However, it is acknowledged that the transition to reusable surgical instruments introduces a paradoxical challenge. While reducing the number of disposed instruments, the necessary decontamination processes before each reuse, critical for infection prevention and patient safety, involve significant energy and water consumption, raising environmental concerns (Drew et al.; Friedericy et al.; Keil et al.; Hiloidhari & Bandyopadhyay).

Beyond the sustainability approach of transition- ing to reusables, a spectrum of potential strategies exists to reduce the environmental impacts associ- ated with surgical instruments. Frameworks suchas Potting's (refer to Figure 1) play a crucial role in outlining sustainability strategies for products through the adoption of a circular system approach. Instead of considering the end-of-life phase of a product as the final stage, in a circular system, products or materials are reintegrated into a product's life cycle making the system more resource-efficient and sustainable, i.e. more circular. Potting's framework presents a well-defined set of 10 strategies arranged in a hierarchy denoted by numbers from R9 to R0, indicating their increasing potency in achieving circularity. Although the category of 'useful application of materials', encompassing strategies R9 and R8 (recover and recycle), currently receives the most attention in circular policies and targets, it is considered a last resort in achieving circularity. This category is characterized by low yield rates and compromised product integrity, representing waste not otherwise usable in other sustainability strategies. Conversely, strategies R7 to R0, emphasizing the extension of product lifespan and smarter product manufacturing and use, represent stages where the most value can be retained for sustainability purposes. Potting et al. propose this hierarchical framework as a general guideline, acknowledging occasional inconsistencies in R-order and uncertainties in categorizing strategies under a specific R. Future research is recommended to delve deeper into sustainability strategies within distinct industries or product categories, and to evaluate the necessity for adjustments or fine-tuning of the framework (Morseletto).

Smarter product use and manufacture	R0	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1	Rethink	Make product use more intensive (e.g. through sharing products or by putting multi-functional products on market).
	R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources
Extend lifespan of product and its parts	R3	Reuse	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4	Repair	Repair and maintenance of defective product so it can be used with its original function
	R5	Refurbish	Restore an old product and bring it up to date
	R6	Remanufacture	Use parts of discarded product in a new product with the same function
	R7	Repurpose	Use discarded products or its part in a new product with a different function
Useful application of materials	R8	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9	Recovery	Incineration of material with energy recovery

Figure 1: Potting et al.'s hierarchical framework on sustainability strategies for products, denoted by R9-R0, indicating their increas-ing potency in achieving circularity (Morseletto)

1.2. Objectives

This literature review aims to determine the environmental effects associated with sustainability strategies for surgical instruments, placing specific emphasis on implementing smarter instrument manufacturing and use practices as well as extendingits lifespan. Furthermore, this review seeks to eval- uate the methodologies employed to assess these environmental effects, identify environmental impact hotspots, and investigate the potential for further environmental impact mitigation. For this research, adjusted definitions of the 10Rs in Potting's framework were utilized, providing descriptions of sustainability strategies particularly for the product category of surgical instruments.

The ultimate objective is to offer valuable insightsthat contribute to the enhancement of environmental sustainability in the context of surgical instruments. Hence, this review is guided by the following research question:

What environmental effects are associated with the implementation of sustainability strategies for surgical instruments, and to what extent can environmental impacts further be mitigated?

To comprehensively address the research question, the following sub-questions have been formulated:

- **What methodologies are employed to assessthe environmental effects of implementing sustainability strategies for surgical instruments?**
- **To what extent does the implementation of sustainability strategies influence the environmental impacts associated with surgical instruments?**
- **What specific environmental impact hotpots emerge during the implementation of these sustainability strategies?**
- **What mitigation potentials does existing literature propose to further reduce environmental impacts?**

2. Methodology

2.1. Search Plan

The search plan adopted in this research follows the methodology outlined in the TU Delft Library's Searching and Resources guidelines (*"Searching and Resources, TU Library"* n.d.). Given that the defined sub-questions are intrinsic to understanding the environmental effects of sustainability strategies for surgical instruments and mitigation potentials, a singular literature search has been conducted to provide a comprehensive overview. Initially, the research question was critically assessed to identify key concepts essential for both broadening and refining the literature search. For each concept, a variety of synonyms and alternative search terms were selected. These terms were systematically combined using logical operators such as OR (between synonyms) and AND (between concepts), ensuring a methodical and structured approach to literature exploration. Given the iterative nature of this approach, search terms were continuously adjusted, added, or removed to achieve an optimal and comprehensive outcome. Further details about the conducted literature search will be elaborated on in Section 3. The findings will be given in Section 4 and extensively discussed in Section 5.

2.2. Definitions

To grasp the full extent of the research, it is necessary to provide detailed explanations of certain definitions.

Environmental effects

In the context of this research, the term "environmental effects" involves a thorough examination of various dimensions, including, among others, resource utilization and climate change. Together, these dimensions define the environmental consequences associated with sustainability strategies for surgical instruments, extending beyond considerations solely related to solid waste generation.

2.2.1. Surgical Instruments

In this research, the term "surgical instruments" specifically refers to medical instruments that are utilized in the controlled setting of the operating theater and come into direct contact with patients during surgical interventions. The particular emphasis is on instruments classified as semi-critical, which come into contact with mucous membranes or non-intact skin, and critical, which penetrate sterile tissues or the vascular system. These instruments must undergo decontamination processes before being used to prevent infection and ensure patient safety (*"What is a Critical, Semi-critical and Non-critical instrumen"* n.d.). It's important to note that, for the purpose of this research, certain items commonly associated with surgical contexts, such as surgical textiles, including personal protective equipment (PPE) and linen, as well as implantable devices, fall outside the scope of this research.

2.2.2. Sustainability Strategies

The 10Rs in Potting's framework were redefined for this research to offer a more detailed description of sustainability strategies specifically tailored to the product category of 'surgical instruments':

- **R0: Refuse**: Replace surgical instruments with alternatives that provide the same function while exerting a smaller environmental impact.
- **R1: Rethink**: (Re)evaluate the design of surgical instruments, including its materials, to minimize their environmental impact. This involves promoting durability to allow for reuses and enabling additional sustainability strategies to further enhance the instrument's lifespan (such as maintenance and repair) or that of its parts (through refurbishment and remanufacturing).
- **R2: Reduce**: Minimize the use of resources in the production and utilization of surgical instru- ments by improving efficiency in handling mate- rials and machines.
- **R3: Reuse**: Promote the repeated use of surgical instruments and/or their components through proper reprocessing and maintenance protocols, extending their lifespan.
- **R4: Repair**: Implement procedures for repairing damaged or malfunctioning surgical instruments, thereby reducing the need for replacements.

- **R5: Refurbish**: Renew previously used surgi- cal instruments by, for instance, replacing worn parts, restoring them to a condition that aligns with safety and performance standards, ensuring prolonged instrument functionality within the same scope of application.
- **R6: Remanufacture**: Employ processes involving the disassembly of discarded surgical instruments, substituting or reconstructing worn-out parts, and reassembling them to meet or exceed original specifications, thereby reducing the demand for newly manufactured instruments.
- **R7: Repurpose**: Explore alternative applications for surgical instruments, or their components, that, after undergoing other sustainability strategies such as repair or refurbishment to extend their functionality, are no longer suitable for their original purpose, thereby extending their usefulness.
- **R8: Recycle**: Process materials from discarded surgical instruments to manufacture new products, contributing to circularity.
- **R9: Recovery**: Explore innovative methods to retrieve valuable components from discarded surgical instruments, which are not recycled, but instead utilized as a source of energy or valuable biochemical compounds, thereby maximizing resource utilization.

As in Potter's framework, R9-R8 fall under the category of 'useful application of materials,' R7-R3 are categorized under 'extending the lifespan of surgical instruments and/or its parts,' and R2-R0 are attributed to the category of 'smarter surgical instrument use and manufacture.' It is important to emphasize that the category 'useful application of materials,' which includes strategies R9 and R8 (recover and recycle), is not within the scope of this research.

3. Literature Search

3.1. Databases

On 4 October 2023, a total of three databases were searched to retrieve literature; one broad aca- demic database, Scopus, and two medical databases, PubMed and MEDLINE. Utilizing multiple databases ensures comprehensive coverage of the literature relevant to the research topic and minimizes positional bias.

3.2. Initial search query

Key concepts were identified and for each concept, a variety of synonyms and alternative search terms were selected. An overview of the identified key concepts and their synonyms and alternative search terms is represented in Table 1. The asterisk (*) is placed to replace 0 or more characters to account for different forms or variations of word. For example, reus* can result in 'reusing', 'reusable' etc. Combining the synonyms with the logical operator OR and the concepts with the logical operator AND resulted in the following search string:

(environment OR ecolog* OR sustainab*) AND (impact OR effect OR influence) AND (refus* OR rethink* OR reduc* OR reus* OR repair* OR reparation OR refurbish* OR remanufactur* OR repurpos*) AND (surgical OR operative) AND (tool OR instrument OR equipment OR device OR machine* OR apparatus OR appliance)*

In all databases the search was limited to the ti-tle, abstract and keywords since these elements encapsulate the essence of the records. Including the full text was avoided to maintain feasibility and prevent an overwhelming number of results. No additional filters were employed across any of the databases. Please refer to Appendix A for the translation of the initial search string into the various databases.

The preliminary search generated 1228 recordsin Scopus, 240 records in PubMed, and 684 records in MEDLINE, resulting in a total of 2152 records. Inverting the order of concepts in the search string, such as placing the 'sustainability strategies' concept at the forefront, was found to have no impact on the number of generated records in all databases. Initial exploration indicated that the search terms 'refuse', 'rethink' and 'reduce' yielded numerous records outside the research scope, often related to biochemical processes or patient outcomes. Notably, when these search terms did appear in relevant records, the other search terms within the 'sustainability strategies' concept alone seemed to be sufficient for retrieving those records. Consequently, the decision was made to omit these specific search terms. Additionally, the choice to exclusively use 'surgical' and 'operative' under the 'surgical' concept was reconsidered as this initial narrow focus was deemed too restrictive for the research scope, potentially overlooking pertinent records. To address this, the broader term 'medical' was introduced for a more inclusive search, reducing the risk of missing relevant records. Ultimately, upon reviewing promising records, alternative terms for the 'environmental' concept were identified. The terms 'footprint' and 'circular' were added to enhance the search's comprehensiveness.

3.3. Final search query

On 13 November 2023, a final search was carried out across all databases using the same search methodology but with the adapted search string:

(environment OR ecolog* OR sustainab* OR circular* OR footprint) AND (impact OR effect OR influence) AND (reus* OR repair* OR reparation OR refurbish* OR remanufactur* OR repurpos*) AND*

(surgical OR operative OR medical) AND (tool OR instrument OR equipment OR device OR machine OR apparatus OR appliance)*

An overview of the identified key concepts and their synonyms and alternative search terms for the final search query is represented in Table 2. Please refer to Appendix A for the translation of the final search string into the various databases. This final search yielded 595 records in Scopus, 105 records in PubMed, and 335 records in MEDLINE, totalling 1035 records. Similar to the initial search query, changing the order of concepts in the search string did not affect the number of generated records across alldatabases.

Table 1: Initial key concepts and synonyms/alternative terms

Environmental	*Effects*	*Sustainability Strategies*	*Surgical*	*Instruments*
environment*	impact	refuse*	surgical	instrument
ecolog*	effect	rethink*	operative	tool
sustainab*	influence	reduc*		equipment
		reus*		device
		repair*		machine*
		reparation		apparatus
		refurbish*		appliance
		remanufactur*		
		repurpos*		

Note: The different concepts are combined using the operator ’AND’, and the alternative terms within each concept are combinedusing the operator ’OR’

Table 2: Final key concepts and synonyms/alternative terms

Environmental	*Effects*	*Sustainability Strategies*	*Surgical*	*Instruments*
environment*	impact	reus*	surgical	instrument
ecolog*	effect	repair*	operative	tool
sustainab*	influence	reparation	medical	equipment
circular*		refurbish*		device
footprint		remanufactur*		machine*
		repurpos*		apparatus
				appliance

Note: The different concepts are combined using the operator ’AND’, and the alternative terms within each concept are combinedusing the operator ’OR’

3.4. Record Selection

The information extracted from the databases was organized in the citation manager Endnote X9. Utilizing a functionality within Endnote, duplicate records were removed automatically. However, due to some inaccuracies in the tool, a few duplicates persisted, requiring manual removal. Each remaining record underwent a screening process where the title and abstract were initially assessed for relevance by a single reviewer, adhering to predefined excluding criteria. Subsequently, the same reviewer conducted a full record screening based on these criteria. From this screening, the remaining records were selected for an in-depth full-text analysis, ensuring that the final records included in the literature review met the eligibility criteria and contained the necessary data for analysis. Additionally, cross-referencing was conducted by examining references and citations respectively within the records selected for full-text analysis, potentially identifying additional relevant records to be included in this research.

3.5. Eligibility

During the screening process, the following exclusion criteria were used:

- Language: non-English
- Accessibility: no full text available
- Format: opinions, surveys or guidelines
- Industry: non-medical
- Field of healthcare: other than surgical medicine, including regenerative medicine/tissue engineering, nanomedicine, pharmaceuticals, public health and healthcare in general.
- Effect within surgical context: solely related to effects other than environmental, as specified in section 2.2.1., including economic, social, quality, and safety effects, as well as considerations exclusively tied to waste generation.
- Surgical instruments: solely related to instruments other than those specified in section 2.2.2., including non-critical devices (e.g. blood pressure cuffs), textiles (e.g. surgical gowns) and implantables.
- Sustainability strategy: primary focus on strategies other than those associated with R0-R7 as specified in section 2.2.3, including recycling and recovering.

Ultimately, during the in-depth full text analysis, records were assessed for eligibility by including records that presented primary data and reported quantitative results associated with environmental effects of sustainability strategies for surgical instruments as specified in 2.2.

4. Results

The PRISMA flow diagram of the record selection process based on the final search query is shown in Figure 2. The following two sections will present the characteristics and methodological designs of the 27 studies included. Table 3 provides a summary of these

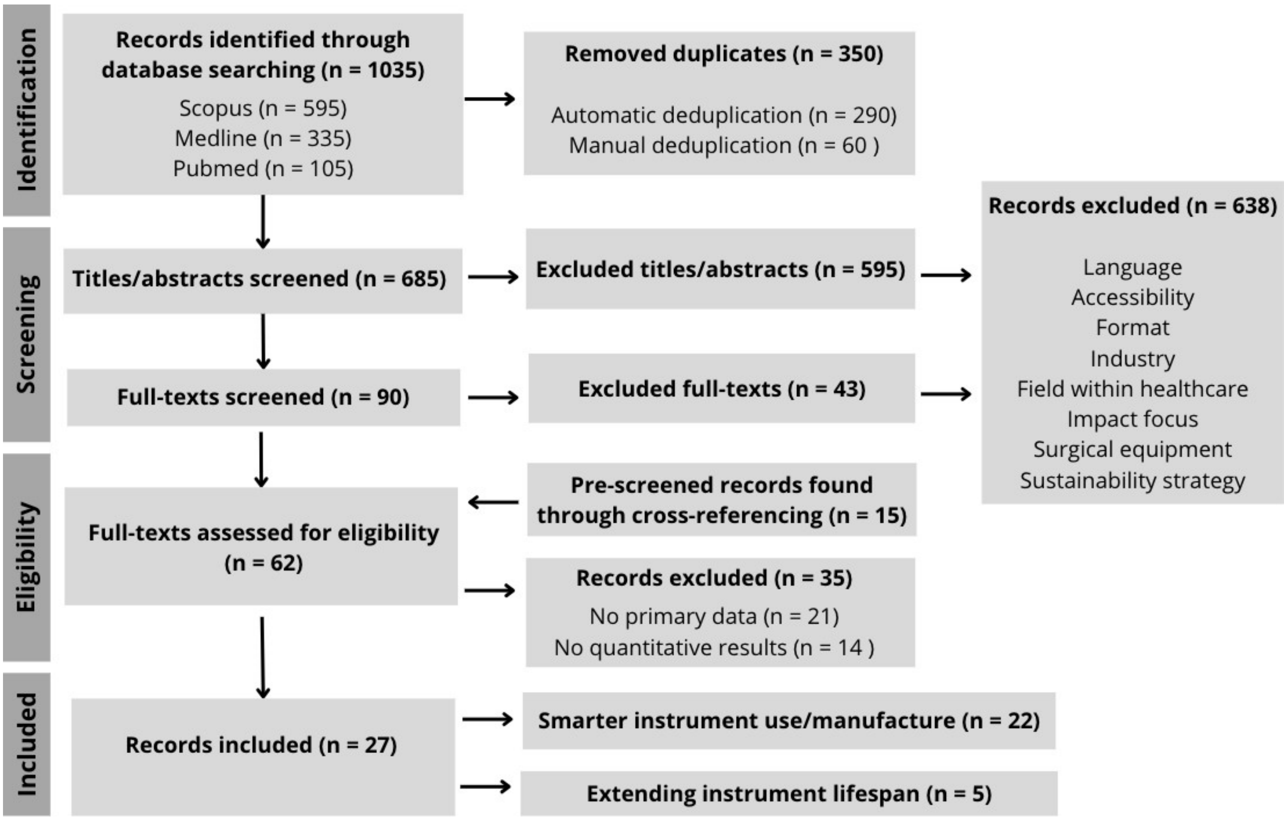

Figure 2: PRISMA flow diagram of the study selection process.

characteristics and designs. For additional details and a comprehensive overview, please refer to Appendix B and C respectively.

4.1. Study characteristics

Sustainability strategies

Among the 27 studies included, there is a thor- ough examination of environmental effects linked to various sustainability strategies for different surgical instruments. The majority (n = 22) primarily delved into the ‘smarter instrument use and manufacture’ category. Specifically, 18 studies concentrated on the sustainability strategy ’refuse’ by comparing the environmental impacts of single-use surgical instru- ments to those of functionally equivalent reusables, hybrid versions, and/or alternative single-use variants. Additionally, two studies focused on the sustainability strategy ’rethink,’ examining the instrument’s design while incorporating sustainability considerations. Lastly, two studies primarily addressed the sus- tainability strategy ’reduce,’ emphasizing ways to increase the efficiency in surgical instrument use to improve environmental outcomes by exploring various packaging methods for sterilization. The remaining five studies primarily concentrated on the category ‘extending the lifespan of surgical instruments and/or its parts.’ Among them, three studies explore the sustainability strategy of ’reuse,’ involving the reuse of surgical instruments instead of using them once. Additionally, one study investigates the environmental effects of the sustainability strategy ’repair,’ focusing on the repair of reusable instruments rather than their replacement. Furthermore, one study delves into the sustainability strategy ’remanufacture,’ examining the environmental effects of remanufacturing single-use surgical instruments instead of producing new ones.

Surgical instruments

In terms of assessed surgical instruments, these devices exhibit a range of complexities. The majority of studies (n = 10) concentrated on ‘conventional’ sur- gical instruments, characterized by simpler designs, including items like vaginal specula and surgical scissors. Nine studies investigated ‘complex’ sur-gical instruments, indicating a more intricate and multi- component construction, such as a flexible ureteroscope and a cardiopulmonary bypass device. Furthermore, collections of surgical instruments, spanning anesthetic equipment and reusable surgical instruments in general, were examined in five studies. The remaining three studies examined a complete set, pack, or kit, like a spinal fusion surgery instrumentset or a central venous catheter insertion kit, each encompassing multiple instruments. Among the investigated disciplines, anesthesia received the most attention with six studies, followed by urology, cardiology and obstetrics & gynecology, each examined three times. The 27 studies spanned various nations, with the USA being the most prominent location (n = 8), followed by the UK (n = 4), Australia (n = 3) and Germany (n = 3).

Environmental effects

Concerning the considered environmental effects, all studies focussed on the climate change dimension by explicitly mentioning one of the following impact categories: carbon footprint, greenhouse gas (GHG) emissions, global warming potential (GWP), or climate change. As such, they uniformly addressed the impact of greenhouse gas emissions on climate change, expressed in terms of carbon dioxide equivalents (CO2e). While only seven studies exclusively concentrated on the climate change dimension using one of the previously mentioned impact categories, the majority (n = 16) addressed numerous other impact categories, thereby encompassing three additional environmental dimensions, namely resource utilization, human health and ecosystem quality. More specifically, these studies delved into the comprehensive resource footprint by exploring material and energy utilization, reporting impact categories such as mineral depletion and non-renewable energy. Health-related impact categories like carcinogens andionizing radiation were employed to assess potential effects on human health. The ecosystem quality dimension's focus included impact categories like freshwater eutrophication and natural land transfor- mation, evaluating interactions with and effects on ecosystems, biodiversity, and the overall health of the natural environment. The remaining four studies reported only a subset of these impact categories, covering only a few of the four distinct environmental dimensions. The choice of characterization method in each study influenced which impacts categories were addressed. Additionally, depending on the characterization method employed, in some studies (n = 8), these 'midpoint' impact categories were combined into distinct aggregated single-score damage endpoints related to climate change, resource utilization, human health and/or ecosystem quality, or even aggregated into one overall impact score, encompassing all four dimensions. For a detailed breakdown of impact categories referenced in each study and their allocation to respective dimensions, please refer to Appendix B and C, respectively.

4.2. Methodological design

Assessment methods

Concerning assessment methods, the predomi- nant approach employed across the majority of studies was life cycle analysis (LCA) (n = 24), with a notable preference for an attributional perspective (n = 19), followed by a consequential one (n = 2). While an attributional LCA gives insight into the current environmental impacts that can be attributed directly to the products' life cycle, including raw material extraction, product manufacturing and packaging, transportation and disposal of the product, a consequential LCA delves into environmental impacts resulting from potential changes in the system (Rizan & Bhutta). Remarkably, one study, while adopting an attributional approach, incorporated a circular economy metric. This metric facilitated the quantification of environmental impacts across multiple cycles of surgical instruments, going beyond the traditional single life cycle assessment (Schulte et al.). The other three studies utilizing some form of LCA specifically reported employing a carbon footprint LCA, being a subset of an attributional LCA, focusing on insights into climate change exclusively. The remaining three studies concentrated on carbon footprint analyses without explicitly disclosing the utilization of an LCA-based methodology.

Inventory databases, characterization methods & software

The selection of inventory databases varied across the studies, with EcoInvent being the most prevalent (n = 19), followed by ELCD (n = 4), USLCI (n = 4), and Idemat (n = 2). Other databases, including GREET, WARM, Australian Data 2007, Industry Data, ICE, SWCCFD, CRCR, and ILCD, were each mentioned once. Furthermore, different characterization methods were employed, with ReCiPe (n = 7), TRACI(n = 4), IPCC (n = 3), and BEES (n = 2) being the most frequently used methodologies. The Impact 2002+, CED, CML, USEtox, and EF methodologies were each reported once. SimaPro was the pre-dominant software choice, applied in 16 cases, while Umberto NXT, Activity Browser, and OpenLCA were each mentioned once. This highlights the extensive diversity of methodological and background inventory data choices made by researchers when assessing environmental impacts.

Functional units

In addition to varying methodological choices, studies employ diverse functional units, which act as reference measures for assessing the environ-mental impacts of different alternatives (Liang). Nine studies opted for the functional unit of "one use,"distributing the supply chain and end-of-life impactsof reusables across their expected lifetime uses. Conversely, another set of nine studies aligned their functional unit with the lifespan of reusable items or the potential number of reuses for a disposable item.

Alternative functional units included ‘per (number of) procedure(s)’ (n = 3), ‘use over a designated period’ (n = 2), ‘provision (over a designated period)’ (n = 2), and ‘per number of instruments’ (n = 1).

Contribution analyses

Contribution analysis, vital for pinpointing environmental hotspots that arise when implementing sustainability strategies, is reported in almost all studies (n = 25), except for two cases.

Scenario analyses

Among the 27 included studies, 19 incorporated a scenario analysis, also known as a sensitivity analysis, to evaluate result robustness and identify potential variations arising from alternative methodological assumptions. Moreover, these analyses were employed to suggest mitigation potentials, complementing the studies’ primary sustainability strategy focus, for enhancing environmental outcomes. The scenario analyses provided valuable insights into optimizing instrument use and extending instrument lifespan, with a specific emphasis on ‘reduce’ (n = 18) and/or ‘reuse’ (n = 8) respectively. Regardingthe sustainability strategy ‘reduce’, the most common assumptions tested were alternate energy sources (n = 10), alternate autoclave loading efficiencies (n = 5) and alternate reprocessing methods (eg. hydrogen peroxide disinfection, n = 5). Some studies also considered the sustainability strategies of ”recover” and/or ”recycle” in their scenario analysis by assuming alternative disposal processes. However, as these sustainability strategies are not the primary focus of this study, they are not explored for suggesting mitigation potentials.

Uncertainty analyses

Finally, eight studies reported conducting uncer- tainty analyses, mainly employing Monte Carlo simulations, to evaluate the overall uncertainty that arises from natural variations in the manufacturing and usage practices of surgical instruments.

4.3. Critical Appraisal

While six LCA studies did not specify the LCA standard followed (ISO 14040 and/or ISO 14044), three studies did not even clearly state adopting a LCA-based methodology. The absence of clear reporting on selected methodologies, including instances where no inventory databases (n = 7), characteriza- tion methods (n = 10), and software (n = 8) usage were reported, poses obstacles to the reproducibility of the studies. Despite the inclusion of numerous mid-point impact categories in most studies, a thorough analysis of these impacts was frequently lacking and endpoint categories were often not reported (n = 19), limiting the interpretability of the outcomes. The lack of transparency extends to outcome reporting, with studies only reporting relative impact values, instead of absolute values, (n = 5), studies solely relyingon visual impact representations (n = 6), potentially leading to inaccuracies when interpreting values from graphs, and studies not reporting any values for some impact categories considered (n = 3). Contribution analysis reporting also faced challenges with studies exclusively depending on visual representations (n = 9) and studies failing to report impacts for every included life cycle phase (n = 8), with some studies combining the impact of one phase with another (e.g., attributing transport or packaging impacts to manufacturing). Some studies exhibited incomplete coverage of all life cycle phases in their LCA (n = 8), neglecting for example the transport or packaging phase of instruments, potentially distorting the overall outcomes. Although the majority of studies (n = 19) conducted scenario analyses to understand the model’s behavior under alternative methodological assumptions, only eight studies reported undertaking uncertainty analyses, such as Monte Carlo simulations, to assess the overall uncertainty that arises from natural variations in manufacturing and use practices of surgical instruments.

A comprehensive overview of the critical appraisal of the 27 included studies can be found in Appendix D.

4.4. Smarter Instrument Use/Manufacture

The 27 studies included in this analysis are classified according to their sustainability strategy focus. In this section, the environmental effects as well as associated hotspots and potential mitigations identified for each sustainability strategy for surgical instruments will be presented. Table 4 provides a summary of these findings. As all studies uniformly addressed the effect on climate change in terms of CO2e, the emphasis will be on this dimension specifically. For a comprehensive set of numerical data on climate change impacts and hotspots per study, please refer to Appendix E.

4.4.1. R0: Refuse

Among the 18 studies investigating the sustainability strategy of ’refuse’, the environmental impact of single-use/disposable instruments was comparedto functionally equivalent reusables in 16 studies, to hybrid versions in 3 studies, and to alternativesingle-use/disposable variants in 2 studies.

Table 3: Summary of study characteristics and methodological designs

reference (year)	sustainability strategy	instrument	discipline	country	primary comparison	functional unit	assessment method (standard)	inventory database(s) [characterization method(s)] (software)	# impact categories	# environmental dimensions	contribution analysis	scenario analysis
Boberg et al. (2022)	refuse	laparoscopic cholecystectomy system	general surgery	Sweden	single-use hybrid reusable	500 uses	attributional LCA (ISO)	EcoInvent [IMPACT 2002+] (SimaPro)	15	4	✔	reduce reuse
Davis et al. (2018)	refuse	flexible ureteroscope	urology	Australia	single-use reusable	1 use	carbon footprint LCA	-	1	1	✔	-
Donaheu et al. (2020)	refuse	vaginal specula	obstetrics & gynecology	USA	acrylic disposabe SS-304 reusable SS-316 reusable	20 uses	carbon footprint LCA	EcoInvent, Idemat, GREET, WARM [IPCC] (SimaPro)	1	1	✔	reduce reuse
Eckelman et al. (2012)	refuse	laryngeal mask airway	anesthesia	USA	disposable reusable	40 uses	attributional LCA (ISO)	EcoInvent [BEES] (SimaPro)	10	4	✔	reduce reuse
Friedericy et al. (2022)	reduce	reusable surgical instrument	nonspecific	The Netherlands	disposable blue wrap reusable RSC	5000 uses	attributional LCA (ISO)	EcoInvent, Idemat [IPCC, ReCiPe] (SimaPro)	3	4	✔	reduce
Hogan et al. (2022)	refuse	flexible cystoscope	urology	Ireland	single-use reusable	20 procedures	carbon footprint analysis	-	1	1	✔	-
Ibbotson et al. (2013)	refuse	surgical scissors	nonspecific	Germany	plastic disposable SS disposable SS reusable	4500 uses	screening LCA (ISO)	EcoInvent, Australian Data 2007 [ReCiPe, CED] (SimaPro)	19	4	✔	reduce
Jabouri and Abbott (2022)	refuse	skin surgery pack	dermatology	UK	single-use reusable	1 use	carbon footprint analysis	-	1	1	✔	-
Kemble et al. (2023)	refuse	flebixle cystoscope	urology	USA	single-use reusable	1 use	carbon footprint LCA	-	1	1	✔	-
Lalman et al. (2023)	reuse	disposable electrophysiological catheter	cardiology	Canada	single-use reuse	5 uses	attributional LCA (ISO)	EcoInvent [ReCiPe] (SimaPro)	22	4	-	reduce
Leiden et al. (2020)	refuse	spinal fusion surgery instrument set	neurology	Germany	disposable reusable	1 procedure	attributional LCA (ISO)	EcoInvent [CML, ReCiPe] (Umberto NXT)	6	4	✔	reduce reuse
Liang (2019)	refuse	laryngeal mask airway	anesthesia	Sweden	disposable reusable	40 uses	attributional LCA (ISO)	EcoInvent, ELCD [ReCiPe] (SimaPro)	9	4	✔	reduce reuse
McGain et al. (2012)	refuse	central venous catheter insertion kit	anesthesia	Australia	single-use reusable	1 use	attributional LCA (ISO)	EcoInvent (SimaPro)	6	2	✔	reduce
McGain et al. (2017)	refuse	anesthetic equipment	anesthesia	Australia	single-use reusable	1 year of clinical operation	consequential LCA (ISO)	EcoInvent (SimaPro)	14	4	✔	reduce
Nikkhah et al. (2023)	rethink	disposable cardiopulmonary bypass device	cardiology	USA	PC PP PE PET	100 devices	attributional LCA (ISO)	USLCI [BEES] (OpenLCA)	10	4	-	-
Rizan and Bhutta (2022)	refuse	laparoscopic cholecystectomy instruments	general surgery	UK	single-use hybrid	1 procedure	attributional & consequential LCA (ISO)	EcoInvent, Industry data [ReCiPe] (SimaPro)	18	4	✔	reduce reuse
Rizan et al. (2022a)	repair	reusable surgical scissor	nonspecific	UK	replace repair off-site repair on-site	1 use	attributional LCA (ISO)	EcoInvent [ReCiPe] (SimaPro)	18	4	✔	reduce reuse
Rizan et al. (2022b)	reduce	reusable surgical instruments	nonspecific	UK	individually wrapped as part of a set in RSC as part of a set in tray wrap	1 use	carbon footprint analysis	ICE, SWCCFD, CFCR, EcoInvent (SimaPro)	1	1	✔	reduce
Rodriquez and Hicks (2022)	refuse	vaginal speculum	obstetrics & gynecology	USA	acrylic disposable SS reusable	1 year of clinical operation	attributional LCA (ISO)	EcoInvent, ELCD, USLCI [TRACI] (SimaPro)	10	4	✔	reuse
Rouvière et al. (2023)	refuse	laryngoscopic blade	anesthesia	France	metal single-use metal reusable	4000 uses	attributional LCA	(SimaPro)	7	4	✔	-
Samenjo et al. (2023)	rethink	reusable syringe extension device	obstetrics & gynecology	Kenya	PP PEEK Al	1 year of clinical operation	attributional LCA	EcoInvent [IPCC] (Activitiy Browser)	1	1	✔	reduce
Schulte et al. (2021)	remanufacture	single-use electrophysiology catheter	cardiology	Germany	virgin manufacture remanufacture	provision of 1	attributional LCA (ISO) & attributional LCA (ISO) + CE metric	[EF]	16	4	✔	-
Sherman et al. (2018)	refuse	laryngoscopic blade	anesthesia	USA	plastic disposable metal disposable SS reusable	1 use	attributional LCA (ISO)	EcoInvent, [TRACI] (SimaPro)	10	4	✔	reduce
Sorenson et al. (2022)	refuse	single-lung ventilation system	pulmonology	Denmark	single-use hybrid	1 use	attributional LCA (ISO)	EcoInvent, ILCD (SimaPro)	9	4	✔	-
Sorenson and Gruttner (2018)	refuse	bronchoscope	pulmonology	Denmark	single-use reusable	1 use	simplified attributional LCA	-	3	2	✔	reduce
Unger and Landis (2014)	reuse	disposable dental bur	dentistry	USA	single-use reuse	30 uses	attributional LCA (ISO)	EcoInvent, USLCI, ELCD [TRACI]	9	3	✔	reduce
Unger and Landis (2016)	reuse	reusable surgical instruments	nonspecific	USA	single-use reuse	1 year of provision	attributional LCA (ISO)	ELCD, Ecolvent, USLCI [USEtox, TRACI]	4	2	✔	reduce

Note: check-mark, numerical values reported; -, unspecified/no numerical values reported; Al, Aluminium; BEES, Building for Environmental and Economic Sustainability; CE, Circular Economy; CED, Cummulative Energy Demand; CFCR, Conversion Factors for Company Rerporting database; CML, Center for Environmental Sciences Leiden; EF, Environmental Footprint; ELCD, European Reference Life Cycle Database; GREET, Greenhouse gases, Regulated Emissions, and Energy use in Transportation; ICE, Inventory of Carbon and Energy; ILCD, Internatioal Reference Life Cycle Data System; IPCC, Interfovernmental Panel on Climate Change; ISO, International Organization for Standardization (ISO 14040 and/or 14044); LCA, Life Cycle Assesment; PC, Polycarbonat; PE, Polyethylene; PEEK, Polyetheretherketone; PET, Polyethylene Terephthalate; PP, Polypropylene; ReCiPe, Revised Continous Improvement and Progressive Embodiment; RSC, Rigid Sterilization Container; SS, Stainless Steel; SWCCFD, Small World Consulting Carbon Factors Dataset; TRACI, Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts; UK, United Kingdom; USA, United States of America; USEtox, Unified System for Evaluating Substances Toxicity; USLCI, US Life Cycle Inventory; WARM, Waste Reduction Model

Effects & hotspots

In Figure 3, the impact of reusable surgical instruments on climate change is illustrated relative to their functionally single-use counterparts, showing a median relative impact of 0.58. This translatesto a median climate change impact reduction of 42% when using reusables rather than their single-use/disposable equivalents. Out of the 16 studies examining this comparison, only four reported higher impacts on climate change for reusable surgical instruments. Specifically, the reusable flexible cystoscope (Hogan et al.) and reusable bronchoscope (Sørensen & Grüttner) were nearly 2 times more polluting than their single-use equivalents (1.75 and 1.82, respectively). For a central venous catheter insertion kit (McGain et al. (2012)) and a spinal fusion instrument set (Leiden et al.), these differences in impact were even more significant (2.94 and 6.67, respectively). In two studies, reusables and their single-use equivalents exhibited comparable impacts (flexible ureteroscope, Davis et al., 1.01; anesthetic equipment, McGain et al. (2017), 0.97).

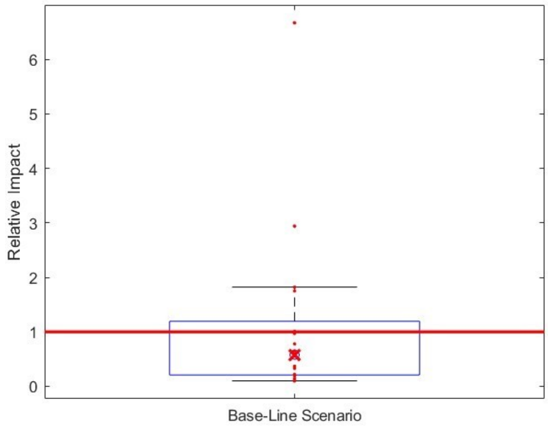

Figure 3: Climate change impact of reusables relative to single-use/disposable equivalents. Note: Each data point (red dot) cor- responds to an individual study's baseline scenario estimate of the impact on climate change using a reusable relative to a functionally equivalent single-use/disposable. The box signifies the interquar- tile range, while the thick red cross within the box represents the median estimate. The bold red line denotes the observation of no difference in climate impact. Numerical data underlying Figure 3 areavailable in Appendix E.

Figure 4 depicts the changes in the relative contributions of different life cycle phases to the climate change impact when reusables are employed instead of their single-use/disposable counterparts. The illustration reveals that, while manufacturing is the primary hot spot for single-use/disposable surgical instruments (median of 73%), a significant climate hotspot emerges in the reprocessing phase when utilizing reusables (median of 77%), which in most studies is primarily attributed to the energy-intensive nature of washers and autoclaves. Notably, only one study (Boberg et al.) identified the manufacturing phase as having a more significant impact on climate change than the reprocessing phase due to the use of single-use membranes in the laparoscopic cholecystectomy system as is suggested by its authors. Additionally, when using reusables, a minor impact hotspot appears in the maintenance/repair phase (median of 7%), while the influence of the disposal and transport phase on climate change become negligible.

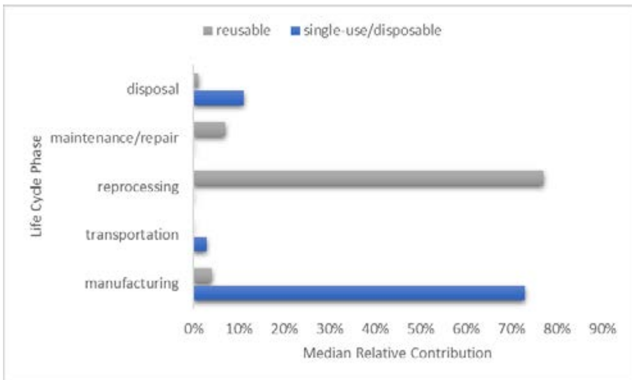

Figure 4: Relative contributions of different life cycle phases tothe climate change impact for single-use instruments/disposables and reusables. Note: The manufacturing phase encompasses raw material acquisition due to the challenge of disaggregating these stages in the included studies. As for the majority of the studies theimpact of the packaging phase is either not reported or added to an-other phase (e.g manufacturing), the packaging phase is excluded from this contribution analysis. Numerical data underlying Figure 4 are available in Appendix E.

In the majority of studies, reusable surgical instruments generally demonstrated lower impacts across the other three environmental dimensions as well. There were a few exceptions: In four out of the nine studies considering this dimension, higher impacts were observed for resource utilization due to extensive water, energy and/or PPE usage (anesthetic equipment, McGain et al. (2017); central venous catheter insertion kit, McGain et al. (2012); bronchoscope, Sørensen & Grüttner; spinal fusion instrument set, Leiden et al.). The reusable spinal fusion instrument set (Leiden et al.) was reported to have a more significant environmental impact across all dimensions, primarily attributed to energy use for steam sterilization. Notably, some studies that demonstrated lower impacts across the other three environmental dimensions did identify higher impacts for reusable instruments in specific midpoint categories, mainly associated with the use of detergents/disinfectants and PPE during the reprocessing phase.

Regarding the studies that compared the impacts of hybrid surgical instruments to single-use/disposable equivalents, the hybrid single-lung ventilation sys- tem (Sørensen et al.) exhibited significant impact increases for climate change (67%) and ecosystem quality but significant impact reductions for resource utilization and human health. While hybrid laparoscopic cholecystectomy instruments (Rizan & Bhutta) yielded significant impact reductions compared to their single-use counterparts in all dimensions, yielding a climate change impact reduction of 76%, the hybrid laparoscopic cholecystectomy system (Boberg et al.) had comparable impacts to the single-use system in all three dimensions. As well as for their single-use equivalents, the manufacturing phase remained the climate change hotspot for hybrid laparoscopic cholecystectomy instruments (Rizan& Bhutta, 62%) and the hybrid laparoscopic cholecystectomy system (Boberg et al., 70%), while the reprocessing phase became the hotspot for the hybrid single-lung ventilation system (Sørensen et al., 42%).

From the two studies comparing metal dispos-able instruments to plastic disposable variants, it wasfound that metal instruments yielded higher impacts across all environmental dimensions compared to plastic variants. In the study by Ibbotson et al., stainless steel disposable scissors were revealed to be more than four times as environmentally polluting in terms of climate change compared to plastic dis- posable scissors, translating to an impact increase of300%. According to Sherman et al., metal disposable laryngoscope blades had a somewhat larger impact on climate change relative to their plastic variants, yielding an impact increase of 16%. The manufacturing phase was identified as the climate change hotspot for both metal and plastic blades. For the metal ones, the high energy consumption of metal mining and refining significantly contributed to this hotspot.

Scenario analysis

Scenario analyses found that the results regarding environmental effects of using reusable instruments rather than their single-use/disposable equivalents are not always robust. Certain studies suggest that factors such as using fossil-heavy energy sources, reduced autoclave loading efficiencies, or a decreased number of reuses may result in an increase in im- pact rather than a reduction for utilizing reusables. Conversely, other studies indicate that employing renewable energy sources, optimizing autoclave loading efficiencies, or increasing the number of reuses can lead to an impact reduction rather than an increase or comparable impacts when using reusables or hybrids instead of their single-use/disposable equivalents. For instance, McGain et al. (2017) found compara- ble climate change impacts for reusable anesthetic equipment and single-use/disposable equivalentsbut scenario analysis revealed that using renewable-based electricity (modeled on the UK/European mix) or natural gas-based electricity (modeled on the U.S. mix) rather than coal-based electricity (modeled on the Australian mix) during reprocessing could leadto climate impact reductions for reusable anesthetic equipment by 86% and 52%, respectively. Furthermore, while Sørensen & Grüttner found a higher climate change impact for reusable bronchoscopes, scenario analysis demonstrated that cleaning more than 2 bronchoscopes per cleaning operation rather than only one resulted in a smaller climate change impact for reusables than for single-use/disposable equivalents. Additionally, regarding the studies that report lower climate change impacts for reusables compared to their single-use/disposable equivalents, these scenario analyses highlight that employing renewable energy sources, optimizing autoclave loading efficiencies, and increasing the number of reuses leads to even larger impact reductions for reusables.

4.4.2. R1: Rethink

Among the two studies examining the ’rethink’ sustainability strategy, one focused on exploring the use of alternative materials for a disposable deviceto reduce environmental impact, while the other delved into the utilization of durable materials and thedesign of a reusable medical device facilitating other sustainability strategies.

Effects & hotspots

A LCA by Nikkhah et al. revealed that the manufacturing off all materials of the disposable cardiopulmonary bypass (CPB) device accounted for nearly two-thirds of the impact on climate change, with disposal by incineration contributing up to one-third. The manufacturing of polycarbonate (PC) emerged as the main contributor to nearly all investigated impact categories for disposable CPB devices, except for cancer and non-cancer (human health), where PVC production dominates the total impact, and fossil fuel depletion (resource utilization), where SS production contributes the most due to crude oil and coal consumption. Consequently, in terms of the sustainability strategy ‘rethink’, a LCA was conducted by considering alternative polymeric materials in the CPB device with the aim of minimizing its environmental impact. Polypropylene (PP), polyethylene (PE), and polyethylene terephthalate (PET), were examined as substitutes for PC. Eliminating PC led to a substantial decrease in all impact categories where PC emerged as the primary contributing factor, with up to an 80% reduction in the ecotoxicity impact category, Specifically, regarding the climate change dimension, adopting PP, PE, and PET as substitutes for PC in 100 CPB devices resulted in impact reductions of 23%, 24% and 17%, respectively. Furthermore, replacing PC with PE yielded a more significant reduction than both PP and PET across nearly all categories.

The study by Samenjo et al. incorporated the sustainability strategy 'rethink' by creating a robust reusable syringe extension device, known as Chloe SED®, constructed from durable materials that allow for multiple reuse cycles (PP, polyetheretherketone (PEEK), aluminum). Moreover, the device features a modular design, facilitating maintenance, repair and upgrades for prolonged use. In the event of irreparable, Chloe SED® 's single-material composition allows for efficient recycling. Reprocessing assessments demonstrated that an aluminum Chloe SED® maintained structural integrity for an extensive 1,000 reuse cycles, outperforming PEEK (25 cycles) and PP (5 cycles). Additionally, a LCA revealed that over aone-year period of clinical operation (500 uses), Chloe SED® in PEEK exhibited the highest global warming potential when considering steam sterilization. Chloe SED® in PP and aluminum yielded impact reductions of 44% and 82%, respectively, compared to Chloe SED® in PEEK. Manufacturing of the Chloe SED® in PP and PEEK emerged as the hotspot phase for climate change (87% and 91% respectively) whereas for the Chloe SED® in aluminum, the reprocessing phase was most critical (79%).

Scenario analysis

In Samenjo et al.'s study on the reusable Chloe SED®, an alternative scenario was explored by considering chemical sterilization as a reprocessing method instead of steam sterilization. While this led to slight increases in the global warming potential for aluminum and PEEK, it significantly enhanced the durability of Chloe SED® in PP and reduced its global warming potential by more than half. However, in this scenario, the Chloe SED® in Al still yielded the largest climate change impact reduction, affirming theresults' robustness.

4.4.3. R2: Reduce

By exploring various packaging methods for the decontamination of reusable instruments, two studies primarily addressed the sustainability strategy 'reduce,' emphasizing ways to increase the efficiency in surgical instrument use to improve environmental outcomes.

Effects & hotspots

Friedericy et al. conducted a LCA, comparing the environmental impacts of using reusable aluminum rigid sterilization containers (RSC) for high volumes (5000 use cycles) as a sterilization packaging system for reusable surgical instruments, as opposed to blue wrap, a multilayer non-woven packaging material made from PP. Landfilled RSCs exhibited a significantly lower carbon footprint relative to incinerated blue wrap, yielding an impact reduction of 85%. The impact of RSCs on climate change is predominantly influenced by their reprocessing phase, accounting for 92%, mainly due to power consumption in washingand sterilization processes. In contrast, the manufacturing and disposal phases contribute the most to the climate impact of blue wrap, representing 64% and 31%, respectively. The smaller impact on climate change for RSCs aligns with the smaller aggregated impact score for RSCs, encompassing the other three environmental impact dimensions, yielding areduction of 52% compared to blue wrap. The toxicity of the carbon footprint, leading to both global warming and related health issues, is reported to be the major factor driving the high aggregated impact score of blue wrap. The authors suggest that in their study, the eco-costs impact category, which represents the sum of all external costs related to emissions and material use during the life cycle, proved to be the most suitable basis for analysis and communication. Concerning this impact category, RSCs demonstrateda significant impact reduction compared to blue wrap (85%).

Unlike Friedericy et al.'s LCA, Rizan et al. (2022b) carried out a carbon footprint analysis specifically to calculate the carbon footprint associated with the packaging and decontamination of reusable surgical instruments, comparing individually packed instruments with instruments included as part of a set. The overall carbon footprint of packaging instruments as part of a set in a rigid container or in tray wrap, along with decontaminating them, was smaller than the total carbon footprint of packaging and decontaminating an individually wrapped reusable surgical instrument in a flexible pouch, yielding impact reductions of 39% and 65%, respectively. Notably, a significant portion (86%) of the carbon footprint associated with reusable aluminum containers was attributed to the washing of these containers. The proportion of the carbon footprint attributed to packaging was lower than the share attributed to the decontamination process for instruments as part of a set, whether packaged in a reusable aluminum container (32% vs. 69%) or a single-use tray wrap (20% vs. 80%), as well as for individually wrapped instruments in flexible pouches (23% vs. 77%).

Scenario analysis

The scenario analysis by Rizan et al. (2022b) revealed that increasing the number of instruments per set resulted in a decreased carbon footprint, and optimizing the autoclave/washer loading efficiency further reduced the carbon footprint. Maximizing both factors led to a 31% and 42% reduction in carbon footprint compared to scenarios where the average number of instruments per set and loading efficiency was used for instrument sets packaged in single-use tray wrap and reusable aluminum containers, respectively. Furthermore, regional variations were observed in this scenario analysis: compared to using natural gas to power the steam sterilizer in the UK (baseline scenario), Australia exhibited a larger carbon footprint, while Iceland showed a smaller carbon footprint. When electricity was modeled as an alternative energy source to power the autoclave, regional differences in carbon footprint becamemore pronounced, with a 14-fold difference between Australia (high-carbon energy source) and Iceland (low-carbon energy source). In most regions, the carbon footprint of using electricity for decontamination exceeded that of using natural gas due to additional steps in electricity generation and distribution, except for Iceland, where low-carbon Icelandic electricity further reduced the carbon footprint. In the scenario analysis by Friedericy et al. the potential effects of transitioning to alternative energy sources was also modeled: compared to utilizing an Europeanelectricity mix, the adoption of electricity generated from local photovoltaic cells led to a significant 74% reduction in the eco-costs of the RSC system.

4.5. Extending Instrument Lifespan

4.5.1. R3: Reuse

All three articles investigating the sustainability strategy of 'reuse' focus on comparing the environmental impact of reusing surgical instruments instead of taking a single-use approach.

Effects & hotspots

In Lalman et al.'s study, disposable electrophysiological catheters are identified as heat-sensitive products, rendering them unable to withstand the heated water vapor used in steam sterilization. As a result, an alternative sterilization method, namely ethylene oxide (ETO) gas sterilization, is employed that involves exposing products to a mixture of ETO gas and other gasses at low temperature. In terms of the climate impact dimension, the global warming potential of reusing electrophyiological cathetersfive times was 20 times higher compared to usingfive catheters only once, translating to a significant increase of 1900%. Across the other three environmental dimensions the impact was also much greater for reusing electrophysiological catheters, with an aggregated impact score more than 24 times that of using catheters once, indicating an increase of 2300%. According to Lalman et al. this heightened impact is partially attributed to the significant electricity consumption during each ETO sterilization cycle due to long cycle times that are required because of the toxicity of residual ETO quantities. Additionally, they report that an extra apparatus is needed for detoxification to convert any remaining ETO to carbon dioxide and water, requiring further electricity.

The study by Unger & Landis(2016) evaluatedthe dimension of climate change and human health, including carcinogenic, non-carcinogenic, and respiratory effects, associated with the one-year provision of seven reusable surgical instruments. These instruments were utilized either as disposables or as reusables, with a maximum of five uses. Reprocessing occurred for devices used more than once, involving the use of an ETO gas sterilizer. Utilizing average reprocessing inputs (ETO, electricity and water), reusing the seven examined devices, as opposed to using them as disposables, marginally decreased global warming impacts (1-4%) but significantly increased human health impacts. Regardless of the number of reuse instances, the primary factor influencing both climate change and human health impacts was the reprocessing life cycle inventory (47-77%) whereas utilizing the instruments as disposables resulted in a manufacturing phase hotspot (81%).

Another study by Unger & Landis (2014) delves into the potential for reuse and the associated environmental implications of dental burs labeled as disposable but possessing the capacity for multiple uses. In an optimal scenario, where both the autoclave and ultrasonic were maximally loaded (100% of loading capacity), the environmental impact of reusing the bur 30 times compared to using 30 disposables exhibited a significantly lower overall impact across all nine impact categories, spanning the climate change, ecosystem quality and human health dimensions. Specifically, for the climate change dimension, reusing the bur reduced the environmental impact by 35%. Whereas the packaging phase contributed the most for both reusing and using the bur only once (39% and 50% respectively), the reprocessing phase for reusing the bur demonstrated only limited impacts(19%) on climate change.

Scenario analysis

The scenario analysis by Unger & Landis (2016) revealed that reusing with limited reprocessing inputs yields impact reductions for both climate change and human health, regardless of the number of reuse instances, and each additional reprocessing instance resulted in even larger reductions. In the other study by Unger & Landis (2014), a scenario analysis found that in a mid-case scenario, (66% of loading capacity), reusing dental burs was environmentally favorablein four impact categories (ozone depletion, smog, respiratory effects, and ecotoxicity), while disposables had the environmental advantage in four categories (acidification, eutrophication, carcinogenic and non-carcinogenic impacts), with the global warming impact category being nearly identical. In the worst-case scenario (33% of loading capacity), reusing dental burs demonstrated more adverse environmental impacts in eight out of nine categories compared to disposable burs (with the exception of ozone depletion).

Lalman et al. explored another alternative reprocessing method, namely hydrogen peroxide disinfection, which involves vaporized hydrogen peroxide rather than heat to decontaminate heat-sensitive electrophysiological catheters. In terms of climate change, reusing through hydrogen peroxide sterilization yielded an impact increase of approximately 100% compared to using electrophysiological catheters once. Regarding the other three environmental dimensions, the impact for reusing through hydrogen peroxide sterilization was also greater, with an aggregated impact score two times that of using catheters once, indicating an increase of 100%, affirming the robustness of the impact increase found for reuse. Only a relatively small difference in land use was observed, which the authors suggested could be attributed to the greater resources required to produce five new catheters compared to disinfecting a single catheter.

4.5.2. R4: Repair

A study by Rizan et al. (2022a) delved into the sustainability strategy of 'repair,' by performing a LCA that specifically assessed the environmental impact of repairing (in this case, sharpening) reusable surgical scissors, either onsite at the hospital or offsite with an external contractor, compared to replacing them.

Effects & hotspots

Compared to replacing a reusable scissor nine times, repairing a reusable scissors nine times offsite exhibited an climate change impact reduction of 19% compared to replacing reusable scissors, and onsite repair had a small additional reduction of 1%. The reprocessing phase was the largest contributor to the global warming potential for both replaced (76%) and repaired reusable scissors, whether offsite (95%) or onsite (97%). The environmental impact of the repair process itself accounted for only 2% of the total global warming potential for scissors repaired offsite andthe use of bulk packaging at the onsite repair site reduced this contribution to nearly 0% for scissors repaired onsite. An average impact reduction of 30% relative to no repair was found across all dimensions, due to differences in the amount of manufacturing of chromium steel. Onsite repair resulted in small additional reductions, with an average additional impact reduction of 2%.

Scenario analysis

A scenario analysis was performed, varying methodological assumptions such as the number of reuses, repairs, and distance to the offsite repair site. Across all impact categories, the analysis consistently revealed that replacing scissors had the highest environmental impacts, while repairing onsite had the lowest, affirming the robustness of environmental impact reductions associated with repair. The highest global warming potential was linked to scissors used only ten times and not repaired, whereas the lowest was associated with scissors used 400 times before onsite repair. Scissors used 400 times without repair had a global warming potential only slightly higher than those that were repaired after 400 uses. Scissors repaired only once, whether onsite or offsite, resulted in a slightly lower global warming potential reduction compared to no repair than when repaired nine times. The variation in distance between the hospital and the offsite repair center had minimal impact on the results.

4.5.3. R6: Remanufacture

Finally, a study by Schulte et al. delves into the sustainability strategy 'remanufacture,' examining the environmental impact of remanufacturing a disposable electrophysiological catheter instead of producing a new one. In this study, the authors initially choseto adopt a supporter perspective to provide insights into short-term impacts. This approach investigates whether a user or client should purchase a virgin catheter or a remanufactured catheter with the same functionality and quality based on environmental criteria. To analyze long-term impacts from a system perspective in the context of a circular economy (CE), a new modeling approach incorporating a circularity metric was introduced. This approach acknowledges that each newly manufactured product can be remanufactured multiple times, passing through several product life cycles. While the supporter perspective focuses on one product life cycle through the cut-off approach, the system perspective considers impacts on other product systems through system expansion.

Effects & hotspots

According to the supporter perspective, lower impact values for 13 out of 16 considered impact categories were identified for using a remanufactured catheter compared to a virgin catheter that is disposed of after single use. Only in the categories of freshwater eutrophication, land use, and water scarcity, the impact was higher for the remanufacturing route compared to the virgin manufacturing route due to the use of disinfectants and cleaning agents. The authors deemed the difference in water scarcity impacts as insignificant. The results indicate that using a remanufactured medical catheter has only half the impact on climate change compared to using a catheter fromthe virgin production route. When applying a system perspective, i.e., a fully circular production system where all catheters are collected and remanufactured according to the analyzed remanufacturing process, using a remanufactured medical catheter also has a lower impact on global warming than using a catheter from the virgin production route, with an impact reduction of 35%. In both the virgin and remanufacturing routes, the manufacturing phase is the primary contributor (71% and 75% respectively). This is attributed to the production and processing of plastics in the former, and the electricity consumption during this process in the latter.

5. Discussion

By employing an LCA-based methodology, the specifics of which vary in each study, the included studies provide a thorough analysis of the environmental effects linked to sustainability strategies for surgical instruments. The strategies falling underthe category of smarter product use/manufacture are discussed separately from those associated with the extension of product lifespan.

Smarter Instrument Use/Manufacture

Opting for reusable surgical instruments over single-use ones is generally considered an envi- ronmentally friendly strategy, resulting in a median climate change impact reduction of 42% across the 16 studies examining this approach. While the manufacturing phase is the primary contributor to the climate change impact of single-use instruments, transitioning to reusables reduces this phase's impact and introduces a significant climate hotspot in the reprocessing phase, mainly due to the energy consumption of washers and autoclaves. In most studies, the reduced impact of the manufacturing phase for reusables can counterbalance the hotspot impact of the reprocessing phase, making reusables preferable over single-use instruments. Scenario analyses in these studies demonstrate that employing renew- able energy sources, optimizing autoclave loading efficiencies, and increasing the number of reuses lead to even further impact reductions for reusables. However, in a few studies, the significant hotspot in the reprocessing phase causes the overall climate change impact of reusables to be similar (flexible ureteroscope, Davis et al.; anesthetic equipment, McGain et al. (2017)), or even surpass that of their single-use equivalents (flexible cystoscope, Hoganet al.; spinal fusion surgery instrument set, Leidenet al.; central venous catheter insertion kit, McGain et al. (2012); bronchoscope, Sørensen & Grüttner). Scenario analysis already revealed that for McGain et al. (2017) and Sørensen & Grüttner, their results were not robust as by using a lower carbon energy source than Australian coal-based (high-carbon) energy and less PPE per cleaning procedure, respectively, reusables became preferable over their single-use equivalents. In the studies conducted by Hogan et al. and McGain et al. (2012), the results can also be attributed to the geographical context of Australia, where reprocessing relies on coal-based energy. Notably, Hogan's findings contrasted with those of Kemble et al.'s study, wherein a reusable flexible cystoscope appeared to be more environmentally friendly due to lower power consumption during reprocessing. Additionally, the type of instrument assessed seems to influence the results. For all conventional instruments, reusables are found to be environmentally preferable, while for studies by Leiden et al. 2020 and McGain et al. (2012), the large size of the set/kit, including multiple instruments, is suggested to be the main reason for the increased climate change impact of reusables. Considering the other three dimensions, reusables were also generally regarded as more environmentally friendly than their single-use equivalents, with only a few exceptions found, primarily related to resource utilization. This is due to the extensive use of energy, PPE, and water during reprocessing (McGain et al. (2012), McGain et al. (2017), Sørensen & Grüttner, and Leiden et al.), suggesting that besides efficient energy use, efficient management of water and PPE is also essential.

Refusing single-use instruments by utilizing hybrid equivalents resulted in varied outcomes regarding environmental effects, as reflected in the impact hotspots. Where the reprocessing phase emerged as a significant hotspot for the hybrid equivalent, hybrids were found less environmentally favorable. Again, scenario analysis highlighted the sensitivity of results to varying reprocessing approaches; increasing the number of reuses showed hybrids could become preferable over single-use instruments. Opting for metal single-use instruments over plastic single-use equivalents, was found to lead to impact increases across all environmental dimensions. This is primarily attributed to the higher impact of the manufacturing phase for metal instruments due to the high energy consumption associated with metal mining and refining.

Table 4: Summary of study findings on environmental effects and associated hotspots and mitigation potentials (part 1)

reference	sustainability strategy	surgical instrument	primary comparison	functional unit	climate change effect	other environmental effects	climate change hotspots	scenario analysis	robustness results	mitigation potential
*	**refuse:** replace with reusable equivalents	various single-use instruments/disposables	single-use/disposables reusables	-	impact reduction (median of 42%; exceptions found in six[1] studies)	impact reductions in all dimensions (exceptions found in four[2] studies)	single-use/disposables: manufacturing (median of 73%) reusables: reprocessing (median of 77%)	**reduce**: alternative energy source **reduce:** alternative autoclave loading efficiency **reuse**: alternative number of reuses	x/✔	Using renewable energy sources, optimizing autoclave loading efficiencies and increasing the number of reuses generally leads to larger impacts reductions in all dimensions.
Boberg et al. Rizan and Bhutta Sorenson et al.	**refuse:** replace with hybrid equivalents	single-use laparoscopic cholecystectomy system, laparoscopic cholecystectomy instruments & single-lung ventilation system	single-use hybrids	-	varied results (no significant effect, impact reduction of 76% & impact increase of 67%)	varied results (no significant impact in all dimensions, impact reductions in all dimensions & both resource utilization and human health impact reductions but ecosystem quality impact increase)	single-use/disposables: manufacturing (65%, 57% & 65%) hybrids: manufacturing (70%, 62%) & reprocessing (42%)	**reuse**: increased number of reuses	x/✔	Increasing the number of reuses leads to larger impact reductions in all dimensions.
Ibbotson et al. Sherman et al.	**refuse:** replace with metal equivalents	disposable surgical scissor & laryngoscopic blade	metal disposable plastic disposable	-	impact increase (300% & 16%)	impact increases in all dimensions	metal disposable: manufacturing (93%) plastic disposable: manufacturing (97%)	-	-	-
Nikkhah et al.	**rethink**: redesign with alternative polymeric materials	disposable CBD	design in PC design in PP design in PE design in PET	100 devices	PP: impact reduction of 23% (vs PC) PE: impact reduction of 24% (vs PC) PET: impact reduction of 17% (vs PC)	impact reductions in all dimensions, with PE exhibiting the largest reductions	design in PC: manufacturing (60%)	-	-	-
Samenjo et al.	**rethink:** design with durable materials	reusable syringe extension device	design in PP design in PEEK design in Al	1 year of clinical operation	PP: impact reduction of 44% (vs PEEK) Al: impact reduction of 82% (vs PEEK)	-	design in PP: manufacturing (87%) design in PEEK: manufacturing (91%) design in aluminum: reprocessing (79%).	**reduce:** chemical vs steam sterilization	✔	Using chemical sterilization leads to a larger climate change impact reduction for the design in PP.
Rizan et al. (2022b)	**reduce:** package as part of a set instead of individually wrapping them	reusable surgical instruments	individually wrapped as part of a set in RSC as part of a set in tray wrap	1 use	in RSC: impact reduction of 39% in tray wrap: impact reduction of 65%	-	individually wrapped: reprocessing (77%) as part of a set in RSC: reprocessing (69%) as part of a set in tray wrap: reprocessing (80%)	**reduce**: increased vs average number of instruments per set **reduce:** 100% vs average autoclave/washer loading capacity **reduce:** Icelandic gas & electricity vs UK natural gas	✔	Both increasing the number of instruments per set and a loading capacity of 100% leads to a larger climate change impact reduction for instruments as part of a set, and using Icelandic gas or electricity increases the reduction even further.
Friedericy et al.	**reduce:** use a reusable RSC as sterilization packaging instead of blue wrap	reusable surgical instruments	disposable blue wrap reusable RSC	5000 uses	impact reduction of 85%	impact reductions in all dimensions (52% for aggregated impact score and 85% for eco-costs)	disposable blue wrap: manufacturing (64%) reusable RSC: reprocessing (31%)	**reduce:** electricity from photovoltaic cells vs European electricity mix	✔	Using electricity from photovoltaic cells leads to larger impact reductions in all dimensions.
Lalman et al.	**reuse:** reuse through ETO sterilization instead of disposal after one use	disposable electrophysiology catheter	single-use reuse	5 uses	impact increase of 1900%	significant impact increases in all dimensions (>2300% for aggregated impact score)	-	**reduce:** hydrogen peroxide vs EtO sterilization	✔	Reusing through hydrogen perioxide sterilization leads to significant smaller impact increases in all dimensions compared to ETO sterilization
Unger and Landis (2016)	**reuse:** reuse through ETO sterilization instead of disposal after one use	reusable surgical instruments	single-use reuse	1 year of provision	impact reduction of 1-4%	significant human health impact increase	single-use: manufacturing (81%) reuse: reprocessing (47-77%)	**reduce:** limited vs average inputs **reuse:** increased number of reuses (2-4) vs one reuse	x\✔ (human health impact results are sensitive to limited inputs)	Limiting reprocessing imputs leads to larger impact reductions in both dimensions and only when limiting inputs, increasing the number of reuses increases these reductions even further.

*Note: *, Boberg et al., Davis et al., Donahue et al., Eckelman et al., Hogan et al., Ibbotson et al., Jabouri & Abbott, Kemble et al., Leiden et al., Liang, McGain et al. (2012), McGain et al. (2017), Rodriguez Morris & Hicks, Rouvière et al., Sherman et al., Sørensen & Grüttner; ¹, Davis et al., Hogan et al., Leiden et al., McGain et al. (2012), McGain et al. (2017), Sørensen & Grüttner; ², Leiden et al., McGain et al. (2012), McGain et al. (2017), Sørensen & Grüttner; checkmark, results are robust; x, results are sensitive to alternative scenario; x/checkmark, some results are robust and some are sensitive; -, unspecified. The mitigation potential is only reported when it is based on the results of a performed scenario analysis. As for the sustainability strategy of refuse the functional unit differs amongst the studies that implement this strategy, the functional unitis denoted as unspecified (-). Al, Aluminium; CBD, Cardiopulmonary Bypass Device; ETO = Ethylene Oxide PC, Polycarbonat; PE, Polyethylene; PEEK, Polyetheretherketone; PET, Polyethylene Terephthalate; PP, Polypropylene; RSC, Rigid Sterilization Container*

Table 4: Summary of study findings on environmental effects and associated hotspots and mitigation potentials (part 2)

reference	sustainability strategy	surgical instrument	primary comparison	functional unit	climate change effect	other environmental effects	climate change hotspots	scenario analysis	robustness results	mitigation potential
Unger and Landis (2014)	**reuse:** reuse through steam sterilization instead of disposal after one use	disposable dental bur	single-use reuse	30 uses	impact reduction of 65%	human health and ecosystem quality impact reductions (average of 60% for all impact categories)	single-use: packaging (50%) reuse: packaging (39%)	**reduce**: 66% & 33% vs 100% autoclave/ultrasonic loading capacity	x (for all dimensions)	-
Rizan et al. (2022a)	**repair:** repair instead of replace	reusable surgical scissor	replaced repaired off-site repaired on-site	1 use	off-site: impact reduction of 19% on-site: impact reduction of 20%	impact reductions in all dimensions (average of 30% and 32% for all impact categories respectively)	replaced: reprocessing (76%) repaired off-site: reprocessing (95%) repaired on-site: reprocessing (97%)	**reduce:** fossil heavy electricity mix vs UK electricity mix **reduce:** repairing once vs 9 times **reduce:** 800 km vs 80 km distance to repair centre **reuse:** 400 & 10 vs 40 uses	✔	Increasing the number of uses to 400 leads to larger impact reductions in all dimensions.
Schulte et al.	**remanufacture:** remanufacture instead of virgin manufacture	disposable electrophysiology catheter	virgin manufactured remanufactured	provision of 1	impact reduction of 35%	impact reductions in all dimensions (except for the midpoint impact categories of eutrophication freshwater, land use and water scarcity)	virgin manufactured: manufacturing (71%) remanufactured: manufacturing (75%)	-	-	-

Note: checkmark, results are robust; x, results are sensitive to alternative scenario; x/checkmark, some results are robust and some are sensitive; -, unspecified. The mitigation potential is only reported when it is based on the results of a performed scenario analysis.

In Samenjo et al.'s study they emphasized the significance of integrating sustainable considerations into surgical instrument design by employing durable materials, ensuring that the instrument can be used multiple times. Their LCA demonstratedthat designing a reusable Chloe SED® in aluminumis environmentally preferable over designs in plastic (PEEK and PP) when reused over a one-year period. This is attributed to the durability of metals, allowing for a much higher number of reuse cycles after steam sterilization compared to plastics, despite the initially higher environmental impact during manufacturing. This in turn explains the significant manufacturing hotspot for Chloe SED® in PEEK and PP over aone-year period of clinical operation, as a larger quantity of devices need to be procured, while for aluminum, the quantity is significantly lower, resultingin a smaller contribution of the manufacturing phase to the overall impact. When opting for durable metals is not feasible for the design of a reusable surgical instrument, the scenario analysis suggests exploring alternative reprocessing methods that don't involve high temperatures, such as chemical sterilization. This approach can extend the lifespan of plastic instruments, allowing it to withstand more reuse cycles before experiencing material deformation. While the reusable Chloe SED® was also manufactured with a modular design to facilitate additional sustainability strategies such as repair and remanufacture, ensuring its prolonged use, the impact of this approach has not been analyzed.

The importance of carefully selecting alternative polymeric materials for single-use instruments is emphasized in Nikkhah et al.'s study on disposable CPB devices. This decision significantly influences all impact dimensions and should be guided by the specific environmental priorities. For instance, the exclusion of PVC for CPB devices is recommended if human health considerations are prioritized, while avoiding SS becomes crucial for those prioritizing fossil resource conservation. Alternatively, if other factors are more important, opting for alternativesto PC is advised. The study's analysis reveals that substituting PC with PE yields the most pronounced reduction across almost all impact categories, rendering PE a promising alternative for PC in disposable CPB devices. Furthermore, the LCA by Nikkhah et al. revealed that, in addition to the manufacturing phase, incineration contributes significantly in the disposable CPB device's life cycle, constituting up to one-third of the climate change impact. This highlights the need of exploring alternative disposal methods, alongside alternative polymeric materials, as a strategy to mitigate the climate impact associated with these devices.

Regarding the sustainability strategy of 'reduce', minimizing the use of resources and materials during the utilization of surgical instruments, according to Rizan et al. (2022b), integrating individually wrapped reusable instruments into sets has environmental benefits associated with decontaminating reusable surgical instruments. While Friedericy et al.'s findings indicate that the aluminum RSC is environmentally preferable as a packaging system for sterilizing instrument sets compared to disposable blue wrap, Rizan et al. (2022b) reached the opposite conclusion. This variation in outcome can be attributed to differences in LCA methodologies. Friedericy et al. assess the environmental impact by comparing a reusable RSC used 5000 times with 5000 blue wraps, while Rizan et al. (2022b) calculate the carbon footprint for both packaging systems per instrument use. In the latter, the higher climate change impact of employing RSC is primarily attributed to the washing of RSCs as there is no washing involved in the single-use blue wrap and no additional impact from sterilization for both packaging options, as this is allocated to the decontamination process of the instruments insidethe packaging. Rizan et al. (2022b) propose this environmental impact could be mitigated by using larger, more efficient washer machines designed specifically for washing reusable rigid containers or by ensuring that the containers are of the smallest sufficient size, making the RSC's potentially environmentally preferable over single-use wraps. When blue wrapis chosen as the packaging method, both studies suggest that recycling can lead to reductions in the overall environmental impact. Nevertheless, contribution analysis by Rizan et al. (2022b) indicates that the reprocessing process will remain the primary hotspot, and scenario analysis revealed that, in addition to integrating individually wrapped instruments into sets, increasing the number of instruments per set, optimizing loading efficiency, and utilizing alternative energy sources such as natural gas or low-carbon electricity could further reduce the climate change impact of decontaminating reusable surgical instruments. This aligns with the outcomes of studies that explore the strategy of refusing single-use instruments and utilize reusables instead, where scenario analyses revealed the potential for mitigation by optimizing loading efficiency and utilizing low-carbon energy sources.

Extending Instrument Lifespan

Based on the insights derived from the three ar- ticles exploring the sustainability strategy of 'reuse,' itcan be concluded that the environmental impact of ex-tending the lifespan of disposable surgical instruments by reusing them is significantly influenced by the reprocessing method and the inputs involved. Lalman et al.'s findings indicate that the use of ethylene oxide (ETO) as a reprocessing method is unfavorable for the environmental impact of reusing surgical instruments, primarily due to the toxicity of ETO residues. This results in high energy consumption during lengthy ETO sterilization cycles and necessitates additional detoxification processes between each usage cycle. However, as highlighted by Samenjo et al., complex instruments composed of certain plastics, such as the electrophysiological catheter in Lalman et al., are sensitive to heat damage. Therefore, the utilization of chemical sterilization methods, such as ETO sterilization, that don't involve high temperatures, as opposed to the conventional steam sterilization method, is necessary. In their scenario analysis, hydrogen peroxide sterilization is considered as an alternative chemical sterilization method. Although this scenario is also not environmentally preferable over using electrophysiological catheters once, the lower toxicity compared to ETO eliminates the need for a stringent detoxification process, resulting in lower overall impacts than ETO sterilization. The study by Unger & Landis (2016) suggests minimizing reprocessing inputs to reduce environmental impacts related to the ETO sterilization process. Under 'average' reprocessing inputs, reusing surgical instruments through ETO sterilization showed a slightly lower global warming potential compared to using them as disposables for a functional unit of one year of provision. However, human health impacts favored the latter due to the toxicity of ETO. Scenario analysis revealed that minimizing reprocessing inputs (ETO, electricity and water) makes reprocessing favorable from both a global warming and human health perspective. Another study by Unger & Landis (2014) emphasizes once again the critical role of efficiency in reprocessing machines. Scenario analysis highlights that inadequate loading of the ultrasonic and autoclave can result in more significant environmental impacts than designating dental burs as disposables. This is in contrast to the environmental benefits of considering burs as reusable for optimal loading efficiencies. Moreover, as the packaging phase proved to be the environmental impact hotspot of dental burs, enhancements to bur packaging is suggested as a way to further enhance the environmental impact of dental burs.

Rather than reusing complex, heat-sensitive single-use instruments through chemical sterilization, the study by Schulte et al. underscores the potential environmental benefits of extending the lifespan of their parts through remanufacturing. In this study, remanufacturing an electrophysiological catheter is identified as environmentally preferable over virgin manufacturing one. Although remanufacturing introduces additional impacts in all dimensions, primarily due to the use of detergents, disinfectants, and extra electricity, these impacts do not surpass the savings achieved in the primary production of plastics for virgin manufactured catheters from both a supportive and systemic perspective. As the system perspec- tive takes circularity into account and models virgin material production upstream for remanufactured catheters, the relative impacts are higher compared to the impacts observed from a supportive perspective. However, these findings are applicable for interpretation within a broader circular economy perspective, including multiple product cycles.

The potential environmental benefits of extend-ing the lifetime of a variety of commonly used simple stainless steel surgical instruments by repairing them, is indicated in the analysis by Rizan et al. (2022a). They found that repairing reusable surgical scissors at the end of their functional life, rather than replacing them with new ones, is environmentally preferable. The study suggests that the marginal difference observed in the environmental impact between onsite and offsite repair centers implies that establishing regional or national repair centers is as effective as developing local repair centers, even for large distances. Scenario analysis further indicates that a single repair event already provides an advantage over replacement. Additionally, the finding that scissors used 400 times without repair had only a slightly higher impact on climate change than those that were repaired after 400 uses, highlights the importanceof increasing the number of reuses. This aligns with the conclusions drawn from studies comparing the environmental impact of single-use surgical instruments to functionally equivalent reusables, where scenario analysis demonstrates that more frequent reuse of reusables leads to a further reduction in environmental impact. It's important to note that the study by Rizan et al. (2022a) recognizes thatrepairing complex instruments might require different packaging and equipment, resulting in a potentially greater environmental burden.

Methodological designs

While most studies primarily focused on the cli- mate change dimension, addressing its effect in terms of CO2e emissions, the conclusions often extended beyond the environmental dimension of climate change to include resource utilization, human health, and ecosystem quality. However, a comprehensive analysis of midpoint impact categories beyond those related to climate change was frequently lacking and endpoint categories were often not reported, limiting the interpretability of the reported outcomes associated with these impact categories. Additionally, interactions among impacts were generally not accounted for. These factors have the potential to influence the results of this research, particularly concerning the dimensions of resource utilization, human health, and ecosystem quality.

The wide range of instrument types assessed, spanning from simpler conventional instruments like a vaginal speculum to more complex instruments such as a cardiopulmonary bypass device, as wellas entire instrument kits or sets, leads to highly variable absolute impact results amongst the includedstudies. This variability persists even for studies assessing similar instruments, occasionally leading to contradictory outcomes, as evident in the studies by Hogan et al. and Kemble et al., and Friedericy et al. and Rizan et al. Such diversity arises from significant differences in LCA methodological choices and assumptions, including variations in utilized inventory databases, characterization methods, and functional units, alongside differences in overall completeness. Consequently, it becomes challenging to compare study outcomes directly and draw overall conclusions regarding the environmental effects of sustainability strategies for surgical instruments.

5.1. Limitations

Limitations of this research are evident in the literature search process. The stringent search string may have resulted in the omission of articles that mention specific instrument groups, such as 'endourologic equipment', or specific instruments without using the terms 'medical,' 'surgical,' or 'operative.' This could potentially have led to the exclusion of relevant content. Additionally, the absence of sustainability-related terms such as 'refuse,' 'rethink,' 'reduce,' 'reprocess,' or 'redesign' in the final search string may have resulted in the overlooking of relevant articles. This might explain the relatively limited focus on the sustainability strategy of rethink among the included articles, despite the substantial environmental benefits of engineering for sustainability within the context of surgical instruments, particularly by emphasizing durability and product-life extension.

To address the challenge of comparing the highly variable impact results among studies and drawing overall conclusions regarding the environmental effects of sustainability strategies for surgical instruments,this research focuses on relative changes rather than absolute values, facilitating more meaningful comparisons. However, it is important to note that this approach might result in small relative effects for large absolute changes in situations where surgical instruments exhibit significant absolute impacts, and large relative effects for the opposite scenario.

5.2. Future research

The significant variability in study outcomes, due to the diversity in assessed instruments and differences in methodological choices for LCAs among researchers, emphasizes the need for the development of practical guidelines for conducting LCAs specifically in the field of surgical instrumentation. These guidelines should be accessible to all stakeholders involved in surgical instrument management and supported by robust peer-review mechanisms to ensure that LCAs in this field adhere to the highest standards, providing reliable and trustworthy conclusions.

Despite the limited focus on the 'rethink' strategy, engineering for sustainability shows high potential for achieving circularity, warranting further exploration. Investigating the environmental effects of repairing complex instruments and remanufacturing reusables alongside disposables while incorporating circularity metrics, presents another interesting topic for future research. While this research focuses solely on environmental effects, considering changes in instrument quality/functionality and associated costs is necessary for effectively implementing sustainability strategies on surgical instruments.

6. Conclusions

In conclusion, by applying refined definitions of sustainability strategies within Potting's framework specifically tailored to the product category of surgical instruments, and through a thorough examination of the environmental effects associated with these strategies, this research offers valuable insights for enhancing environmental sustainability in the context of surgical instruments.

Literature strongly advocates switching to reusable surgical instruments and implementing additional strategies such as integrating metal into their designs, optimizing reprocessing practices, increasing reuse cycles, and repairing damaged instruments, to minimize their environmental impact. When utilizing disposables/single-use instruments, plastic variants are recommended over their metal counterparts, with a focus on redesigning using alternative poly- meric materials and remanufacturing to enhance environmental benefits. However, recognizing that the environmental effects of refusing or reusing disposables depend on reprocessing practices, the need for careful consideration is emphasized, especially for complex instruments. The significant variability in study outcomes underscores the importance of developing practical guidelines for conducting LCAs specifically in the field of surgical instrumentation. These guidelines should be accessible to all stakeholders involved in surgical instrument management to ensure the generation of reliable conclusions regarding the environmental effects of sustainability strategies for surgical instruments.

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APPENDIX A

Initial search string

Scopus:
(TITLE-ABS-KEY (environment* OR ecolog* OR sustainab*) AND TITLE-ABS-KEY (impact OR effect OR influence) AND TITLE-ABS-KEY (refus* OR rethink* OR reduc* OR reus* OR repair* OR reparation OR refurbish* OR remanufactur* OR repurpos*) AND TITLE-ABS-KEY (surgical OR operative) AND TITLE-ABS-KEY (tool OR instrument OR equipment OR device OR machine* OR apparatus OR appliance)) → 1228

PubMed:
(environment*[Title/Abstract] OR ecolog*[Title/Abstract] OR sustainab*[Title/Abstract]) AND (impact[Title/Abstract] OR effect[Title/Abstract] OR influence[Title/Abstract]) AND (refus*[Title/Abstract] OR rethink*[Title/Abstract] OR reduc*[Title/Abstract] OR reus*[Title/Abstract] OR repair*[Title/Abstract] OR reparation[Title/Abstract] OR refurbish*[Title/Abstract] OR remanufactur*[Title/Abstract] OR repurpos*[Title/Abstract]) AND (surgical[Title/Abstract] OR operative[Title/Abstract]) AND (tool[Title/Abstract] OR instrument[Title/Abstract] OR equipment[Title/Abstract] OR device[Title/Abstract] OR machine*[Title/Abstract] OR apparatus[Title/Abstract] OR appliance[Title/Abstract]) → 240

MEDLINE:
TS=(environment* OR ecolog* OR sustainab*) AND TS=(impact OR effect OR influence) AND TS=(refus* OR rethink* OR reduc* OR reus* OR repair* OR reparation OR refurbish* OR remanufactur* OR repurpos*) AND TS=(surgical OR operative) AND TS=(tool OR instrument OR equipment OR device OR machine* OR apparatus OR appliance) → 684

Final search string

Scopus:
(TITLE-ABS-KEY (environment* OR ecolog* OR sustainab* OR circular* OR footprint) AND TITLE-ABS-KEY (impact OR effect OR influence) AND TITLE-ABS-KEY (reus* OR repair* OR reparation OR refurbish* OR remanufactur* OR repurpos*) AND TITLE-ABS-KEY (surgical OR operative OR medical) AND TITLE-ABS-KEY (tool OR instrument OR equipment OR device OR machine* OR apparatus OR appliance)) → 595

PubMed:
(environment*[Title/Abstract] OR ecolog*[Title/Abstract] OR sustainab*[Title/Abstract] OR circular*[Title/Abstract] OR footprint[Title/Abstract]) AND (impact[Title/Abstract] OR effect[Title/Abstract] OR influence[Title/Abstract]) AND (reus*[Title/Abstract] OR repair*[Title/Abstract] OR reparation[Title/Abstract] OR refurbish*[Title/Abstract] OR remanufactur*[Title/Abstract] OR repurpos*[Title/Abstract]) AND (surgical[Title/Abstract] OR operative[Title/Abstract] OR medical[Title/Abstract]) AND (tool[Title/Abstract] OR instrument[Title/Abstract] OR equipment[Title/Abstract] OR device[Title/Abstract] OR machine*[Title/Abstract] OR apparatus[Title/Abstract] OR appliance[Title/Abstract]) → 105

MEDLINE:
TS=(environment* OR ecolog* OR sustainab* OR circular* OR footprint) AND TS=(impact OR effect OR influence) AND TS=(reus* OR repair* OR reparation OR refurbish* OR remanufactur* OR repurpos*) AND TS=(surgical OR operative OR medical) AND TS=(tool OR instrument OR equipment OR device OR machine* OR apparatus OR appliance) → 335

APPENDIX B

Table B: Additional details of study characteristics and methodological designs (part 1)

reference (year)	sustainability strategy	instrument	primary comparison	life cycle phases* (exclusions)	impact categories	environmental dimensions	impact reporting	contribution reporting	alternate assumptions	uncertainty analysis
Boberg et al. (2022)	refuse	laparoscopic cholecystectomy system	single-use hybrid reusable	✔	global warming, mineral extraction, non-renewable energy, aquatic eutrophication, aquatic acidification, land occupation, terrestrial ecotoxicity, terrestrial acid-/nutrification, aquatic ecotoxicity, respiratory organics, ozone layer depletion, ionizing radiation, respiratory inorganics, non-carcinogens, carcinogens + 4 damage endpoints	climate change resource utilization human health ecosystem quality	A	A[1]	energy source, autoclave loading efficiency, type of transport, number of reuses	✔
Davis et al. (2018)	refuse	flexible ureteroscope	single-use reusable	(transportation)	carbon footprint	climate change	A	A	-	✔
Donaheu et al. (2020)	refuse	vaginal specula	acrylic disposable SS-304 reusable SS-316 reusable	✔	carbon footprint	climate change	A	R	energy source, autoclave loading efficiency, reprocessing method, number of reuses	-
Eckelman et al. (2012)	refuse	laryngeal mask airway	disposable reusable	✔	climate change, carcinogens, non-carcinogens, criteria air pollutants, water use, acidification, smog formation, , ozone depletion, eutrophication, terrestrial ecotoxicity	climate change resource utilization human health ecosystem quality	C	R	autoclave loading efficiency, type of transport, number of reuses	-
Friedericy et al. (2022)	reduce	reusable surgical instrument	disposable blue wrap reusable RSC	✔	carbon footprint + aggregated impact score + eco costs	climate change resource utilization human health ecosystem quality	A	A	energy source	-
Hogan et al. (2022)	refuse	flexible cystoscope	single-use reusable	✔	carbon footprint	climate change	A	A	-	✔
Ibbotson et al. (2013)	refuse	surgical scissors	plastic disposable SS disposable SS reusable	✔	climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionising radiation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, fossil depletion, CED + 3 damage endpoints	climate change resource utilization human health ecosystem quality	C[1]	R[1]	energy source	-
Jabouri and Abbott (2022)	refuse	skin surgery pack	single-use reusable	(transportation)	carbon footprint	climate change	A	A	-	-
Kemble et al. (2023)	refuse	flebixle cystoscope	single-use reusable	✔	carbon footprint	climate change	A	A	-	-
Lalman et al. (2023)	reuse	disposable electrophysiological catheter	single-use reuse	✔	global warming (human health), global warming (terrestrial ecosystems), global warming (freshwater ecosystems), stratospheric ozone depletion, ionizing radiation, ozone formation (human health), fine particulate matter formation, ozone formation (terrestrial ecosystems), terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine eotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, water consumption (human health), water consumption (terrestrial ecosystems), water consumption (aquatic ecosystems), 3 damage endpoints + aggregated impact score	climate change resource utilization human health ecosystem quality	R[1]	-	reprocessing method	-
Leiden et al. (2020)	refuse	spinal fusion surgery instrument set	disposable reusable	✔	global warming potential, cumulative energy demand, abiotic depletion potential, acidification potential, particulate matter + aggregated impact score	climate change resource utilization human health ecosystem quality	R[1]	R[1]	reprocessing method, number of reuses	-
Liang (2019)	refuse	laryngeal mask airway	disposable reusable	✔	climate change (human health), climate change (ecoystem), ozone depletion, eutrophication, acidification, toxicity, land use, fossil resource scarcity, photochemical oxidant formation + 3 damage endpoints	climate change resource utilization human health ecosystem quality	R[1]	R[1]	energy source, ingredients detergent solution, number of reuses	-
McGain et al. (2012)	refuse	central venous catheter insertion kit	single-use reusable	✔	CO2 emissions, water use, mineral use, aquatic ecotoxicity, terrestrial ecotoxicity, solid waste	climate change & resource utilization	A[2]	A	energy source	✔
McGain et al. (2017)	refuse	anesthetic equipment	single-use reusable	✔	climate change, water use, eutrophication, human ecotoxicity, terrestrial ecotoxicity, marine ecotoxicity, ozone depletion, ionizing radiation, urban land transformation, natural land transformation, mineral depletion, fossil fuel depletion, photochemical oxidant formation, air particulate matter	climate change resource utilization human health ecosystem quality	A[2]	C	energy source	✔

*Note: *, complete coverage of all life cycle phases (manufacturing, packaging, transportation, use/reprocessing, disposal); check-mark, reported; -, unspecified/not reported; A, reported as absolute values; R, reported as relative values; C, reported as absolute and relative values; [1], values are presented visually; [2], not all values are reported; CED, Cumulative Energy Demand; CO2, carbon dioxide; RSC, Rigid Sterilization Container; SS, Stainless Steel*

Table B: Additional details of study characteristics and methodological designs (part 2)

reference	sustainability strategy	instrument	primary comparison	life cycle phases* (exclusions)	impact categories	environmental dimensions	impact reporting	contribution reporting	alternate assumptions	uncertainty analysis
Nikkhah et al. (2023)	rethink	disposable cardiopulmonary bypass device	PC PP PE PET	(use/reprocessing)	global warming, eutrophication, acidification, smog, water intake, human health air pollutants, ecotoxicity	climate change resource utilization human health ecosystem quality	C[2]	-	-	✔
Rizan and Bhutta (2022)	refuse	laparoscopic cholecystectomy instruments	single-use hybrid	✔	global warming, stratospheric ozone depletion, ionising radiation, ozone formation (human health), ozone formation (terrestrial ecosystems), fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, water consumption + 3 damage endpoints	climate change resource utilization human health ecosystem quality	A	R	energy source, number of reuses, type of transport	-
Rizan et al. (2022a)	repair	reusable surgical scissor	replace repair off-site repair on-site	✔	global warming, stratospheric ozon depletion, ionising radiation, ozone formation (human health), ozone formation (terrestrial ecosystems), fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, rmineral resource scarcity, fossil resource scarcity, water consumption + 3 damage endpoints	climate change resource utilization human health ecosystem quality	C	R	energy source, number of repairs, distance to repair center, number of reuses	-
Rizan et al. (2022b)	reduce	reusable surgical instruments	individually wrapped as part of a set in RSC as part of a set in tray wrap	(manufacturing, transportation, disposal)	carbon footprint	climate change	A	A	energy source, autoclave/washer loading efficiency	✔
Rodriquez and Hicks (2022)	refuse	vaginal speculum	acrylic disposable SS reusable	(packaging, transportation)	acidification, carcinogenics, ecotoxicity, eutrophication, fossil fuel depletion, global warming, non-carcinogenics, ozone depletion, respiratory effects, smog	climate change resource utilization human health ecosystem quality	A	A	number of reuses	✔
Rouvière et al. (2023)	refuse	laryngoscopic blade	metal single-use metal reusable	✔	global warming, land occupation, human toxicity, environmental toxicity, depletion of mineral resources, depletion of fossil resources, depletion of water resources	climate change resource utilization human health ecosystem quality	R[1]	R	-	-
Samenjo et al. (2023)	rethink	reusable syringe extension device	PP PEEK Al	(packaging, transportation, disposal)	carbon footprint	climate change	A	A	reprocessing method	-
Schulte et al. (2021)	remanufacture	single-use electrophysiology catheter	virgin manufacture remanufacture	(use/reprocessing)	climate change, acidification terrestrial and freshwater, cancer human health effects, ecotoxicity freshwater, eutrophication freshwater, eutrophication marine, eutrophication terrestrial. ionising radiation, land use, non-cancer human health effects, ozone depletion, photochemical ozone formation, resource use energy carriers, resource use mineral and metals, respiratory inorganics, water scarcity	climate change resource utilization human health ecosystem quality	C	C	-	-
Sherman et al. (2018)	refuse	laryngoscopic blade	plastic disposable metal disposable SS reusable	✔	global warming, acidification, carcinogenics, ecotoxicity, eutrophication, fossil fuel depletion, non-carcinogenics, ozone depletion, respiratory effects, smog	climate change resource utilization human health ecosystem quality	C	A[1]	reprocessing method	-
Sorenson et al. (2022)	refuse	single-lung ventilation system	single-use hybrid	✔	climate change, ozone depletion, particulate matter, ionizing radiation human health, ionizing radiation ecosystems, photochemical ozone formation, acidification, land use, mineral, fossil & resource depletion	climate change resource utilization human health ecosystem quality	C	A[1]	-	-
Sorenson and Gruttner (2018)	refuse	bronchoscope	single-use reusable	(manufacturing, packaging, transportation)	GHG emissions, resource scarcity, energy consumption	climate change & resource utilization	A	A[1]	number of reusable scopes per cleaning operation	-
Unger and Landis (2014)	reuse	disposable dental bur	single-use reuse	✔	global warming, ozone depletion, smog, acidification, eutrophication, carcinogenics, non carcinogenics, respiratory effects, ecotoxicity	climate change human health ecosystem quality	C	R[1]	autoclave/ultrasonic loading efficiency	-
Unger and Landis (2016)	reuse	reusable surgical instruments	single-use reuse	✔	global warming, carcinogenic, non-carcinogenic, and respiratory effects	climate change & human health	R[1]	R[1]	reprocessing inputs, number of reuses	-

*Note: *, complete coverage of all life cycle phases (manufacturing, packaging, transportation, use/reprocessing, disposal); check-mark, reported; -, unspecified/not reported; A, reported as absolute values; R, reported as relative values; C, reported as absolute and relative values; [1], values are presented visually; [2], not all values are reported; Al, Aluminium; GHG, Green House Gas; PC, Polycarbonat; PE, Polyethylene; PEEK, Polyetheretherketone; PET, Polyethylene Terephthalate; PP, Polypropylene; RSC, Rigid Sterilization Container; SS, Stainless Steel*

APPENDIX C

Sustainability strategies

Smarter instrument use and manufacture (n = 22)

Refuse R0 (n = 18)
Rethink R1 (n = 2)
Reduce R2 (n = 2)

Extending the lifespan of surgical instruments and/or its parts (n = 5)

Reuse R3 (n = 3)
Repair R4 (n = 1)
Remanufacture R6 (n = 1)

Surgical instruments

Conventional surgical instruments (n = 10)

Vaginal specula (n = 2)
Surgical scissors (n = 2)
Laryngoscopic blade (n = 2)
Dental bur (n = 1)
Syringe extension device (n = 1)
Laryngeal mask airway (n = 2)

Complex surgical instruments (n = 9)
Flexible ureteroscope (n = 1)
Flexible cystoscope (n = 2)
Electrophysiological catheter (n = 2)
Bronchoscope (n = 1)

Laparoscopic cholecystectomy system (n = 1)
Single-lung ventilation system (n = 1)
Cardiopulmonary bypass device (n = 1)

Instrument sets/kits/packs (n = 3)

Spinal fusion surgery instrument set (n = 1)
Central venous catheter insertion kit (n = 1)
Skin surgery pack (n = 1)

Collection of surgical instruments (n = 5)

Anesthetic equipment (n = 1)
Reusable surgical instruments (n = 3)
Laparoscopic cholecystectomy instruments (n = 1)

Disciplines

General surgery (n = 2)
Urology (n = 3)
Anesthesia (n = 6)
Nonspecific (n = 5)
Dermalogy (n = 1)
Cardiology (n = 3)
Neurology (n = 1)
Pulmonology (n = 2)
Dentistry (n = 1)

Obstetrics gynecology (n = 3)

Country's

UK (n = 4)
Australia (n = 3)
USA (n = 8)
Sweden (n = 2)
The Netherlands (n = 1)
Germany (n = 3)
Canada (n = 1)
Denmark (n = 2)
France (n = 1)
Ireland (n = 1)
Kenya (n = 1)

Environmental dimensions

Climate change + resource utilization + human health + ecosystem quality (n = 16)
Climate change (n = 7)
Climate change + resource utilization (n = 2)
Climate change + human health (n = 1)
Climate change + human health + ecosystem quality (n = 1)

Corresponding impact categories

(Note: following the characterization methods of ReCiPe and IMPACT2002+)
Climate change (n = 27)

Climate change
Global warming (potential)
Carbon footprint
GHG emissions

Resource Utilization (n = 18)
Resource depletion/scarcity
Mineral resources
extraction/depletion/scarcity

Metal extraction/depletion/scarcity
Fossil resources/fuel depletion/scarcity
Abiotic depletion potential
Non-renewable energy
Cumulative energy demand
Water consumption/use/depletion/intake

Human Health (n = 18)
Respiratory organics
Respiratory inorganics

Human toxicity (non-carcinogens carcinogens)
Ionizing radiation
Criteria air pollutants
Particulate matter formation
Ozone (layer) depletion
Smog/photochemical oxidant/ozone formation

Ecosystem Quality (n = 17)

(Aquatic/freshwater/marine) eutrophication

(Aquatic/freshwater/marine or terrestrial) acidification (potential)
(Aquatic/freshwater/marine or terrestrial) ecotoxicity
(Agricultural/urban) land occupation/use Natural land transformation

Functional units

One use (n = 9)
Aligned with lifespan of reusable instrument (n = 9)
Per (number of) procedure(s) (n = 3)
Use over a designated period (n = 3)
Provision (n = 2)
Per number of instruments (n = 1)

Assessment methods

Carbon footprint analysis (n = 3)
Life cycle analysis (n = 24, of which n = 18 guided by an ISO LCA standard)

- Attributional LCA (n = 19)
- Carbon footprint (attributional) LCA (n = 3)
- Consequential LCA (n = 2)

Inventory databases

EcoInvent (n=19)
Idemat (n = 2)
GREET (n =1)
WARM (n = 1)

Australian Data 2007 (n = 1)
ELCD (n = 4)
Industry Data (n = 1)
ICE (n = 1)
SWCCFD (n = 1)
CRCR (n = 1)
USLCI (n = 4)
US-EI (n = 1)
ILCD (n = 1)

Characterization methods

Impact 2002+ (n = 1)
IPCC (n = 3)
BEES (n = 2)
ReCiPe (n = 7)
CED (n = 1)
CML (n = 1)
TRACI (n = 4)
USEtox (n = 1)
EF (n = 1)

Software

SimaPro (n = 16)
Umberto NXT (n = 1)
Activity Browser (n = 1)
OpenLCA (n = 1)

Contribution analysis (n = 25)

Scenario analysis (n = 19)

Reduce (n = 18)

- energy source (n = 10)
- autoclave loading efficiency (n = 5)
- reprocessing method (n = 5)
- type of transport (n = 3)
- number of reuses per cleaning operation (n = 1)
- distance to repair center (n = 1)
- number of repairs (n = 1)
- ingredients detergent solution (n = 1)

Reuse (n = 8)

Uncertainty analysis (n = 8)

APPENDIX D

Table D1: Descriptions of Critical Appraisal Criteria

Appraisal criteria	Description
Goal	The goal consists of the intented application, the rationale and the audience. If the goal is fully described (all three parts) give one point, and if at least one part is described give 0.5 points
Surgical Instrument	Assign one point if the specific product is described and 0.5 points if the product category is described. In case of products for which no specific product can be described (such as services or bundles of goods) assign one point if the product category is described.
LCA-based methodology	Assign one point if the use of a LCA-methodology is clearly stated and the LCA standard is specified, assign 0.5 points if the use of a LCA-methodology is clearly stated but LCA standard is not specified
Functional Unit	Assign one point if the functional unit refers to the function of the product system. In case a functional unit is provided but it is not refered to the function of the product systems assign 0.5 points
Scope Life Cycle Phases	Assign one point if the scope of the study is clearly specified and all life cycle stages are included (manufacturing, packaging, transportation, use/reprocessing, disposal), assign 0.5 points if the scope of the study is clearly specified but not all life cycle stages are included
Methodologies	Assign one point if the LCA-methodology is fully described (inventory database, characterization method, software) and assign 0.5 points if at least two parts are described
Impact Categories	Assign one point if both used midpoints and endpoint categories are reported and 0.5 if only one category is reported.
Impact Reporting	Assign one point if all impacs are reported absolutely (numerically) or both absolutely and relatively, assign 0.5 points if not all impacts are reported or if the impacts are reported relatively and/or visually
Contribution Analysis	Assign one point if the results for each included life cycle phase is reported numerically, assign 0.5 point if not all life cycle phase impacts are reported (either numerically or visually) or if impacts are reported visually and assign zero points when no life cycle phases are reported
Scenario/Sensitivity Analysis	Assign one point if the study reports a scenario/sensitivity analysis
Uncertainty Analysis	Assign one point if the study reports an uncertainty analysis

Note: Based on the Transparency Checklist utilized by Keil et al.; This critical appraisal is a simplified version of the one utilized by Keil et al. and focuses primarily on the studies' methodologies

Table D2: Results Critical Appraisal

reference	goal	surgical instrument	LCA-based methodology	functional unit	scope life cycle phases	methodologies	impact categories	impact reporting	contribution analysis	scenario analysis	uncertainty analysis	sum	score
Boberg et al.	0.5	1	1	1	1	1	1	1	0.5	1	1	10	91%
Davis et al.	0.5	1	0.5	1	0.5	0	0.5	1	0.5	0	1	4.5	41%
Donaheu et al.	0.5	1	0.5	1	1	1	0.5	1	0.5	1	0	8	73%
Eckelman et al.	0.5	1	1	1	1	1	1	1	0.5	1	0	9	82%
Friedericy et al.	0.5	1	1	1	1	1	0.5	1	0.5	1	0	8.5	77%
Hogan et al.	0.5	1	0	1	1	0	0.5	1	0.5	0	1	6.5	59%
Ibbotson et al.	0.5	1	1	1	1	1	1	0.5	0.5	1	0	8.5	77%
Jabouri and Abbott	0.5	0.5	0	1	0.5	0	0.5	1	0.5	0	0	4.5	41%
Kemble et al.	0.5	1	0.5	1	1	0	0.5	1	1	0	0	6.5	59%
Lalman et al.	0.5	1	1	1	1	1	1	0.5	0	1	0	8	73%
Leiden et al.	0.5	0.5	1	1	1	1	1	0.5	0.5	1	0	8	73%
Liang	0.5	1	1	1	1	1	1	0.5	0.5	1	0	8.5	77%
McGain et al. (2012)	0.5	0.5	1	1	1	0.5	0.5	0.5	1	1	1	8.5	77%
McGain et al. (2017)	0.5	0.5	1	0.5	1	0.5	0.5	0.5	0.5	1	1	7.5	68%
Nikkhah et al.	0.5	0.5	1	0.5	0.5	1	0.5	0.5	0	0	1	6	55%
Rizan and Bhutta	0.5	0.5	1	1	1	1	1	1	0.5	1	0	8.5	77%
Rizan et al. (2022a)	0.5	1	1	1	1	1	1	1	1	1	0	9.5	86%
Rizan et al. (2022b)	0.5	0.5	0	1	0.5	0.5	0.5	1	1	1	1	7.5	68%
Rodriquez and Hicks	0.5	0.5	1	0.5	0.5	1	0.5	1	1	1	1	8.5	77%
Rouvière et al.	0.5	0.5	0.5	1	1	0	0.5	0.5	0.5	0	0	5	45%
Samenjo et al.	1	1	0.5	0.5	0.5	1	0.5	1	1	1	0	8	73%
Schulte et al.	0.5	1	1	1	0.5	0	0.5	1	1	0	0	6.5	59%
Sherman et al.	0.5	0.5	1	1	1	1	0.5	1	0.5	1	0	8	73%
Sorenson et al.	0.5	0.5	1	1	1	0.5	0.5	1	0.5	0	0	6.5	59%
Sorenson and Gruttner	0.5	1	0.5	1	0.5	0	0.5	1	0.5	1	0	6.5	59%
Unger and Landis (2014)	0.5	1	1	1	1	0.5	0.5	1	0.5	1	0	8	73%
Unger and Landis (2016)	0.5	0.5	1	0.5	1	0.5	0.5	0.5	0.5	1	0	6.5	59%

Note: Critical Appraisal percentage scores are obtained by dividing the sum by the maximum score (11) and multiplying by 100%

APPENDIX E

Table E: Comprehensive set of numerical data on climate change impacts and hotspots per study

(a) Refuse (part 1)

reference (instrument)	primary comparison	absolute value reported (kg CO2/CO2e)	relative value reported	calculated relative value	environmental effect	hotspot reporting	manufacturing	packaging	transportation	use/ reprocessing	maintenance/ repair	disposal	unspecified
Boberg et al. 2022 (laparoscopic cholecystectomy system)	single-use	565	-	1		A[1]	65%	-	4%	0%	x	31%	-
	hybrid	507	-	0.9	-10%	A[1]	70%	-	1%	1%	x	28%	-
	reusable	118	-	0.21	-79%	A[1]	60%	-	0%	10%	x	30%	-
Davis et al. 2018 (flexible ureteroscope)	single-use	4.43	-	1		A	93%	-	x	0%	x	7%	-
	reusable	4.47	-	1.01	+1%	A	1%	0%	x	88%	10%	0%	-
Donaheu et al. 2020 (vaginal specula)	acrylic disposable	17.54	-	1		R	91%	-	7%	0%	x	3%	-
	SS-304 reusable	5.72	-	0.33	-67%	R	25%	-	0%	74%	x	0%	-
	SS-316 reusable	6.51	-	0.37	-63%	R	34%	-	0%	65%	x	0%	-
Eckelman et al. 2012 (laryngeal mask airway)	disposable	11.3	100%[1]	1		R	50%	-	15%	0%	x	11%	24%
	reusable	7.4	65%[1]	0.65	-35%	R	-	-	-	77%	x	-	23%
Hogan et al. 2022 (flexible cystoscope)	single-use	2.41	-	1		A	68%	-	2%	0%	x	30%	-
	reusable	4.23	-	1.75	+75%	A	0%	-	0%	83%	x	17%	-
Ibbotson et al. 2013 (surgical scissors)	plastic disposable	2800[1]	-	1		x	-	-	-	-	x	-	100%
	SS disposable	12000[1]	-	4.35	+335%	x	-	-	-	-	x	-	100%
	SS reusable	300[1]	-	0.11	-89%	x	-	-	-	-	-	-	100%
Jabouri and Abbott 2022 (skin surgery pack)	single-use	1.436	-	1		A	63%	-	x	0%	x	37%	-
	reusable	1.121	-	0.78	-22%	A	37%	-	x	41%	x	22%	-
Kemble et al. 2023 (flebixle cystoscope)	single-use	2.4	-	1		A	70%	9%	8%	0%	x	13%	-
	reusable	0.53	-	0.22	-78%	A	0%	1%	0%	95%	4%	0%	-
Leiden et al. 2020 (spinal fusion surgery instrument set)	disposable	-	15%[1]	1		R[1]	80%	-	2%	0%	x	18%	-
	reusable	-	100%[1]	6.67	+567%	R[1]	4%	-	7%	84%	x	5%	-

(b) Refuse (part 2)

reference (instrument)	primary comparison	absolute value reported (kg CO2/CO2e)	relative value reported	calculated relative value	environmental effect	hotspot reporting	manufacturing	packaging	transportation	use/ reprocessing	maintenance/ repair	disposal	unspecified
Liang 2019 (laryngeal mask airway)	disposable	-	100%[1]	1		x	-	-	-	-	x	-	100%
	reusable	-	15%[1]	0.15	-85%	x	-	-	-	-	x	-	100%
McGain et al. 2012 (central venous catheter insertion kit)	single-use	0.407	-	1		A	56%	41%	2%	0%	x	1%	-
	reusable	1.211	-	2.94	+194%	A	0%	10%	0%	80%	-	0%	-
McGain et al. 2017 (anesthetic equipment)	single-use	5775	-	1		x	-	-	-	0%	x	-	100%
	reusable	5575	-	0.97	-3%	A+R	-	-	-	93%	x	-	7%
Rizan and Bhutta 2022 (laparoscopic cholecystectomy instruments)	single-use	7.194	100%	1		R	57%	-	29%	0%	x	14%	-
	hybrid	1.756	24%	0.24	-76%	R	62%	-	0%	37%	x	0%	-
Rodriquez and Hicks 2022 (vaginal speculum)	acrylic disposable	2215	-	1		A	100%	x	x	0%	x	0%	-
	SS reusable	443.41	-	0.2	-80%	A	33%	x	x	66%	x	0%	-
Rouvière et al. 2023 (laryngoscopic blade)	single-use	-	100%[1]	1		R	89%	-	0%	0%	x	11%	-
	reusable	-	10%[1]	0.1	-90%	R	3%	34%	0%	63%	x	0%	-
Sherman et al. 2018 (laryngoscopic blade)	plastic blade disposable	0.38	-	1		A[1]	97%	-	-	0%	x	3%	-
	metal blade disposable	0.44	-	1.16	+16%	A[1]	93%	-	-	0%	x	7%	-
	SS blade reusable	0.22	-	0.58	-42%	A[1]	0%	-	-	98%	-	2%	-
Sorenson et al. 2022 (single-lung ventilation system)	single-use	1.25	60%[1]	1		A[1]	65%	0%	6%	0%	x	29%	-
	hybrid	2.1	100%[1]	1.67	+67%	A[1]	29%	1%	2%	42%	x	26%	-
Sorenson and Gruttner 2018 (bronchoscope)	single-use	1.6	-	1		A[1]	75%	-	-	0%	x	25%	-
	reusable	2.9	-	1.82	+82%	A[1]	x	x	x	76%	x	24%	-

(c) Rethink

reference (instrument)	primary comparison	absolute value reported (kg CO2/CO2e)	relative value reported	calculated relative value	environmental effect	hotspot reporting	manufacturing	packaging	transportation	use/ reprocessing	maintenance/ repair	disposal	unspecified
Nikkhah et al. 2023 (disposable cardiopulmonary bypass device)	PC	18.65	-	1		A/R	60%	-	-	x	x	34%	6%
	PP	-	0.77[1]	0.77	-23%	x	-	-	-	x	x	-	100%
	PE	-	0.76[1]	0.76	-24%	x	-	-	-	x	x	-	100%
	PET	-	0.83[1]	0.83	-17%	x	-	-	-	x	x	-	100%
Samenjo et al. 2023 (reusable syringe extension device)	PP	48.24	-	0.56	-44%	A	87%	x	x	13%	x	x	-
	PEEK	86.2	-	1		A	91%	x	x	9%	x	x	-
	Al	15.5	-	0.18	-82%	A	21%	x	x	79%	x	x	-

(d) Reduce

reference (instrument)	primary comparison	absolute value reported (kg CO2/CO2e)	relative value reported	calculated relative value	environmental effect	hotspot reporting	manufacturing	packaging	transportation	use/ eprocessing	maintenance/ repair	disposal	unspecified
Friedericy et al. 2022 (reusable surgical instrument)	disposable blue wrap	1869	-	1		A	64%	-	5%	0%	x	31%	-
	reusable RSC	285	-	0.15	-85%	A	8%	-	0%	92%	x	0%	-
Rizan et al. (2022b) (reusable surgical instruments)	individually wrapped	0.189	-	1		A	x	23%	x	77%	x	x	-
	as part of a set in RSC	0.077	-	0.41	-39%	A	x	32%	x	69%	x	x	-
	as part of a set in tray wrap	0.066	-	0.35	-65%	A	x	20%	x	80%	x	x	-

(e) Reuse

reference (instrument)	primary comparison	absolute value reported (kg CO2/CO2e)	relative value reported	calculated relative value	environmental effect	hotspot reporting	manufacturing	packaging	transportation	use/ reprocessing	maintenance/ repair	disposal	unspecified
Lalman et al. 2023 (disposable electrophysiological catheter)	single-use	-	5%[1]	1		x	-	-	-	-	x	-	100%
	reuse	-	100%[1]	20	+1900%	x	-	-	-	-	x	-	100%
Unger and Landis 2016 (reusable surgical instruments)	single-use	-	100%[1]	1		R[1]	81%	-	-	0%	x	19%	-
	reuse	-	96-99%[1]	0.96-0.99	-1-4%	R[1]	14-40%	-	-	47-77%	x	5-11%	-
Unger and Landis 2014 (disposable dental bur)	single-use	1.19	100%[1]	1		R[1]	0%	50%	18%	0%	x	32%	-
	reuse	0.42	35%[1]	0.35	-65%	R[1]	0%	39%	17%	19%	x	25%	-

(f) Repair

reference (instrument)	primary comparison	absolute value reported (kg CO2/CO2e)	relative value reported	calculated relative value	environmental effect	hotspot reporting	manufacturing	packaging	transportation	use/ reprocessing	maintenance/ repair	disposal	unspecified
Rizan et al. 2022 (reusable surgical scissor)	replace	0.0703	100%	1		R	18%	0%	0%	76%	x	6%	-
	off-site repair	0.057	81%	0.81	-19%	R	3%	0%	0%	95%	2%	0%	-
	on-site repair	0.0563	80%	0.8	-20%	R	3%	0%	0%	97%	0%	0%	-

(g) Remanufacture

reference (instrument)	primary comparison	absolute value reported (kg CO2/CO2e)	relative value reported	calculated relative value	environmental effect	hotspot reporting	manufacturing	packaging	transportation	use/ reprocessing	maintenance/ repair	disposal	unspecified
Schulte et al. 2021 (single-use electrophysiology catheter)	virgin manufactured	1.75	-	1		A	71%	10%	2%	x	x	17%	-
	remanufactured	1.14	-	0.65	-35%	A	75%	11%	2%	x	x	12%	-

Note: Data on the sustainability strategies of refuse, rethink, reduce, reuse, repair and remanufacture is given in (a)+(b), (c), (d), (e), (f) and (g), respectively. A, value is reported absolutely;, R, value is reported relatively; ¹, value is presented visually; -, unspecified. Negative environmental effects indicate an impact reduction and positive environmental effects indicate an impact increase. When hotspots are reported absolutely, relative values are calculated. If the impact of a phase is reported to be added to another phase (such as transport or packaging being added to manufacturing), this is also indicated for that phase with a dash (-). If a phase is entirely excluded from the LCA, it is marked with a cross (x). The maintenance/repair phase is considered as an additional phase for reusables, only included in five studies. As disposables/single-use are disposed of after one use, the maintenance/repair phase of these instruments always receive a cross. The manufacturing phase encompasses raw material acquisition due to the challengeof disaggregating these stages in the included studies. When the sterilization of disposables is mentioned as a separate impact phase, it is also incorporated into the manufacturing phase

Appendix B

Survey Opening Statement

You are being invited to participate in a research study titled ‘Evaluating the Environmental Impact of Reusable versus Reposable Laparoscopic Instruments for the da Vinci Robot: A Comprehensive Life Cycle Assessment,' led by Anna Gerbens, a Biomedical Engineering Master’s student, under the supervision of Professors Nader Francis, Tim Horeman and Stefania Marconi, and in collaboration with the European Association for Endoscopic Surgery (EAES) Research Committee.

This study sets out to conduct an in-depth Life Cycle Assessment (LCA) to compare the environmental impact of a novel reusable laparoscopic instrument for the da Vinci robot with that of the conventional option which is reusable for only a limited number of times. LCAs are comprehensive tools used to evaluate the environmental consequences throughout a product's lifecycle—from raw material extraction to disposal. A recent systematic review has identified challenges in the application of LCAs to surgical instruments, leading to methodological inconsistencies and the emergence of contradictory outcomes. The objective of this research is to overcome these challenges, providing a trustworthy environmental impact comparison between these two instrument types through a high-quality LCA.

We kindly ask you to share the linked survey, a vital component of our research study, with your OR team. This survey seeks to understand your sustainability perspectives and experiences with LCA practices within the surgical instrumentation sector. Depending on your familiarity with LCAs, completing the survey takes between 1 to 10 minutes.

Your participation is completely voluntary. You can withdraw at any time without having to provide a reason, and you can skip any questions you prefer not to answer. Our goal is to collect broad perspectives on sustainability and LCA practices related to surgical instrumentation—there are no incorrect responses. Please rest assured that the survey is designed to protect your anonymity, and only those who opt to provide further insights by leaving their email at the end of the survey will be contacted for future feedback. This information will remain confidential and solely for research purposes, handled with utmost care and integrity. Any published data will be anonymized.

By submitting this survey, you consent to the conditions outlined above. For any questions or concerns, please reach out to the lead researcher, Anna Gerbens.

Thank you for your attention,

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Appendix C

Table C: Overview of Excluded Life Cycle Processes and Their Expected Impacts

Excluded life cycle process / aspect	Relevance	Expected effect on device impact
Finishing processes (e.g. anodizing, surface polishing)	Finishing processes like anodizing and surface polishing are resource-intensive, requiring energy, chemicals, and water consumption, and produce chemical waste and metal particles.	**Underestimation both devices** - Including the impacts of finishing processes would increase manufacturing impacts for both devices. However, given that these processes are expected to be relatively similar for both devices, the comparative outcome would likely remain unchanged.
Final assembly of devices	Final assembly, where components are put together into a complete device, requires electrical energy for operating tools and machinery.	**Underestimation both devices** - Including the impacts of final assembly would slightly increase manufacturing impacts for both devices. Due to its modular design, which simplifies assembly, these impacts would likely be minimal for the reusable device.
Transport packaging	Packaging materials used immediately after final assembly, such as protective foam or plastic wraps, which are especially relevant if parts are sensitive and require substantial protection, as well as bulk packaging associated with transport, add waste and resource usage.	**Underestimation both devices** - Including the impacts of this packaging would increase transport impacts for both devices. However, given that packaging is expected to be relatively similar for both devices, the comparative outcome would likely remain unchanged.
Hospital storage & infrastructure	Hospital storage and infrastructure requirements, including specific storage conditions, may contribute to indirect emissions due to additional energy use and space requirements.	**Underestimation both devices** - Including the impacts of hospital storage & infrastructure attributable to each individual device would slightly increase use impacts for both devices. However, given that these processes are expected to be relatively similar for both devices, the comparative outcome would likely remain unchanged.
Capital goods (e.g. robotic surgery systems, autoclaves, disinfector, baskets, trays)	Capital goods, such as robotic systems, are utilized across a wide variety of procedures and support multiple instruments. While some of these systems carry high embedded environmental costs, primarily due to their significant energy consumption and the substantial environmental impact from their manufacturing, the environmental burden attributable to each individual device is generally small in comparison.	**Underestimation both devices** - Including the impacts of capital goods attributable to each individual device would slightly increase use impacts for both devices. However, given that these processes are expected to be relatively similar for each device, the comparative outcome would likely remain unchanged.
Manual cleaning	Manual cleaning involves water and energy use, detergent consumption, and generates wastewater. It also requires personal protective equipment (PPE) like gloves and masks, as well as disposable wipes, which contribute to waste and resource use.	**Underestimation both devices** - Including the impacts of manual cleaning would increase reprocessing impacts for both devices. However, given that these processes are expected to be relatively similar for each device, the comparative outcome would likely remain unchanged.
Flushing system	A specialized flushing system, involving additional equipment and targeted routing of disinfectants and steam to channel disinfectant and steam through its shaft, effectively clearing biological debris and contaminants. This system is designed to ensure that hard-to-reach internal areas are adequately cleaned, adding to resource demand and emissions.	**Underestimation reposable device** - Including the flushing system's impact would increase the reposable device's reprocessing impact. In contrast, the reusable device likely avoids the need for a complex setup due to its modular design that features an open, accessible shaft.
Metal incineration	In practice, metals undergo incineration before being landfilled, which requires additional energy and reduces any energy recovery benefits	**Underestimation reposable device** – Including the impact from metal incineration would slightly increase the reposable device's waste treatment impact
Circularity over multiple lifecycles	Recycling metals and plastics creates the potential for a closed-loop system where end-of-life materials are recovered and reused in new production of similar devices. The reuse of intact parts creates a potential for remanufacturing.	**Overestimation reusable device** – Including circularity and part reuse would significantly reduce the reusable device's overall impact over multiple cycles, as its manufacturer prioritizes recycling metals and plastics into new devices and the modular design facilitates part reuse.

Appendix D

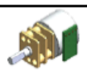
Table D: Overview of Inventory Data Quality

Product	Life cycle apect	Primary data	Secondary data (specific)	Secondary data (average)	Expert judgment
Reposable device	Composition: materials				x
	Composition: weights	x			
	Material production			x	
	Device manufacturing			x	x
	Transport			x	x
	Reprocessing practices			x	x
	Disposal			x	
	Waste treatment			x	x
Reusable device	Composition: materials	x		x	
	Composition: weights	x			
	Material production			x	
	Device manufacturing	x		x	
	Transport			x	x
	Reprocessing practices			x	x
	Tip beak replacements	x		x	
	Disposal			x	
	Waste treatment			x	x
Disinfecting washer	Operational use			x	
Sterilising autoclave	Operational use			x	
Sterilisation packaging	Full lifecycle		x		

Note: Primary data refers to device-specific information obtained directly from the manufacturer/distributor or through direct measurements of the physical device. Secondary data (specific) consists of device-specific information gathered indirectly from databases or literature. Secondary data (average) consists of estimates based on typical practices for similar applications found in databases or literature. Expert judgement refers to estimates derived from the insights and experience of industry experts.

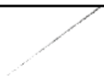
Appendix E

Table E1: Breakdown of Materials, Manufacturing & Waste Treatment Inventory Results and Input Data for Reusable Device Components

Preview	Description	Assembly	Quantity	Material	Weight (g)	Manufacturing	Input EcoAudit
	DIN EN ISO 7045 - M1.6 X 6 - Z - 6N	MU	8	-	-	Off-the-shelf	***Excluded from the comparison****
	Collect tunnel block	GB	1	SS 316	0,22	CNC lathe machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Lock washer DIN 6799 - 3.2	GB	11	SS 316 **	0,096	CNC machining **	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Washer DIN 433 - 2.2	GB	8	SS 316 **	0,029	CNC machining **	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Circlip DIN 471 - 12 X 1	GB	4	SS 316 **	0,606	CNC machining **	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Circlip DIN 471 - 13 X 1	GB	1	SS 316 **	0,657	CNC machining **	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	DIN 913 - M1.6 X 4-N	SB, MU	8, 4 ***	SS 316 **	0,068	CNC machining **	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	DIN 913 - M2 X 4-N	GB	4	SS 316 **	0,085	CNC machining **	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Circlip DIN 471 - 17 X 1	GB	3	SS 316 **	0,859	CNC machining **	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	DIN EN ISO 7046-1 - M2 X 5 - Z - 5N	GB, MU	8, 9 ***	SS 316 **	0,151	CNC machining **	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	DIN EN ISO 7046-1 - M3 X 8 - Z - 8N	GB, MU	10, 3 ***	SS 316 **	0,542	CNC machining **	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	DIN EN ISO 4762 M1.6 X 4 - 4N	GB, MU	4, 4 ***	SS 316 **	0,262	CNC machining **	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Stepper motor	MU	4	-	-	Off-the-shelf	***Excluded from the comparison****
	MU base frame	MU	1	Alu 7075	-	CNC machining	***Excluded from the comparison****
	MU cover main	MU	1	ABS	-	Injection molding	***Excluded from the comparison****
	Magnet mount	MU	2	ABS	-	Injection molding	***Excluded from the comparison****
	Mount for coupling disk MU	MU	4	Alu 7075	-	CNC machining	***Excluded from the comparison****
	MU frame plate	MU	1	Alu 7075	-	CNC machining	***Excluded from the comparison****
	Hall sensor mount	MU	2	ABS	-	Injection molding	***Excluded from the comparison****

	Bushing 3-5mm (3mm)	MU	4	PEEK	-	CNC machining	***Excluded from the comparison ****
	Robot assembly support	MU	1	ABS	-	Injection molding	***Excluded from the comparison ****
	SB frame	SB	1	ABS	24,29	Injection molding	ABS (high-impact, injection molding)- virgin - polymer molding - fine machining - 2% removed - downcycle - 75% recovered
	Drape clip on	SB	1	ABS	-	Injection molding	***Excluded from the comparison ****
	SB shaft	SB	4	Alu 7075	0,1	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Coupling complement disk	SB	8	Alu 7075	0,85	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Bushing 3-5mm (2mm)	SB	4	PEEK	0,03	CNC machining	PEEK (30% carbon fiber) - virgin - polymer extrusion - fine machining - 50% removed - landfill - 0% recovered
	Middle shaft key case	GB	1	Alu 7075	8,73	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Spur gear 12mm 20 teeth	GB	2	PEEK	0,75	CNC, lasrer / water cutting	PEEK (30% carbon fiber) - virgin - polymer extrusion - fine machining - 50% removed - landfill - 0% recovered
	Spring base	GB	2	ABS	0,05	Injection molding	ABS (high-impact, injection molding)- virgin - polymer molding - fine machining - 2% removed - downcycle - 75% recovered
	Spur gear 17 mm 25 teeth	GB	1	PEEK	0,99	CNC machining	PEEK (30% carbon fiber) - virgin - polymer extrusion - fine machining - 50% removed - landfill - 0% recovered
	Bushing 12-19mm	GB	2	PEEK	0,89	CNC machining	PEEK (30% carbon fiber) - virgin - polymer extrusion - fine machining - 50% removed - landfill - 0% recovered
	Actuation shaft for inner rod	GB	1	Alu 7075	2,28	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Shafts dissembly button	GB	1	ABS	1,73	Injection molding	ABS (high-impact, injection molding)- virgin - polymer molding - fine machining - 2% removed - downcycle - 75% recovered
	Collet fastener	GB	1	SS 316	7,6	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Spur gear 13mm 25 teeth	GB	1	PEEK	1,36	CNC machining	PEEK (30% carbon fiber) - polymer extrusion - fine machining - 50% removed - landfill - 0% recovered
	Bushing 4-5mm	GB	8	PEEK	0,06	CNC machining	PEEK (30% carbon fiber) - virgin - polymer extrusion - fine machining - 50% removed - landfill - 0% recovered
	GB base frame	GB	1	Alu 7075	24,93	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Spur gear 4mm 20 teeth	GB	2	PEEK	1,12	CNC machining	PEEK (30% carbon fiber) - virgin - polymer extrusion - fine machining - 50% removed - landfill - 0% recovered
	Spur gear 4mm 15 teeth	GB	1	PEEK	0,59	CNC machining	PEEK (30% carbon fiber) - virgin - polymer extrusion - fine machining - 50% removed - landfill - 0% recovered

	Spur gear collect tunnel	GB	1	PEEK	1,47	CNC machining	PEEK (30% carbon fiber) - virgin - polymer extrusion - fine machining - 50% removed - landfill - 0% recovered
	Collet transporter	GB	1	SS 316	16	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Actuation shaft for outer shaft	GB	1	Alu 7075	2,28	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Actuation shaft for transporter	GB	1	Alu 7075	2,29	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	GB frame plate	GB	2	Alu 7075	14,82	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	GB cover	GB	1	ABS	22,11	Injection molding	ABS (high-impact, injection molding)- virgin - polymer molding - fine machining - 2% removed - downcycle - 75% recovered
	Outer shaft key case	GB	1	Alu 7075	7,84	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Button shaft	GB	2	ABS	0,07	Injection molding	ABS (high-impact, injection molding)- virgin - polymer molding - fine machining - 2% removed - downcycle - 75% recovered
	Collect tunnel	GB	1	SS 316	14,38	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Collet pin	GB	1	Alu 7075	0,12	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Actuation shaft for middle shaft	GB	1	Alu 7075	2,28	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Collect gripper	GB	1	SS 316	0,65	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Shaft assembly pin	GB	4	Alu 7075	0,03	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Coupling disk	GB	8	SS 316	0,23	Laser cutting	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Coupling disk washer	GB, MU	4, 4 ***	SS 316	0,03	Laser cutting	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Shaft snap key	GB	2	Alu 7075	1,05	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Support frame	GB	1	Alu 7075	4,11	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Bushing 17-19mm	GB	1	PEEK	0,3	CNC machining	PEEK (30% carbon fiber) - virgin - polymer extrusion - fine machining - 50% removed - landfill - 0% recovered
	Spring	GB	4	SS 316 **	0,09	CNC machining **	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Hall sensor	MU	2	-	-	Off-the-shelf	***Excluded from the comparison****

	Magnet	MU	2	-	-	Off-the-shelf	***Excluded from the comparison ****
	Rivet coupling pin	GB, MU	4, 4 ***	Alu 7075	0,04	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Outer shaft	OA	1	SS 316	17,982	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Bushing	OA	1	SS 316	3,204	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	H-hinge axis	OA	3	SS 316	0,015	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	H-hinge	OA	1	SS 316	0,225	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Slider high	OA	1	SS 316	0,709	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Slider low	OA	1	SS 316	0,6	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Slider pin	OA	2	SS 316	0,02	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Tip base	OA	1	SS 316	0,598	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Mid shaft	MA	1	SS 316	23,865	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Bushing	MA	1	SS 316	1,899	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Inner shaft	TB	1	SS 316	6,923	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	SS thread	TB	1	SS 316	0,389	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Threaded bushing	TB	1	SS 316	0,27	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Housing thread	TB	1	SS 316	0,144	Injection molding	Stainless steel, austenitic, AISI 316, annealed - virgin - metal powder forming - fine machining - 2% removed - recylce - 75% recovered
	Housing jaws	TB	1	SS 316	0,083	Injection molding	Stainless steel, austenitic, AISI 316, annealed - virgin - metal powder forming - fine machining - 2% removed - recylce - 75% recovered
	Open-close pin	TB	1	SS 316	0,02	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Housing pin	TB	1	SS 316	0,048	CNC machining	Stainless steel, austenitic, AISI 316, annealed - virgin - forging - fine machining - 50% removed - recylce - 75% recovered
	Left jaw	TB	1	SS 316	0,474	Injection molding	Stainless steel, austenitic, AISI 316, annealed - virgin - metal powder forming - fine machining - 2% removed - recylce - 75% recovered

	Right jaw	TB	1	SS 316	0,404	Injection molding	Stainless steel, austenitic, AISI 316, annealed - virgin - metal powder forming - fine machining - 2% removed - recylce - 75% recovered
Total			167		270		

*Note: -, unspecified; ABS, Acrylonitrile Butadiene Styrene; Alu, Aluminium; CNC, Computer Numerical Control; GB, Gearbox; MA, Mid Axis; MU, Motor Unit; OA, Outer Axis; PEEK, Polyetheretherketone; SB; Sterile Barrier; SmCo, samarium–cobalt; SS, Stainless Steel; TB, Tip Beak; *, component lies outside the product system; **, this concerns an off-the-shelf component, so the information provided is based on secondary data; ***, as some of these parts are used specifically within the motor unit assembly, that quantity is excluded, and only the number of parts used for the remainder of the driver is included.*

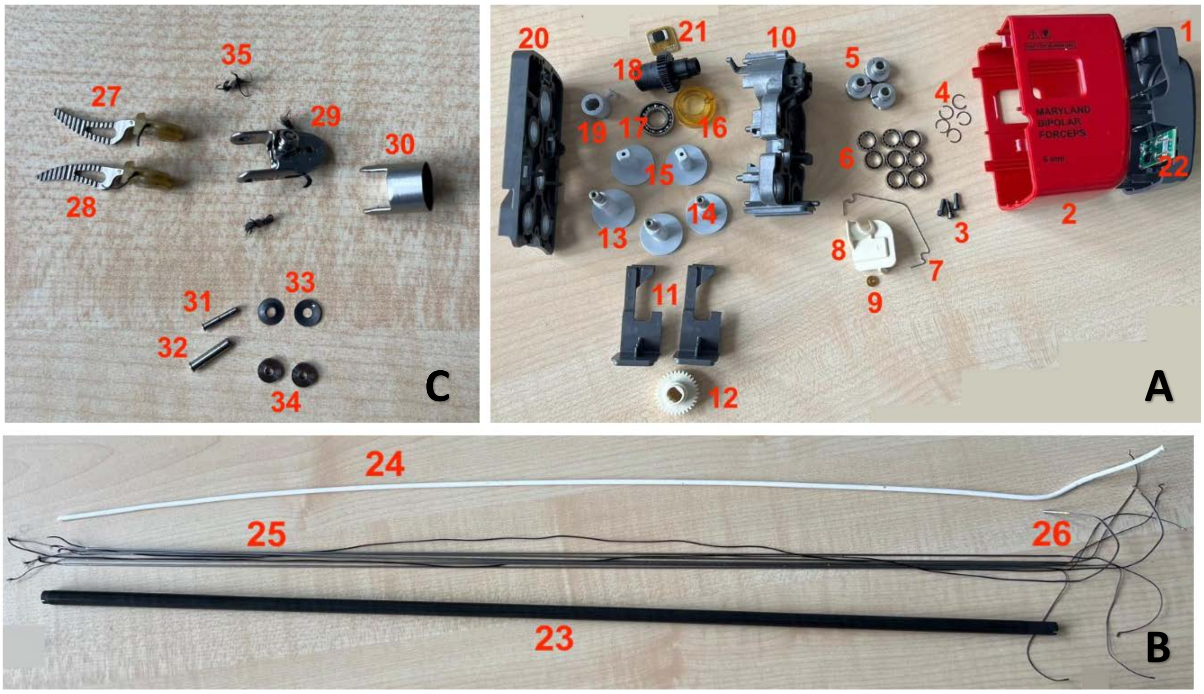


Figure E: Disassembled Sample Reposable Device. *Note: **A,** driver assembly; **B**, shaft assembly; **C,** tip grasper assembly. Components 21, 22, and 26 relate solely to the device's bipolar function and are therefore excluded from the comparison. There were initially four units of component 34, but two were lost during the disassembly process.*

Table E2: Breakdown of Materials, Manufacturing & Waste Treatment Inventory Results and Input Data for Reposable Device Components

Preview	Quantity	Material	Weight (g)	Manufacturing	Input EcoAudit
Driver					
1	1	ABS	18,010	Injection molding	ABS (high-impact, injection molding) - virgin - polymer molding - fine machining - 2% removed - combust - 95% recovered
2	1	ABS	26,948	Injection molding	ABS (high-impact, injection molding) - virgin - polymer molding - fine machining - 2% removed - combust - 95% recovered
3	3	Ti	0,249	CNC machining	Titanium, alpha-beta alloy, Ti6Al-4V, annealed - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
4	5	SS	0,021	CNC machining	Stainless steel, austentic, AISI 304, annealed - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
5	3	Alu	1,298	CNC machining	Aluminium, 7075, T73 - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
6	8	SS	0,507	CNC machining	Stainless steel, austentic, AISI 304, annealed - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
7	1	SS	0,167	CNC machining	Stainless steel, austentic, AISI 304, annealed - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
8	1	ABS	1,444	Injection molding	ABS (high-impact, injection molding) - virgin - polymer molding - fine machining - 2% removed - combust - 95% recovered
9	1	Brass	0,092	CNC machining	Brass, CuZn36Pb3, C36000, soft (free-cutting brass) - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
10	1	ABS	18,274	Injection molding	ABS (high-impact, injection molding) - virgin - polymer molding - fine machining - 2% removed - combust - 95% recovered
11	2	ABS	2,531	Injection molding	ABS (high-impact, injection molding) - virgin - polymer molding - fine machining - 2% removed - combust - 95% recovered
12	1	ABS	1,763	Injection molding	ABS (high-impact, injection molding) - virgin - polymer molding - fine machining - 2% removed - combust - 95% recovered
13	3	ABS	1,407	Injection molding	ABS (high-impact, injection molding) - virgin - polymer molding - fine machining - 2% removed - combust - 95% recovered
14	3	SS	3,070	CNC machining	Stainless steel, austentic, AISI 304, annealed - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
15	2	ABS	1,407	Injection molding	ABS (high-impact, injection molding) - virgin - polymer molding - fine machining - 2% removed - combust - 95% recovered
16	1	PMMA	1,199	Injection molding	PMMA (molding and extrusion) - virgin - polymer molding - fine machining - 2% removed - combust - 95% recovered
17	1	SS	2,929	CNC machining	Stainless steel, austentic, AISI 304, annealed - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
18	1	ABS	2,956	Injection molding	ABS (high-impact, injection molding) - virgin - polymer molding - fine machining - 2% removed - combust - 95% recovered
19	1	ABS	0,595	Injection molding	ABS (high-impact, injection molding) - virgin - polymer molding - fine machining - 2% removed - combust - 95% recovered
20	1	ABS	18,066	Injection molding	ABS (high-impact, injection molding) - virgin - polymer molding - fine machining - 2% removed - combust - 95% recovered
21	1	-	-	-	***Excluded from the comparison****
22	1	-	-	-	***Excluded from the comparison****
Shaft					
23	1	CFRP	31,078	Injection molding	Epoxy/HS carbon fiber, UD prepreg, QI lay-up - virgin - compression modling - cutting and trimming - 2% removed - combust - 70% recovered
24	1	PTFE	3,243	CNC machining	PTFE (15% glass fiber) - virgin - polymer extrusion - fine machining - 50% removed - landfill - 0% recovered

25	6	SS	3.307 **	CNC machining	Stainless steel, austentic, AISI 304, annealed - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
26	2	-	-	-	***Excluded from the comparison ****
Tip Beak					
27	1	SS	0.477 ***	Injection molding	Stainless steel, austentic, AISI 304, annealed - virgin - metal powder forming - fine machining - 2% removed - landfill - 0% recovered
28	1	SS	0.475 ***	Injection molding	Stainless steel, austentic, AISI 304, annealed - virgin - metal powder forming - fine machining - 2% removed - landfill - 0% recovered
29	1	SS	1,546	Injection molding	Stainless steel, austentic, AISI 304, annealed - virgin - metal powder forming - fine machining - 2% removed - landfill - 0% recovered
30	1	SS	1,245	Injection molding	Stainless steel, austentic, AISI 304, annealed - virgin - metal powder forming - fine machining - 2% removed - landfill - 0% recovered
31	1	SS	0,050	CNC machining	Stainless steel, austentic, AISI 304, annealed - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
32	1	SS	0,078	CNC machining	Stainless steel, austentic, AISI 304, annealed - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
33	2	SS	0,008	CNC machining	Stainless steel, austentic, AISI 304, annealed - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
34	4	SS	0,053	CNC machining	Stainless steel, austentic, AISI 304, annealed - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
35	2	SS	0,022	CNC machining	Stainless steel, austentic, AISI 304, annealed - virgin - forging - fine machining - 50% removed - landfill - 0% recovered
Total	63		180		

*Note: -, unspecified; ABS, Acrylonitrile Butadiene Styrene; Alu, Aluminium; CAP, Cellulose Acetate Propionate; CFRP, Carbon Filled Reinforced Polymer; CNC, Computer Numerical Control; PMMA, Polymethyl Methacrylate; PTFE, Polytetrafluoroethylene; SmCo, Samarium–Cobalt magnet; SS, Stainless Steel; Ti, Titanium; *, This component is essential only for the bipolarity function of the reposable device and is therefore excluded from the comparison; **, Although the cables are excluded from the comparison due to the lack of suitable predefined processes, their weight is still included in the component's total weight, as they could not be separated from the rest; ***, Although the yellow insulating part is excluded from the comparison because it is only relevant to the device's bipolarity function, its weight is still included in the component's total weight, as it could not be separated from the rest. Combust was selected to represent the end-of-life scenario of incineration.*

Appendix F

To calculate the devices' allocated impacts per cycle for the disinfecting washer, sterilising autoclave, and per unit of sterilisation packaging, the following formula is applied for both baseline and alternative scenarios:

$$\text{Allocated Impact} = \frac{\text{Estimated Impact}}{\text{Machine Loading Efficiency} \times \text{Tray Loading Capacity}}$$

Machine loading efficiency is defined as the number of instrument trays accommodated in a single machine cycle, while tray loading capacity refers to the number of devices per tray. For sterilisation packaging, the machine loading efficiency is set to 1, assuming one unit covers one instrument tray. Estimated impacts per machine cycle and per unit of sterilisation packaging are detailed in Table 5. Values for machine loading efficiencies of the disinfecting washer and sterilising autoclave, along with tray loading capacities for both reusable and reposable devices across baseline and alternative scenarios, are available in Tables F1 and F2. The allocated impacts per cycle and per unit are then scaled by the total cycles/units each device undergoes over its lifecycle, as provided in Table F3. To match the functional unit that accounts for one reusable and seven reposable devices, the calculated impact for the reposable device is further multiplied by seven. For final allocated use-phase impacts per device aligned with the functional unit, please refer to Table F3.

Table F1: Machine-loading Efficiencies

Product	Baseline scenario (mean machine load)	Halving mean machine load	Maximal machine load
disinfecting washer	8.1 (67.5%)	4.05 (33.75%)	12 (100%)
sterilising autoclave	11.33 (62.94%)	5.67 (31.47%)	18 (100%)

Note: Machine loading efficiencies are measured in terms of occupied slots, with the assumption that each occupied slot holds one instrument tray.

Table F2: Tray Loading Capacities

Device	Baseline scenario (ratio of 1 : 2)	Ratio of 1 : 1	Ratio of 1 : 3
reposable	6	6	6
reusable	12	6	18

Note: Tray loading capacities are expressed as the number of devices per instrument tray.

Table F3: Use Phase LCIA Results

			Baseline scenario (mean machine load & tray load capacity of 1 : 2)		Halving mean machine load		Maximal machine load		Similar tray load capacity		Tray load capacity of 1 : 3	
Device	Process/material	Nr of cycles/units	Climate change (kg CO2e)	Energy demand (MJ)	Climate change (kg CO2e)	Energy demand (MJ)	Climate change (kg CO2e)	Energy demand (MJ)	Climate change (kg CO2e)	Energy demand (MJ)	Climate change (kg CO2e)	Energy demand (MJ)
Reposable	Operatinal use desinfecting washer	13	1.14	11.58	2.28	23.17	0.77	7.82	1.14	11.58	1.14	11.58
	Operational use sterilising autoclave	14	3.56	37.48	7.18	74.95	2.25	23.59	3.56	37.48	3.56	37.48
	Sterilisation packaging	14	0.87	11.22	0.87	11.22	0.87	11.22	0.87	11.22	0.87	11.22
	Total		5.57	60.28	10.33	109.34	3.89	42.63	5.57	60.28	5.57	60.28
	Total per FU		38.99	421.96	72.31	765.38	27.23	298.71	38.99	421.96	38.99	421.96
Reusable	Operatinal use desinfecting washer	100	4.39	44.56	8.78	89.12	2.97	30.08	8.78	89.12	2.93	29.71
	Operational use sterilising autoclave	100	12.78	133.85	25.56	267.70	8.05	84.25	25.56	267.70	8.52	89.23
	Sterilisation packaging	100	3.12	40.08	3.12	40.08	3.12	40.08	6.24	80.16	2.08	26.72
	Total per FU		20.29	218.49	37.46	396.90	14.14	154.41	40.58	436.98	13.53	145.66
Difference			18.7	203.47	34.85	368.48	13.09	144.3	-1.59	-15.02	25.46	276.3

Note: To match the functional unit (FU) that accounts for one reusable and seven reposable devices, the calculated impact for the reposable device is further multiplied by seven.

Appendix G

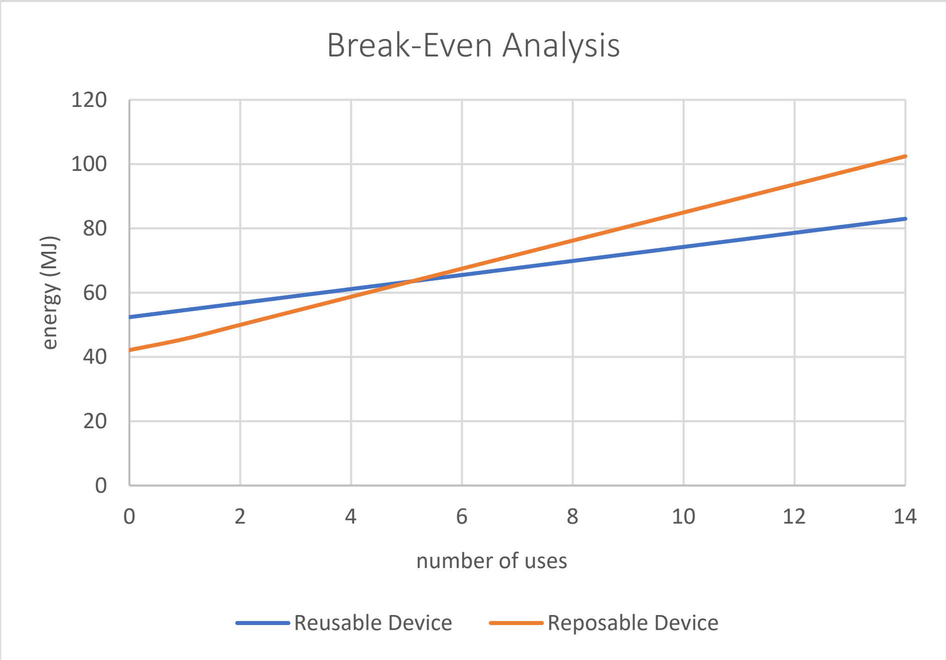


Figure G1: Break-Even Analysis. *Note: This figure illustrates the break-even point, defined as the number of device uses at which energy demand impacts are equal for both devices.*

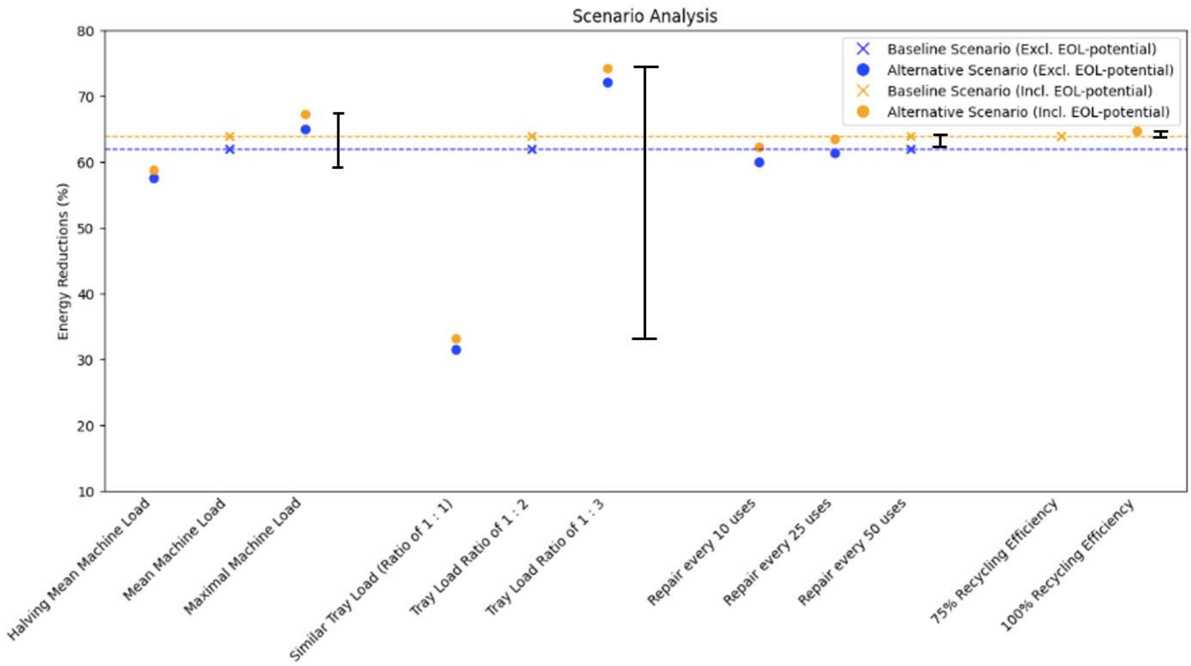


Figure G2: Scenario Analysis. *Note: This figure presents the comparative impact results for the energy demand category between the two devices across baseline and alternative scenarios, with crosses representing baseline scenarios and dots representing alternative scenarios for both excluding and including end-of-life (EOL) potential. The scenario analysis assesses life cycle aspects including machine load efficiency, tray load capacity, repair frequency, and recycling efficiency. Results are shown as energy demand impact reduction percentages for the reusable device relative to the disposable device, with variations across scenarios, including EOL potential, for each life cycle aspect marked by a distance indicator. Dashed lines highlight the baseline scenarios, clearly differentiating the one that excludes EOL potential from the one that includes it.*

Appendix H

Table H1: Comparative Results Across Baseline and Alternative Scenarios Excluding End-Of-Life Potential

A	Baseline scenario (mean machine load)		Halving mean machine load		Maximal machine load	
Device	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)
Reposable	58.01	716.93	91.33	1060.35	46.25	593.68
Reusable	24.13	272.74	41.31	451.15	17.99	208.66
Savings	33.88	444.19	50.02	609.2	28.26	385.02
Savings (%)	58.4	62.0	54.8	57.5	61.1	64.9
B	Baseline scenario (Ratio of 1 : 2)		Similar tray load (ratio of 1 : 1)		Ratio of 1 : 3	
Device	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)
Reposable	58.01	716.93	58.01	716.93	58.01	716.93
Reusable	24.13	272.74	44.43	491.23	17.38	199.91
Savings	33.88	444.19	13.58	225.7	40.63	517.02
Savings (%)	58.4	62.0	23.4	31.5	70.0	72.1
C	Baseline scenario (repair every 50 uses)		Repair every 25 uses		Repair every 10 uses	
Device	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)
Reposable	58.01	716.93	58.01	716.93	58.01	716.93
Reusable	24.13	272.74	24.41	276.48	25.25	287.70
Savings	33.88	444.19	33.6	440.45	32.76	429.23
Savings (%)	58.4	62.0	57.9	61.4	56.5	59.9

*Note: Alternative scenarios have been considered for the lifecycle aspects of **A**: machine load efficiency, **B**: tray load capacity, and **C**: repair frequency.*

Table H2: Comparative Results Across Baseline & Alternative Scenarios Including End-Of-Life Potential

A	Baseline scenario (mean machine load)		Halving mean machine load		Maximal machine load	
Device	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)
Reposable	60.07	709.23	93.40	1052.65	48.32	585.98
Reusable	22.85	255.88	40.03	434.30	16.71	191.81
Savings	37.22	453.35	53.37	618.35	31.61	394.14
Savings (%)	62.0	63.9	57.1	58.7	65.4	67.3

B	Baseline scenario (Ratio of 1 : 2)		Similar tray load (ratio of 1 : 1)		Ratio of 1 : 3	
Device	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)
Reposable	60.07	709.23	60.07	709.23	60.07	709.23
Reusable	22.85	255.88	43.15	474.38	16.10	183.06
Savings	37.22	453.35	16.92	234.85	43.97	526.17
Savings (%)	62.0	63.9	28.2	33.1	73.2	74.2

C	Baseline scenario (repair every 50 uses)		Repair every 25 uses		Repair every 10 uses	
Device	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)
Reposable	60.07	709.23	60.07	709.23	60.07	709.23
Reusable	22.85	255.88	23.05	258.72	23.66	267.22
Savings	37.22	453.35	37.02	450.51	36.41	442.01
Savings (%)	62.0	63.9	61.6	63.5	60.6	62.3

D	Baseline scenario (75% recycling efficiency)		100% recycling efficiency	
Device	Climate change (kg CO_2-eq)	Energy demand (MJ)	Climate change (kg CO_2-eq)	Energy demand (MJ)
Reposable	60.07	709.23	60.07	709.23
Reusable	22.85	255.88	22.54	250.49
Savings	37.22	453.35	37.53	458.74
Savings (%)	62.0	63.9	62.5	64.7

*Note: Alternative scenarios have been considered for the lifecycle aspects of **A**: machine load efficiency, **B**: tray load capacity, **C**: repair frequency and **D**: recycling efficiency.*

Appendix I

Table I1: Contribution Analysis Reposble Device

Phase	Climate change (kg CO2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)
Materials	2.46	29.7	38.70	37.8
Manufacturing	0.20	2.4	2.67	2.6
Transport	0.05	0.6	0.70	0.7
Use	5.57	67.2	60.28	58.9
Disposal	0.01	0.1	0.07	0.1
Total (one lifecycle)	8.29	100	102.42	100
End-of-life potential	0.29		-1.10	
Total	8.58		101.32	

Table I2: Contribution Analysis Reposble Device per FU

Phase	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)
Materials	17.22	29.7	270.90	37.8
Manufacturing	1.41	2.4	18.69	2.6
Transport	0.35	0.6	4.88	0.7
Use	38.99	67.2	421.96	58.9
Disposal	0.04	0.1	0.50	0.1
Total (one lifecycle)	58.01	100	716.93	100
End-of-life potential	2.07		-7.70	
Total	60.07		709.23	

Table I3: Contribution Analysis Reusable device per FU

Phase	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)
Materials	3.24	13.4	46.10	16.9
Manufacturing	0.40	1.6	5.29	1.9
Transport	0.06	0.2	0.85	0.3
Use	20.29	84.1	218.49	80.1
Repair	0.14	0.6	1.87	0.7
Disposal	0.01	0.0	0.14	0.1
Total (one lifecycle)	24.13	100	272.74	100
End-of-life potential	-1.28		-16.85	
Total	22.85		255.88	

Table I4: Contribution Analysis Reposable Device for Alternative Scenario's

	Baseline scenario (mean machine load)				Halving mean machine load				Maximal machine load			
Phase	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)
Materials	17.22	29.7	270.90	37.8	17.22	18.9	270.90	25.5	17.22	37.2	270.90	45.6
Manufacturing	1.41	2.4	18.69	2.6	1.41	1.5	18.69	1.8	1.41	3.0	18.69	3.1
Transport	0.35	0.6	4.88	0.7	0.35	0.4	4.88	0.5	0.35	0.8	4.88	0.8
Use	38.99	67.2	421.96	58.9	72.31	79.2	765.38	72.2	27.23	58.9	298.71	50.3
Disposal	0.04	0.1	0.50	0.1	0.04	0.0	0.50	0.0	0.04	0.1	0.50	0.1
Total (one lifecycle)	58.01	100	716.93	100	91.33	100	1060.35	100	46.25	100	593.68	100
End-of-life potential	2.07		-7.70		2.07		-7.70		2.07		-7.70	
Total	60.07		709.23		93.40		1052.65		48.32		585.98	

Note: For the reposable device, alternative scenarios have been considered for the lifecycle aspects of machine load efficiency.

Table I5: Contribution Analysis Reusable Device for Alternative Scenario's

A	Baseline scenario (mean machine load)				Halving mean machine load				Maximal machine load			
Phase	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)
Materials	3.24	13.4	46.10	16.9	3.24	7.5	46.10	10.2	3.24	18.0	46.10	22.1
Manufacturing	0.40	1.6	5.29	1.9	0.40	1.0	5.29	1.2	0.40	2.2	5.29	2.5
Transport	0.06	0.2	0.85	0.3	0.06	0.1	0.85	0.2	0.06	0.3	0.85	0.4
Use	20.29	84.1	218.49	80.1	37.46	86.5	396.90	88.0	14.14	78.6	154.41	74
Repair	0.14	0.6	1.87	0.7	0.14	0.3	1.87	0.4	0.14	0.8	1.87	0.9
Disposal	0.01	0.0	0.14	0.1	0.01	0.0	0.14	0.0	0.01	0.1	0.14	0.1
Total (one lifecycle)	24.13	100	272.74	100	41.31	100	451.15	100	17.99	100	208.66	100
End-of-life potential	-1.28		-16.85		-1.28		-16.85		-1.28		-16.85	
Total	22.85		255.88		40.03		434.30		16.71		191.81	

B	Baseline scenario (ratio of 1 : 2)				Similar tray load (ratio of 1 : 1)				Ratio of 1 : 3			
Phase	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)
Materials	3.24	13.4	46.10	16.9	3.24	7.3	46.10	9.4	3.24	18.6	46.10	23.1
Manufacturing	0.40	1.6	5.29	1.9	0.40	0.9	5.29	1.1	0.40	2.3	5.29	2.5
Transport	0.06	0.2	0.85	0.3	0.06	0.1	0.85	0.2	0.06	0.3	0.85	0.4
Use	20.29	84.1	218.49	80.1	40.58	91.3	436.98	89.0	13.53	77.8	145.66	72.9
Repair	0.14	0.6	1.87	0.7	0.14	0.3	1.87	0.4	0.14	0.8	1.87	0.9
Disposal	0.01	0.0	0.14	0.1	0.01	0.0	0.14	0.0	0.01	0.1	0.14	0.1
Total (one lifecycle)	24.13	100	272.74	100	44.43	100	491.23	100	17.38	100	199.91	100
End-of-life potential	-1.28		-16.85		-1.28		-16.85		-1.28		-16.85	
Total	22.85		255.88		43.15		474.38		16.10		183.06	

C	Baseline scenario (repair every 50 uses)				Repair every 25 uses				Repair every 10 uses			
Phase	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)
Materials	3.24	13.4	46.10	16.9	3.24	13.3	46.10	16.7	3.24	12.8	46.10	16.0
Manufacturing	0.40	1.6	5.29	1.9	0.40	1.6	5.29	1.9	0.40	1.6	5.29	1.8
Transport	0.06	0.2	0.85	0.3	0.06	0.2	0.85	0.3	0.06	0.2	0.85	0.3
Use	20.29	84.1	218.49	80.1	20.29	83.1	218.49	79.0	20.29	80.4	218.49	75.9
Repair	0.14	0.6	1.87	0.7	0.42	1.7	5.61	2.0	1.26	5.0	16.83	5.8
Disposal	0.01	0.0	0.14	0.1	0.01	0.0	0.14	0.1	0.01	0.0	0.14	0.0
Total (one lifecycle)	24.13	100	272.74	100	24.41	100	276.48	100	25.25	100	287.70	100
End-of-life potential	-1.28		-16.85		-1.36		-17,76		-1.59		-20.48	
Total	22.85		255.88		23.05		258.72		23.66		267.22	

D	Baseline scenario (75% recycling efficiency)				100% recycling efficiency			
Phase	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)	Climate change (kg CO_2-eq)	Climate change (%)	Energy demand (MJ)	Energy demand (%)
Materials	3.24	13.4	46.10	16.9	3.24	13.4	46.10	16.9
Manufacturing	0.40	1.6	5.29	1.9	0.40	1.6	5.29	1.9
Transport	0.06	0.2	0.85	0.3	0.06	0.2	0.85	0.3
Use	20.29	84.1	218.49	80.1	20.29	84.1	218.49	80.1
Repair	0.14	0.6	1.87	0.7	0.14	0.6	1.87	0.7
Disposal	0.01	0.0	0.14	0.1	0.01	0.0	0.14	0.1
Total (one lifecycle)	24.13	100	272.74	100	24.13	100	272.74	100
End-of-life potential	-1.28		-16.85		-1.69		-22.25	
Total	22.85		255.88		22.54		250.49	

*Note: For the reusable device, alternative scenarios have been considered for the lifecycle aspects of **A**: machine load efficiency, **B**: tray load capacity, **C**: repair frequency and **D**: recycling efficiency.*