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# MECH3890 Individual Engineering Project

## *Healthcare Mechatronics Lab - Investigating the application of circular economy principles in the redesign of laparoscopic scissors*

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**SCHOOL OF MECHANICAL ENGINEERING**

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# MECH3890 – Individual Engineering Project

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| PROJECT TITLE: Healthcare Mechatronic Lab | |
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**Abstract**

This paper presents a comprehensive analysis of the environmental impact of laparoscopic scissors through life cycle analysis (LCA). It explores the ability to reduce these impacts by applying the principles of design for a circular economy, focusing on reusability and material reduction. Utilising the SOLIDWORKS 3D CAD modelling software and the SOLIDWORKS Sustainability Add-in various design modifications were assessed. The results indicate substantial reductions in environmental impact by increasing the reusability of the device. Stainless Steel proved to be the optimal material for sustainability, however the weight additions were significant. In contrast, the use of Titanium proved to be slightly worse for the environment but better from a mass perspective. Overall, the adoption of these circular economy design principles is critical to reducing the environmental impact of laparoscopic scissors and other medical equipment.

## Contents

## List of Figures

## List of Tables

# 1.Introduction

One of the major headlines in the modern-day is climate change. Environmentalists warn the over-consumption of materials, especially fossil fuels, causes global resource depletion. To ensure the protection of these resources for future generations, control must be added to the demand for these resources [1]. The emissions associated with the Medical Industry are one of the major contributors to climate change - contributing to 4.4% of global emissions [2]. Medical equipment used by the NHS produces 10% of annual emissions [3].

Within most industries and organisations, there is a very linear approach to economic and product lifestyles. Lifestyles tend to be: 'take-make-use-destroy' [4]. Recognising the limitations of this linear approach is where the concept of the *circular economy* becomes critical. A circular economy suggests a product should remain in its highest value state for as long as possible. Embracing a circular approach is imperative for a more sustainable future. Transitioning to a circular economy also aligns with the NHS' promise of reaching net-zero carbon by 2045 [5].

Specifically within the NHS and the whole medical industry, one of the key contributors to the overall emissions are disposable items used in surgery [6, 7]. Such as single-use stainless steel (SS) and aluminium scissors used in Laparoscopic surgery. Due to cross-contamination reasons, such devices must be autoclaved at the end of life [8]. This process significantly increases the environmental impact (EI) of the single-use devices. The reliance on throwaway practices underlines the urgency of reducing these emissions. However, guaranteeing safety, complying with medical standards and ensuring fundamental functionality introduce challenges when redesigning these devices for a more circular economy.

Several studies show laparoscopic surgery is becoming increasingly popular, with Bingmer et al. showing a 462% increase in laparoscopic surgeries performed between 2000 and 2018 [9, 10]. Subsequently, this poses a concern for NHS' journey to reach net-zero carbon, as the increase in surgeries leads to a growing increase in global emissions.

Single-use devices are a large contributor to the NHS' EI and are growing in demand. Therefore, this project will focus on taking the design principles of a circular economy and applying them to redesign the laparoscopic scissor device.

## 1.1 Aim

Develop a new and innovative design for laparoscopic surgery tools to minimise their EI through the application of design principles of a circular economy.

## 1.2 Objectives

1. Conduct a literature review on the circular economy and how it relates to the design of laparoscopic devices
2. Develop a 3D Computer Aided Design (CAD) Model, representative of a current laparoscopic scissor from a physical model
3. Select and Validate an EI method against the initial design of the laparoscopic scissors
4. Design a new 3D model by applying the design principles of the circular economy
5. Select and analyse EI factors of the new laparoscopic scissor
6. *(Optional)* Build a prototype of the new device to provide tangible validation of the laparoscopic scissor design

### 1.3 Project Report Layout

This paper discusses the difference aspects of sustainable design and the effect of these on the environment. Chapter 2 provides and overview of life cycle analysis and the concepts of a circular economy, establishing a foundation for the project. Chapter 3 details the validation of both the software and the model used for the life cycle analysis. In Chapter 4 the first two design changes are explored, finding the most beneficial options for improvement. Chapter 5 combines the key findings from Chapter 4 into a final design change and outlines the fabrication methods. Finally, Chapter 6 concludes the paper, highlighting the focus areas for improvement and areas of future research.

# 2.Background

## 2.1 Laparoscopic Surgery

Laparoscopic surgery (Laparoscopy) is keyhole surgery used to diagnose and treat conditions through small cuts and a camera for procedures in the tummy or pelvis [11]. Since the late 1980s, it has transformed the way minimally invasive surgery is performed. Subsequently, it has started to replace the more common open surgery [9]. Moreover, studies show the increasing popularity of Laparoscopy, with Bingmer et al. showing a 462% increase in Laparoscopic surgeries between 2000 and 2018 [9, 10]. By undertaking this newer Laparoscopic technique patients are receiving many new benefits. These include no open wounds, so less pain and discomfort and increased recovery time, predicated as little as three weeks [12]. Likewise, having an overall positive effect on patient's well-being [13]. The surgeons also have less contact time, decreasing risk of infection [13].

While this surgery has these benefits for both patient and doctor, the environment is being negatively impacted. Laparoscopic surgery is currently performed with laparoscopic tools. Surgeons justify using single-use laparoscopic tools over concerns for "quality" and "safety" [14]. However, there is little evidence suggesting single-use tools are safer to use [14]. According to Whiting et al. these single-use consumables were one of the largest contributors to the carbon emissions of surgery, contributing 32% [15]. Tennison et al. delved further into this finding the NHS' medical instruments contribute to 10% of their overall annual emissions [3], with disposable equipment being identified as a key contributor to carbon emissions [6, 7]. The single-use items used in operating rooms cannot be recycled due to their contamination and infection potential [16]. As these surgeries are vital yet negatively impact the environment, this project will focus on how laparoscopic scissors can be made more sustainable by applying the design principles of a circular economy.

## 2.2 Circular Economy

A circular economy can be defined as a system where materials once extracted for use, never become waste and nature is renewed. This may be done by restoration, re-engineering, or composting allowing them to go around the circular loop several times having been restored from obsolesce [17, 18]. A key idea is to keep the product in its high-value state to preserve the materials' life by keeping them in the economic system and giving the product several iterations around the life cycle rather than just one [19]. Moving towards a circular economy is vital to ensure future generations have the resources they require.

Many think recycling is the best option for the environment. However, the circular economy suggests recycling is less favourable because the product is not in its high-value state. A study conducted by Thiel found that of each considered variable, recycling had the smallest effect on lowering a product's EI [20]. A more favourable idea would be to switch to a reusable device. Recycling still improves the EI of a product compared to other disposal methods.

When designing for the circular economy there are important design principles for sustainability - extended use, recovery and recycling [21]. The design should prioritise reusability, essential for keeping the device in the economic loop. Next is to incorporate repairability into the design. This could be a more modular device so parts can be replaced, removed and repaired without needing a completely new product. There must also be a consideration of recovery, meaning once the device has become obsolete, it could be transformed into a product for another use. This may involve the product being broken down into its constituent elements for use elsewhere. Finally, at the ultimate end of a product's life it should be recyclable, for lots of materials this is not so easy hence why the other mentioned principles are vital.

Studies show applying these principles of a circular economy causes the EI of medical devices to decrease. Specifically a study on surgical scissors demonstrated material removal from the scissor had the largest effect on the EI [20]. Another study on the same device showed that reusing and repairing the device decreased the EI [22]. This demonstrates the importance of applying these principles when it comes to reducing a product's EI.

## 2.3 Environmental Impact Assessment

An EI assessment (EIA) is a tool used to assess a product or organisation's EI [23, 24]. There are then several ways to carry out an EIA when measuring the EI of a product. One way is a life cycle assessment. This specialises in quantifying the EIs such as carbon footprint, energy consumption, and water pollution across a product's lifetime. Alternatively, there is a life cycle cost analysis which determines the associated costs with a product's life [25]. But, this lacks most of the EIs like carbon footprint. Finally, there is a circular economy assessment. This method identifies the circular economy performance of an organisation [24].

A life cycle analysis (LCA) is an internationally standardised means of quantifying the EI of a product. It takes an inventory of inputs and delivers outputs such as material and energy generated by each stage of a product's life, as shown in Figure 3.1. The system boundary defines what is included in the analysis. The system boundary has been defined in Section 3.3.1 for this project. The system boundary can be defined individually for each LCA, being as simple or complex as required. It can cover the whole product life cycle (cradle-to-grave) starting from raw material extraction and extending to its disposal [26, 27]. Alternatively, it can consider only the raw material extraction and the product manufacturing (cradle-to-gate). LCAs are commonly used by businesses to aid in decision-making for the EI of their products [28]. This is because they are a great tool for identifying improvement opportunities at various phases of a product's life [29].

There are also different levels of LCAs. These are conceptual, the most basic. Simplified which uses more generic data and standard modules. Finally, detailed, which is a full in-depth analysis using highly specific data for each product [30].

LCAs also have limitations. One is the limitations is difficulty tracking all the emissions from a single device over its lifetime. For example, when considering what happens after the laparoscopic scissor is used, it should be sterilised. However, some may be transported in an electric vehicle or in bulk. These different methods would affect the device's EI. The device will go through many processes that accumulate a high degree of uncertainty, presenting a significant problem when generating accurate results. To minimise a device's EI all these processes should be optimised [22]. An LCA can also be impacted by the quality of data available, this defines how valid the LCA is. Finally, if there is an incident, such as an oil spill, the energy coming from an oil factory would not take into account the oil spillage in the LCA. However, this would have a significant EI [30].

### 2.3.1 Software

There are many different LCA software, some of the most popular include SimaPro [31], OneClickLCA [32], Ecochain Mobius [33], GaBi [34] and openLCA [35]. SimaPro is ideal for performing a detailed LCA as it allows the user to specify every detail of the product's life cycle, with full data transparency [31]. Moreover, it has high-level analytical features such as uncertainty analysis, weak point analysis and complex waste treatment[36]. However, this software is not free unlike openLCA which also allows a detailed LCA. One thing these software have in common is the steep learning curve for new users. For example, SimaPro is specifically designed for Academics and experienced consultants [37]. Likewise, most of these products don't allow for real-time design changes and calculations directly from a CAD model. SOLIDWORKS (SW) on the other hand offer a Sustainability Add-in that is much more limited as an LCA software but has a lower learning curve and enables real-time design changes. The software is limited to minimal disposal methods and few manufacturing techniques. But this makes the software easier for new users as there are fewer inputs and all of the manufacturing data already integrated. So for comparing different models, SW Sustainability is ideal. Furthermore, the background data used for lots of the calculations in the SW Sustainability software are taken from Sphera, which is one of the largest and highest quality life cycle inventory databases [38] with over 15000 databases updated annually [39].

#### 2.3.2 Methodology

When performing a life cycle analysis the methodology used plays an important role. To list a few of the methods that can be used, CML [40], TRACI [41], ReCiPe [42], Eco-Indicator [43], and IMPACT [44]. Research conducted into the most commonly used LCA methodologies shows that the top two are CML and ReCiPe [45, 46, 47]. This is logical since the CML method is free and covers a variety of baseline and non-baseline factors such as Photochemical Ozone Creation Potential [40]. Similarly, ReCiPe focuses on several midpoint impact categories such as global warming and water use that through damage pathways predict endpoint factors such as damage to ecosystems or human health [42].

### 2.4 Summary

In summary, laparoscopic surgery is growing in popularity due to its health benefits to patients and surgeons. However, they use lots of equipment that is disposed of after use which is not good for the environment. Disposable equipment is a key contributor to the emissions of the medical industry and the NHS. With the goal of the NHS to reduce to carbon zero by 2045, all carbon emissions must be reduced from anywhere possible. One way to do this is to redesign some of this disposable equipment by considering the principles of a circular economy (longer lasting and reduced material). This can be challenging in the medical industry as there are extra considerations such as cross-contamination, for surgical devices.

It is also important there is an accurate way of testing the device's EI to ensure the changes made in design are having the desired effect. One of the most common methods to measure this is an LCA, which takes inputs about a product and its life cycle and returns values representing its EI such as carbon footprint. There are different LCA software, but the optimal choice for this project is the SW Sustainability Add-in due to the ability to make design changes and see the effects in real-time. Different softwares also offers different methods of measuring EI. SW offers CML and TRACI. But there are others like ReCiPe and IMPACT. CML is a common method used and is specifically standardised for Europe, making it an ideal choice for this analysis.

## 3.Software Validation

### 3.1 Introduction

It is important to validate the methodology and software used, as well as the SW Model representing the laparoscopic scissor, as the model was not provided by the supplier. To validate the SW Software and the model being used to represent the laparoscopic scissor, the findings from Rizan et al. [48] were used to compare against the results from the initial SW Model. The data is shown in Table 3.2. Once the model is created an LCA on SW Sustainability is performed on the representative SW device. The data found from this is then compared against the LCA performed by Rizan et al. [48] to validate the Sustainability Add-in.

### 3.2 Model Creation

First, a CAD model of the laparoscopic scissor was created. To perform an LCA the product data is required. For this project, the product is a commercially available laparoscopic scissor. The product inputs are the types and amounts of materials. Since this is a commercially available device, accessing the CAD and specific material information was challenging. However, with access to a physical version of the device and information about the material weights from the work conducted by Rizan et al. [48], it was possible to take measurements of the device to create a representative model in CAD.

A CAD model allows for visualisation and feasibility assessment of the new designs. It enables the quantification of EIs through an LCA and suggests the key areas for potential improvements. Given the specific material weights, decisions can be made about material removal and the environmental benefits can be determined. It can also help assess the trade-off between material reduction and device reliability. Future work could also utilise this model for finite element analysis or alternative methods to determine the device lifespan with the design changes. Thus, the CAD model is beneficial for project progression and potential future studies.

The reusable device was split into 12 components (labelled in figure). The components were made as parts in SW before being combined into the final assembly. To create the complicated components images were uploaded to the SW Software to create the device. Measuring some of the internal components was a challenge but with access to the weight of the device, it was possible to match up the material weights to the parts. Similarly, some external components were also challenging to measure as the device moved. Similarly some of the parts were in difficult-to-reach places, not necessarily internal but in a position where it was not possible to get a ruler in to measure the dimensions. As the main premise of the project is to get a proof of concept for some of the designs and show that they will be better for the environment an extremely accurate model was not one of the requirements so long as it was sufficient enough to represent the physical model. Furthermore, to simplify the model creation any materials with a weight less than 1% of the total weight have not been considered in any further analysis. This is common in an LCA because it simplifies the analysis by removing unnecessary features of the LCA which are likely of no consequence [49].

Not all of the information has been given for the materials so some assumptions have been made. One is the type of stainless steel used is 316 Stainless Steel because it is commonly used in medical devices such as surgical equipment [50]. Another assumption is the Aluminium used is 6061 Aluminium Alloy, as it is a biocompatible metal and is currently used in medical devices [51, 52, 53]. The plastic material is known to be Polyphenylene sulfide (PPS) from the analysis of Rizan et al. [48].

*Table 3.1: A Bill of Materials for the handle showing each of the parts labelled in Appendix B and the materials and mass' of each part according to SW.*

| Part Number | Part Name | Quantity | Material | Mass per unit (g) |
|---|---|---|---|---|
| 1 | Right Handle | 1 | PPS | 19.07 |
| 2 | Left Handle | 1 | PPS | 19.07 |
| 3 | Centre Connection | 1 | PPS | 11.85 |
| 4 | Scissor Screw | 1 | SS | 10.5 |
| 5 | Front Tightener | 1 | PPS | 5.82 |
| 6 | Centre Linkage | 1 | PPS | 1.74 |
| 7 | Metal Teeth | 1 | SS | 1.62 |
| 8 | Metal Latch | 1 | SS | 1.09 |
| 9 | Handle Linkage | 2 | SS | 0.56 |
| 10 | Scissor Attachment | 1 | SS | 0.53 |
| 11 | 2mm Metal Cylinder | 2 | SS | 0.22 |
| 12 | 1.5mm Metal Cylinder | 2 | SS | 0.125 |
| | Total | 15 | | 73.1 |

A similar process was used to create the disposable scissor device, this is outlined in more detail in Appendix C. The total mass of each material can be found by summing all of the material weights from the two devices. The results are detailed in Table 3.2. There are some clear differences between the masses of each material because some geometries and dimensions had to be estimated as there was no way to measure accurately all of the components. In the handle, zinc, nickel and copper are not present, as they represent less than 1% of the total weight of the model. The scissor component used to make the CAD model did not have the plastic part with it. Therefore Silicone has not been included and the plastic component had to be estimated from online imaging. This meant that PPS was used to represent all of the plastic.

The models do not match exactly to the weights provided in Table 3.2, however, they are very similar, with only a 1g difference for the handle and a 2g difference for the scissor. Also in both models, the weight distributions between all of the components are very similar and therefore the model is representative enough of the actual device.

*Table 3.2: The weights and weight percentage of the hybrid laparoscopic scissor device measured by Rizan et al. [48] compared against the weights measured in SW*

| | Rizan et al. [48] | | | | SOLIDWORKS | |
|---|---|---|---|---|---|---|
| | reusable handle | | Single-use scissor | | reusable handle | Single-use scissor |
| Material | Weight (g) | Weight (%) | Weight (g) | Weight (%) | Weight (g) | Weight (g) |
| PPS | 51.9 | 71.33 | 0.8 | 3.18 | 57.55 | 4.51 |
| 316 SS | 19.97 | 27.44 | 14.84 | 59.03 | 15.56 | 10.165 |
| Copper | 0.3 | 0.41 | —— | —— | 0 | —— |
| Zinc | 0.3 | 0.41 | —— | —— | 0 | —— |
| Nickel | 0.3 | 0.41 | —— | —— | 0 | —— |
| 6061 Al | —— | —— | 8.7 | 34.61 | —— | 12.14 |
| Silicone | —— | —— | 0.8 | 3.18 | —— | 0 |
| Total | 72.77 | 100 | 25.14 | 100 | 73.12 | 27.45 |

## 3.3 LCA Parameters

### 3.3.1 System Boundary

Figure 3.1 describes the system boundary for the LCA of this product. Using the SW Software has its limitations in the depth of analysis that can be performed. Another significant problem is finding the information for all the processes during the device's lifetime. A detailed look into a product's life cycle is a complicated task.

This system boundary in Figure 3.1 is sufficient for this project as the main areas of the life of the product are considered. Furthermore, the analysis is mainly focused on improving the impact of the device therefore the trends are more important than the detailed results.

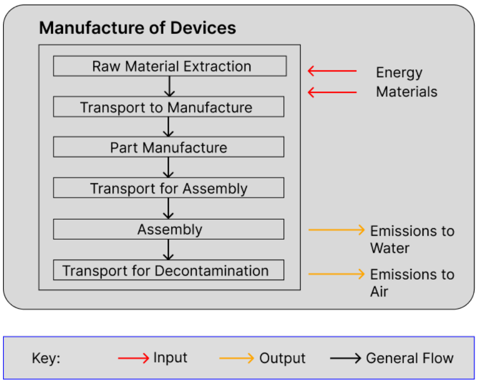



*Figure 3.1: Shows the system boundary for the life cycle of laparoscopic scissor components. The full system boundary for the entire life of the laparoscopic scissor can be seen in Appendix A. This diagram is based of the diagram used by Rizan et al. in their analysis [48].*

### 3.3.2 SOLIDWORKS Inputs

Lots of the inputs have been obtained from the LCA performed by Rizan et al. [48] on the same laparoscopic scissor. For example, the manufacturing and assembly regions, and the transportation have been taken from the information used by Rizan et al. [48]. The only alteration is that SW provides no method of courier so the distance travelled by courier has been altered to be a truck. A summary of all of the inputted parameters are in Table E.1.

The SW Sustainability Add-In is limited to a use time rather than a use count. The reusable part of the device can be reused 500 times, according to the manufacturing guidance [48]. As the number of laparoscopic cholecystectomy surgeries performed each year with this device is around 61220 in the UK [54], it would be used every day for its entire lifetime. Therefore, lasting 500 days.

For the manufacturing processes injection moulded (IM) was used for the plastic [48] and milling was chosen for the metal processes. For the metal components Rizan et al. explain that the data used for the analysis takes average processes into account [48]. This means for the metalwork processes, the average electricity usage for the manufacturing location has been used. For example, sometimes the energy will come from solar panels or power stations. So an average value has been taken for the energy for this manufacture. SW provides different options for manufacturing metals, such as die casting, milling, and forging. For the metal components, a milling process has been assumed as the device is manufactured on a large scale currently and this method would be suitable for this manufacture and to produce all of the parts. SW also provides information on the percentage scrap rate, giving an average percentage of parts that must be scrapped due to manufacturing mistakes. So the processes already loaded into SW have been used to give accurate values for the different manufacturing methods used, and all of the extra features like scrap rate have been left as default values.

Notably, some inputs such as fuel for assembly and energy for use have been set as false. This is because it is assumed that once the parts are created they are put together without any machinery, as there is no complicated manufacturing process. This has been assumed as Rizan et al. [48] provide no information in their LCA about fuel needed for assembly. For the use the energy has been left as false because the decontamination process is not being considered in this analysis. This is outside of the system boundary used for this analysis.

This particular analysis is also not concerned with the end of life of the device because the focus of this life cycle analysis is from cradle-to-gate. As the inputs must be filled in, data must be entered in for the end of life of the product. To ensure that the other results are unaffected between cases the end of life input has been made constant. Since the devices are critical devices on the *Spaulding Scale* [55, 56], these devices must be incinerated so 100% incineration is used as the input for each part across each design.

## 3.4 LCA Results

### 3.4.1 Outputs

Two outputs have been chosen to represent the EI of this product. The first of these outputs is the carbon footprint, which is expressed as $CO_2$ but incorporates other carbon equivalents such as carbon monoxide and methane that are also released into the atmosphere from burning fossil fuels [57]. It is also the goal of the NHS to reduce their carbon to net 0 by 2045 [5] and so will be a good indication for the NHS on the effective ways of reducing their carbon footprint.

The second output being considered is Energy Consumption. This is the amount of non-renewable energy used in the product's life [57]. This has been a considered measure because it encompasses the non-renewable energy used. As technology progresses, more renewable sources of energy will likely be used. This gives an idea of where the energy consumption in the product's life is coming from.

The carbon footprint and energy consumption are given for different stages of a device's life cycle: material, manufacture, use, end of life and transportation. The material represents the extraction of the raw materials and the processing of these materials. The manufacture contains the method of manufacture of each part and any energy used in the assembly process. Use represents any energy that needs to be used during use. For example, some devices may be required to be plugged in or charged and this would result in some energy consumption. End of life involves the carbon released during the disposal process of the device, which can be chosen in the analysis. Finally, transportation is the carbon and energy used to move the materials from extraction to processing, then from processing to manufacture, manufacture to assembly, and assembly to use. As not all of these are being fully investigated the carbon footprints suggested by this report do not represent the total amount of carbon that will be released from the device over its entire lifetime.

### 3.4.2 Results

Using the inputs described in Section 3.3 two LCAs have been performed on both the reusable handle and the single-use scissor. The results are shown in Table 3.3. This table shows a comparison between the two devices both per device that is created and also per use of each device. The results for the carbon footprint have then been summarised against the results from Rizan et al. [48] in Table 3.4.

*Table 3.3: Carbon Dioxide released and the Energy Consumed in each of the stages of the life cycle of the Handle.*

| Device | Material | Manufacture | End of Life | Transportation | Total |
|---|---|---|---|---|---|
| Handle (kg $CO_2$) | 0.566 | 0.068 | 0.040 | 0.007 | 0.681 |
| Handle (kg $CO_2$/use) | 0.001 | 0.0001 | 8.04e-5 | 1.35e-5 | 0.0014 |
| Handle (MJ) | 11.029 | 1.288 | 0.029 | 0.100 | 12.446 |
| Handle (MJ/use) | 0.022 | 0.003 | 5.90e-5 | 0.0002 | 0.0249 |
| Scissor (kg $CO_2$) | 0.251 | 0.012 | 0.036 | 0.0004 | 0.300 |
| Scissor (MJ) | 3.346 | 0.230 | 0.028 | 0.0061 | 3.610 |

*Table 3.4: Snapshot of the carbon footprint results obtained by Rizan et al.[48] compared to the results obtained in SW.*

| Component | Process | Carbon Footprint per use (g CO2) Laparoscopic scissors | |
|---|---|---|---|
| | | Hybrid [48] | SW Sustainability |
| Reusable component | Raw material extraction and manufacture | 1.27 | 1.2672 |
| | Transportation | 0.01 | 0.0135 |
| | Decontamination | 79 | N/A |
| | Waste | 0.37 | N/A |
| | End of Life | N/A | 0.0804 |
| Single-use component | Raw material extraction and manufacture | 232 | 263.3104 |
| | Transportation | 2 | 0.4157 |
| | Waste | 64 | N/A |
| | End of Life | N/A | 35.9159 |
| Total | | 378 | 301.0031 |

## 3.5 Comparison

There are differences in the results obtained by SW and Rizan et al. [48], as shown in Table 3.4. The total carbon footprint determined by Rizan et al. was 378g of $CO_2$, about 77g higher than found in SW. The main difference between these results is the decontamination of the product is not considered in the SW study. The EI of the decontamination equates to 79g of $CO_2$. After removing this from the total, the results from SW match up very closely. Also, when considering the individual categories for the reusable handle the 'Raw Material Extraction and Manufacture', and 'Transportation' are very accurate as seen in Table 3.4. For the single-use component, the results are within the correct magnitude but have a larger difference.

These differences are likely due to the inputs of the LCA. For example, they may have access to more accurate data for the manufacturing processes than SW provides. Similarly for all of the parts to be assembled into the correct location, for this study they are all being considered to be made and manufactured in the same place however, this is unlikely and Rizan et al. [48] may have taken this into account. This study is also completed on a representative CAD model that does not contain all the material and slightly different weights which will also introduce further error. That being said the values are within the same magnitude and the results follow the same trend as Rizan et al. [48], showing that the single-use part of the hybrid scissor has a higher impact per use than the reusable components.

The results in both of these studies also match up to a similar study on endoscopic equipment by López-Muñoz et al. [58]. This study contains different quantities of carbon produced for the devices but the trend is the same. This study shows that production is the next highest contributor to carbon footprint, if not considering the disposal method. Overall this justifies the accuracy and reliability of the SW Sustainability Add-in.

The effect on the end of life has been investigated for some different types of plastics by Pasqualino et al., who suggest incineration is for the majority the worst disposal method [59]. Due to legislation, this method cannot be changed, presenting a major limitation when trying to reduce the device's EI. This is another reason the end of life is not considered.

### 3.6 Areas of improvement

Table 3.3 shows the best area to focus on for reducing laparoscopic scissors EI is the materials. For both devices, the amount of $CO_2$ and energy consumed is highest for the material. This agrees with the results found by Rizan et al. which show that raw material extraction and manufacture produce the highest amount of carbon when decontamination is not considered [48]. The next area to look into is the manufacture of the reusable handle, milled for metals and injection moulding for plastics. The single-use scissor analysis suggests that the end of life of this device is more harmful than the manufacture. However, the data for the end of life may not be entirely accurate so it is difficult to know. The lowest impact area is transportation. This can be controlled by bulk shipping and using electric vehicles.

When comparing the two devices it is clear the EI of the reusable handle is higher than the EI of the single-use scissor per device. However, as the scissor device has to be replaced after every use, its EI per use is significantly higher, as shown in Table 3.3. Rizan et al. [48] also found this to be the case. Furthermore, in a literature review conducted by Sousa et al. [60], the majority of the papers found single-use medical devices had the highest EI.

Rizan et al. [48] considered the decontamination of the reusable handle which increased the EI, but was still not as high as the single-use scissor. The handle is also used with multiple attachments, such as graspers and scissors. Furthermore, there already are some fully reusable laparoscopic scissors, although they are claimed to be not as sharp as the single-use equivalents [48]. Therefore, the reusable aspects of the device should be targeted to improve. As this study focuses on cradle-to-gate analysis and the materials and manufacture of the reusable handle are worse overall, the reusable handle has been studied and tests conducted to reduce its EI with a focus on the impact of the material.

To further investigate which areas of the handle should be focused on the carbon footprint has been broken down for each of the components that make up the reusable handle. The visualisation feature in SW demonstrates the heavier components shown in Table 3.1. As there are two handles, optimisation of these two components will significantly reduce the overall carbon footprint of the device. There is an example of this visualisation shown in Figure D.1.

# 4.Eco-design Optimisation

## 4.1 Introduction

Taking circular economy design principles and applying them to the CAD model creates two design changes. The first incorporates re-usability, aiming to keep the device in its highest value state for as long as possible. The second focuses on reducing the device's material.

## 4.2 Reusable Design Change

To create a device to last forever the proposed design change is to make the handle entirely metal. This will make the product last longer as each time the device is subjected to the harsh decontamination process it will remain structurally stable. Moreover, as it is metal the device will also experience minimal wear during each use.

## 4.3 Reduced Device Design Change

As material has the worst EI, shown in Table 3.3 and a study by Thiel et al. [20], this design change removes as much material as possible. Reducing the material should reduce the EI of all stages of the life cycle, as there is less material to manufacture, dispose of and transport.

An initial analysis was performed by removing 125mm$^3$ of PPS and SS to determine which had the largest effect. The results showed removing SS from the device reduces the EI by the largest amount. Therefore, it was important to reduce as much of this material as possible.

As most of the current components have likely been ergonomically optimised changing the shape seemed impractical. Instead, material was removed from inside. The handle is one of the most ergonomically developed components. It is the area the surgeons are constantly holding so must be comfortable and withstand applied forces. To keep the shape a hollow design is used. A wall thickness of 1mm was used removing as much material as possible. Material has also been removed from other components. The plastic tightener at the front has had some grips removed rather than hollowed out as this part will experience high loads when the screw is being tightened. Whereas some parts were already optimised for so there wasn't much to remove. The notable changes in weight for the components can be seen in Figure 4.3.

## 4.4 Infilled Design Change

A downside of material removal is the "built to last" time may be reduced, due to the thin walls cracking under loading. To combat this some of the material can be added back by creating an infill. The new infills for the handles of the device can be seen in Figure 4.1, which uses a honeycomb and triangular shape for the infill to increase the device's strength.

These two infill shapes chosen are considered the strongest, with honeycomb having a very high compressive strength [61] and the highest strength-to-weight ratio of any infill pattern [62]. Some claim the triangular infill pattern is one of the strongest, less likely to deform and provides more structural support to the walls [62]. However, most agree changing the density or orientation of these infill patterns is more effective than the actual pattern itself [63]. For this change, the infills have a support distance of 1mm in thickness and a shape size of 8mm. To understand these dimensions, Figure 4.1 shows diagrams of the infill designs.

As the handles take the majority of the force when being held by the doctors and the already small nature of the centre console, the honeycomb shape has only been applied to this part of the device so the other areas could be optimised with material removal.


*(a) Honeycomb Infill* *(b) Triangular Infill*

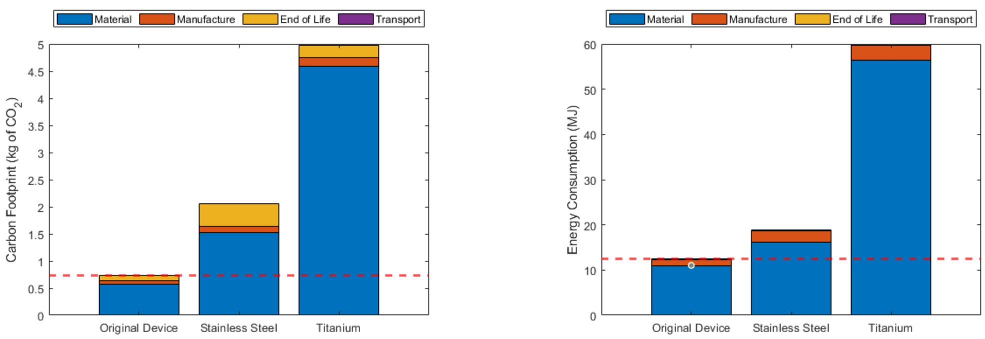
*Figure 4.1: A sectioned view of the handle showing the two infill designs. The zoomed-in images outlined in blue show the dimensions used to define the infill. The thickness of the material labelled 1 is 1mm. The size of the shape is determined by drawing an outer circle joining the points of each shape, the diameter of this circular is shown by dimension 2 labelled in the diagram and is 8mm. NOT TO SCALE.*

## 4.5 LCA Parameters

The main change from Table E.1 for the reusable design is the device is made out of metal. The first is made from 316 SS and the second from medical-grade Titanium, Ti-6Al-4V alloy. This Titanium (Ti) has been chosen as it has good bio-compatibility and is corrosion-resistant making it an ideal choice for a reusable medical device [64, 65, 66]. Ti also has a higher melting point than SS so it is less likely to be affected by the decontamination process. Another change is with the manufacturing process, now set to milled for each metal. Finally, as the idea is for the device to last forever, the "built to last" time has been set to maximum (1000 years).

For the reduced design most of the parameters remained the same. The main change was to the SW model. To consider the effect of the "built to last" time decreasing, parts 1-6 of Table 3.1, have a "built to last" time of 250 days. This represents 2 of the components are required for the 500 day use time. For a full breakdown of these inputs please see Table E.2.

## 4.6 Results




*(a) Carbon Footprint* *(b) Energy Consumption*

*Figure 4.2: Shows the Carbon Footprint and Energy consumption for each of the different stages of life of the reusable devices compared with the initial device.*

By changing to metals the mass increased due to the higher densities. The SS was significantly heavier than the original device. The weight increased to 309.88 grams, an increase of almost 325% from the original 73.1 grams. Changing from SS to Ti indicates a decrease in weight but still an overall increase from the original device. For more detail on the mass of each component please see Figure F.1.

The effect of making the device metal on the EI can be seen in Figure 4.2. Notably the material stage of life still has the largest carbon footprint and energy consumption compared to the other stages. Although the Ti weight is lower than SS, using Ti is worse for the environment.

The other design change has the opposite effect on the weight of the components. Figure 4.3 shows for all of the components that had material removed. For the "Material Removal" device there is a weight decrease from 73.2 to 44.67. Out of the infill patterns added, the triangular infill adds more mass to the handles compared to the honeycomb pattern.

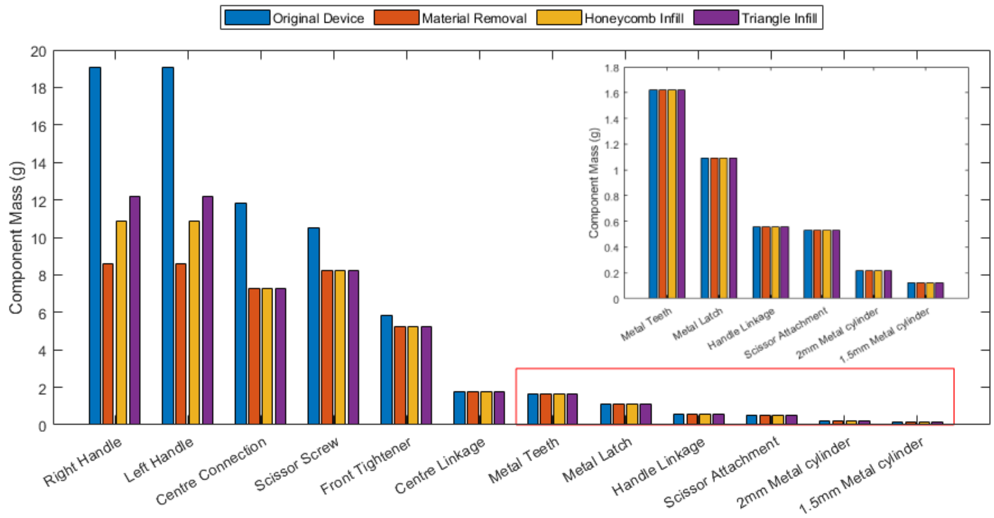
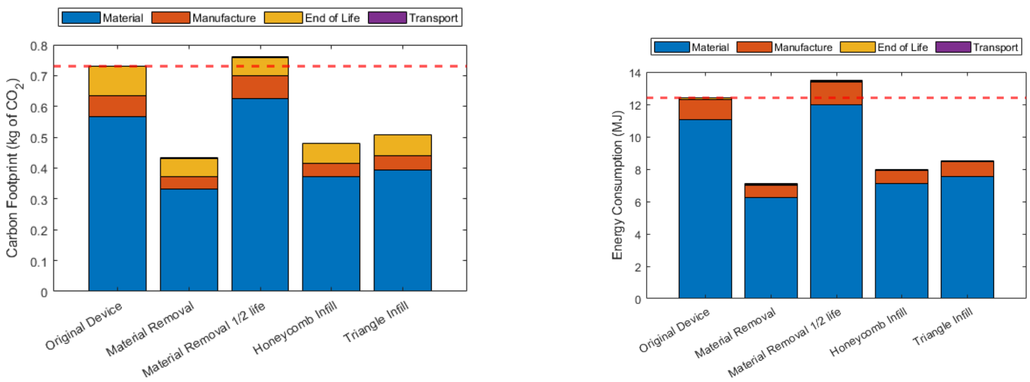



*Figure 4.3: Shows the mass of all 12 parts that are used to represent the reusable handle device and the respective masses of each for the material reduction design change.*




*(a) Carbon Footprint*

*(b) Energy Consumption*

*Figure 4.4: Shows the Carbon Footprint and Energy consumption for each of the different stages of life of the material removal design change devices compared with the initial device.*

Unlike the metal device, the correlation between mass and EI has a positive correlation. With a decrease in mass, there is also a decrease in the EI as shown in Figure 4.4. The figure also shows materials still have the largest EI compared to each other stage in the life cycle.

### 4.7 Discussion

Firstly, there was a more significant weight increase using SS than using Ti. The large increase in weight for the SS components may become a problem for surgeons using the device. As laparoscopy is a delicate surgery it is important surgeons fatigue as slowly as possible. Fatigue can result in higher risks for patients [67]. A scissor must be continuously expanded and contracted, increasing physical fatigue - amplified if the scissor is heavy. SS was chosen as it is already used in some parts. However, the weight is an issue. Changing to a medical-grade Ti alloy, caused a 138.93g decrease from the SS device. Therefore, this change will have less of an effect on the surgeons using the devices. Regardless, there is still an increase in the device weight which will result in faster fatigue, but this fatigue rate will be reduced.

Changing to metal components increases the EI of the devices. The material change alone resulted in almost another 1kg of $CO_2$ for SS and 4kg of $CO_2$ for Ti. This is due to the increased costs of extracting the raw materials and processing them into the alloys. These findings align with the results obtained by López-Muñoz et al. [58] who suggest SS components have a much higher carbon footprint compared to plastics. There is also an increase in the EI from manufacturing. This is likely because all the components are now milled. Ti is worse than SS, likely due to the material properties of the Ti alloy.

Despite this, the devices will last much longer than the original device, so per use the metal devices will have a lower EI. The SS device should be used for almost 3 lifetimes of the original device and the Ti device should last for almost 7 lifetimes to be considered more environmentally friendly. The Ti device does need to be used for longer than the SS device, but because of how common the surgeries are, Ti may be a good alternative to SS as it will be used for that length of time and it has a lower weight.

SW Sustainability provides the ability to investigate the cost impact of these design changes. Although the Ti device is not significantly worse for the environment, the cost of this device dramatically increased. Cost is not a key parameter of this project so has not been studied in depth but it is something that was observed when performing the analysis. From the magnitude of that cost increase, it is worth considering when it comes to actually creating this device.

This is where the material removal design change comes in. This design reduces the amount of material in the device and consequently weight, reducing the EI. It also reduces the cost as less material is used for each of the devices. Reducing the material meant a decrease in $CO_2$ of 0.14437 kg and a reduction of 2.898 MJ energy consumed. Thus, removing this material would be better for the environment.

Although this device is better for the environment, this initial study considered the device and all its components to still last 500 days. As explained previously the material removal can reduce the ”built to last” time. To mimic this another LCA was performed where the reduced components have half the lifetime. It was found that reducing this ”built to last” time increased the EI to be larger than the original device. This is in all stages of the product’s life, which was expected as many of the processes now have to happen twice such as double the transportation and double the manufacture for 6 of the parts that have the reduced life. This suggests that reducing the material and the lifetime is not beneficial for the environment.

It is also observed that the EI of transportation increases. The components will be transported more frequently as they are replaced more often. However, the method of transportation is very important. For example, if an electric vehicle is used, the EI will likely decrease. This was not considered in this study and transport has consistently been a low-impact area meaning more focus should be applied to reducing the material than the method of transportation.

From Figure 4.4 the two infill patterns cause an increase in carbon footprint and energy consumption per device, compared to the ”Material Removal” device. But they have a reduced impact compared to the original device the ”Material Removal 1/2 life”. This is because there is still a net material removal which can be seen in Figure 4.3.

The triangle infill was worse for the environment than the honeycomb due to the extra material added. As both devices have the same lifetime it is difficult to compare the two patterns and suggest which is better. The triangular infill is considered one of the strongest infills [62] and so is the honeycomb so failure could occur in both devices at a similar time and this may not be due to the repetitive use or heating and cooling during decontamination. Therefore, further testing would be required to be able to distinguish the lifetimes of the two infill patterns.

The mass of the ”Material Removal” and infill devices, showed minimal change from the original device. This is because most of the material was removed from the lightweight plastic. There was an overall weight reduction of 28.43g, with 21g being lost from the two handle components by making them hollow. This should have little effect on the device’s use. It may aid the surgeons to have more control over the instrument during surgery. Furthermore, when the infills are added there is a 4.6g increase for the honeycomb and a further 2.6g increase for the triangle. Similarly, for the surgeons, the change in mass will be less noticeable allowing them to continue as if no changes have been made.

Finally, to manufacture these devices milling and injection moulding have been used. These may not be practical for all of the designs. For example, the metal handles are unlikely to be milled. Due to the limitations of the software these have been left in this way. Later an individual manufacture analysis has been conducted to determine the effect that is expected to happen.

### 4.8 Key Findings

The reusable device is environmentally better per use and the SS device has a much lower EI compared to the Ti device. The Ti device is lighter, so more practical and has a reduced EI of transportation and end of life. Due to the insignificance of transport and end of life on the overall EI, this doesn’t justify the use of Ti as the impact of the materials is dramatically higher.

Both designs show a reduction in EI compared to the original. When considering a cradle-to-gate analysis the second design is better, as the EI from the production is lower. Similarly, the reduced device is more practical because the plastic is lighter. Furthermore, if a further structural analysis showed removing the material didn’t reduce the device’s lifetime then this device would be ideal for a manufacturer. This is because of the lower cost and EI.

Material still has the overall largest impact on the environment. Even with the reductions, the gap between the material impact and the impact of the other stages is significant. This agrees with the results obtained by López-Muñoz et al. [58] who suggest the initial production is the highest impactor for endoscopic devices [58]. On the other hand, a study conducted on IPC Sleeves shows that in the life cycle of the reusable version, the primary manufacture is one of the lower contributors. This is likely due to the materials that these sleeves are made of as they are not made with any metals with the main component being non-woven polyester [68].

## 5.Combing Sustainable Design Solutions

### 5.1 Introduction

This chapter discusses the next design change which incorporates the principles of reusability and reducibility, being constructed entirely of metal whilst minimising as much of the metal material the device is made from. Both SS and Ti have been brought forward for testing to examine whether a slightly heavier device made of SS or a Ti model is better for the environment. For the reducibility aspect, all the material removal designs has been brought forward.

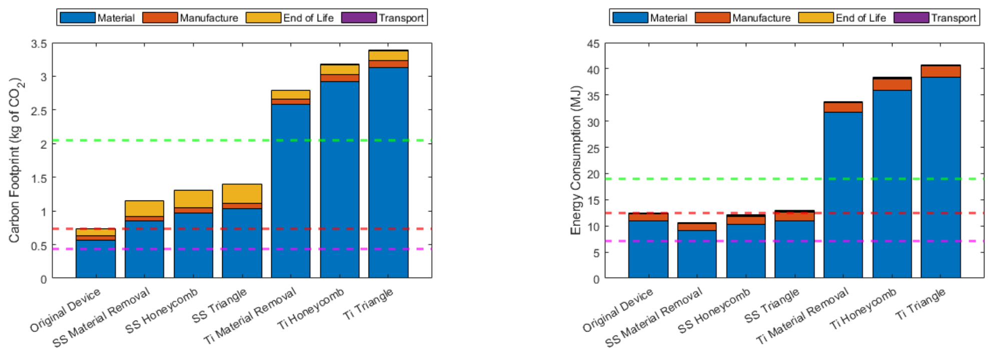
This change means the device has more structural stability because of the higher strength of metals. However, a shell thickness of only 1mm suggests the metal is still likely to wear and crack because of the intense decontamination process and repetitive use. Moreover, any impurities from manufacturing such as cracks will have more of an effect because of the thin surface. Therefore, the two infill patterns used have also been added to the metal device to determine the EI from the infill.

### 5.2 LCA Parameters

The inputs for this LCA are identical to the parameters used for the first design change because the changes made here are of the device rather than the life cycle. It does have an increased ”built to last” time as making the device from metal causes a significant lifetime extension. For all details of the entered parameters please see Table E.3

Following the LCA for the design change a separate LCA has been performed for each manufacturing method SW provides for SS. The important parameter used in this analysis is the manufacturing data. The region is Europe because changing this could result in different values depending on where the energy comes from. For example, the USA may use more energy from less renewable sources compared to Europe. All the other inputs related to manufacture, have been set to the default.

### 5.3 Results




*(a) Carbon Footprint* *(b) Energy Consumption*

*Figure 5.1: Shows the Carbon Footprint and Energy consumption for each of the different stages of life of the reusable, material removal design change devices compared with the initial device. The pink line shows the results of the previous ”Material Removal” design which had the lowest impact per device. The green line shows the results of the device which was best per use.*

A similar figure to Figure 4.3 can be created for this device. It shows the masses of each of the individual components however the trends are the same as the trends for the reusable and reduced devices individually. This graph is shown in Figure F.2. The main differences between these components are with the handles as the infill geometry is only added to the handles.

Overall, there is a mass reduction of 44% for the total mass of the device which can be seen in Figure 5.2 which shows a comparison of all the mass results together. By using this graph and Figure 5.1 it is possible to see which device is best for the environment per use and per device.

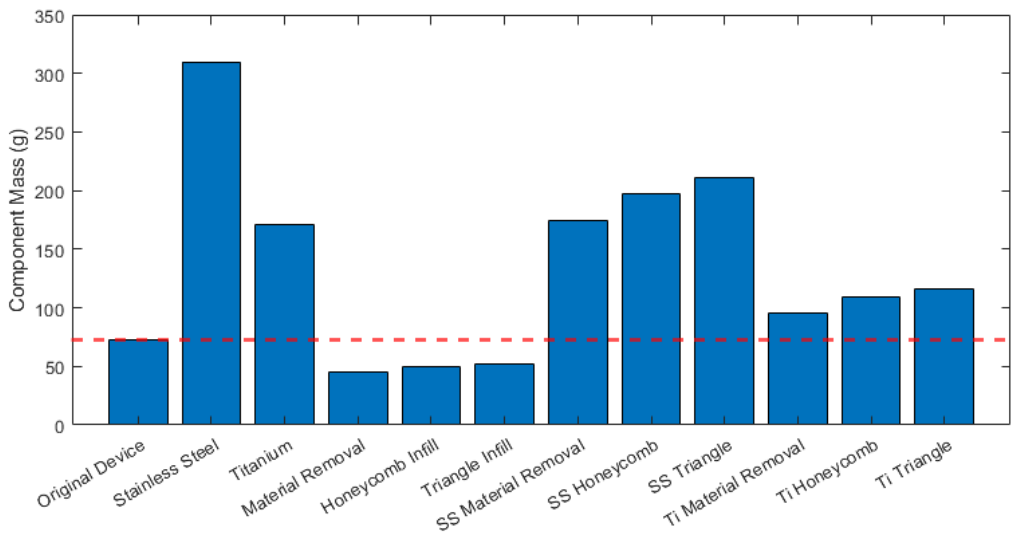



*Figure 5.2: A comparison of the weights between all of the devices that have been created in this project.*

### 5.4 Discussion

By making the change from plastic to metal once again the device's lifetime increases. By making this change the same trend has been experienced as with the initial design change. For each device, using Ti increases the EI of the material by over three times for both carbon footprint and energy consumption. This is likely due to the extraction method and location of these materials. As the harder it is to extract the raw materials from the ground the more carbon is released and energy is used. This increase can be explained by the cost increase in processing of the initial raw materials.

The EI of manufacturing has also increased, similar to the first design change. Using Ti, however, has a positive effect on the EI of the product's transportation. Resulting in a lighter payload so less fuel is used. This could especially be magnified if lots of these devices were transported simultaneously as 100 SS devices would weigh significantly more than 100 Ti devices, but they would both occupy the same space. Alternatively, the lower impact could be due to the distance the Ti has to travel to reach its manufacturing location. The closest source of this grade of SS may be much further away than the Ti. It may be a combination of these that causes a lower carbon footprint in transportation.

When considering only the changes made to the geometry, the design changes follow the same trend as hollowing out the plastic device. The hollow device had the lowest EI and the triangle infill had the highest. The changes to the geometry caused an increase in all the life cycle stages. However, this increase was only small with only 0.244 kg of extra $CO_2$ being released changing from the hollow device to the triangular device when created from SS. This suggests that adding an infill to the device will not increase the EI significantly so if the infill were to increase the lifetime of the device then it would be beneficial to do. This is the same as with the plastic components.

By comparing the new devices with the original device, it can be shown that the "SS Material

Removal” device only needs to be used for just over one and a half lifetimes of the original device. Similarly, the other two SS devices need to be used for just over one and a half lifetimes. They do need to be used for longer. However, not significantly longer therefore suggesting that adding the infills would be beneficial to the product.

On the other hand, the ”Ti Material Removal” device will need to be used for just under four lifetimes and the infill designs will need to be used for over 4 lifetimes. The difference between these devices is more significant than the SS devices. This was expected as Ti was found to be worse for the environment in the initial study.

By comparing this with the metal devices with no material removal there is a decrease in the length of time the devices need to last. This is the case for all of the SS and Ti devices. This was also the case when the PPS was removed suggesting that removing material is always beneficial to the environment.

It is possible to determine the difference between each device per use of the device. Figure G.1 shows the carbon footprint of the devices when compared per use of the device. The lifetime of the metal devices has just been set to 10 times the lifetime of the plastic devices for this graph. It shows that making the device reusable has one of the largest effects on the EI of all the devices. This can be seen by the magnitude of all of the bars, as they have decreased significantly from the original carbon footprint values. It can also be shown that the metal devices if used for 10 lifetimes of the original device, become much better for the environment and that the best device is the SS device with the material removed.

Thinking about the weight of the new metal devices, when compared directly to the plastic devices the weight increases. But by removing the material the weight of the metal devices is lower than the first design change devices. The original SS device weighed 309.88 g whereas the ”SS Material Removal” device weighed only 173.94. This is only slightly more than the weight of the original Ti device. Due to the significant weight decrease and the fact that this device has the lowest EI of all the devices per use, this may be the best design change to take forward.

Before suggesting the hollow SS device to be the best there is one further thing to consider. Whether or not making the device from SS will enable it to last forever. As the metal of the handles is so thin slight imperfections would likely cause critical failure. This is why considering an infill is still important here. Adding the infill to the SS device, however, increases the EI and weight. The honeycomb pattern adds 25g back to the total weight. This is quite a significant increase for the surgeons especially with a weight of already 100g more than the original.

This is why it is important to consider the Ti material even though it has a higher EI. With the infill pattern added the Ti device will need to be used for longer than the SS to be better for the environment. Nevertheless, the Ti device has a much lower weight than the SS device. If an infill is required then going with a Ti device would be beneficial for the surgeons using the device. The main consideration then is whether or not using Ti over SS can be done on the scale required for the industry and the cost of using Ti over SS as it is much more expensive. This will involve the manufacturing methods that are available to create the parts and the EI that they will have.

## 5.5 Manufacture Analysis

When it comes to the manufacture of the plastic device with the reduced material, due to some of the parts becoming hollow, manufacturing can become more challenging. Injection moulding the component as a single part is not possible. It would be possible to create a multi-piece assembly that the part is then made up from but this would result in a join in the handle which could create a weakness meaning the handle won't last as long. Overall, the change would result a higher EI. Ideally, the part would want to be manufactured as a single piece.

Testing the EI within SW was not possible as there are only two options for manufacturing PPS. It is also stated by Rizan et al. that their study used injection moulding as the manufacturing method for these plastics [48]. As the plastics in the analysis conducted for each of the studies are manufactured through injection moulding, the manufacturing carbon will have some errors as injection moulding may not be the best use or even a practical one.

An alternative method could be blow moulding but this would require an external hole in the plastic so the molten plastic tube inside the mould can be blown up to push the material to the outer wall. This would mean that the part is not completely sealed, which again affects the structural stability. Another potential issue is the challenge of decontaminating the inside of the part through such a small opening.

Another alternative way of manufacturing this part is 3D printing. While injection moulding tends to be used for mass production, 3D printing is used for more complex parts and both techniques are two of the most important polymer manufacturing techniques [69]. 3D printing would enable the device to be made with a high accuracy percentage [70]. This is beneficial as errors will occur infrequently. 3D printing will also enable more flexibility in the manufacture. So the infill can be created to different specifications for each design depending on whether the handle is being used for scissors or a grasper. This is beneficial as the two devices may require more or less pressure during use so the structural support will be present as needed. This will also allow the manufacturer to save material when creating some of the devices.

A disadvantage of 3D printing this model is the possibility of requiring supports. This will use more material than required for the device, so this method would be worse for the environment. If this plastic could be reused however and go back into the printer this would make 3D printing more sustainable. Injection moulding is also orders of magnitude faster than 3D printing [69], meaning large-scale manufacture may be difficult. Therefore, combining these two manufacturing methods may be more viable for achieving a high rate and complex product. This can be done by manufacturing the more complicated components by 3D printing and some of the unchanged components by injection moulding. Moreover, this would be beneficial as the time to print will increase by adding the infill. Comparing the two infill patterns in terms of manufacturing time, the triangular design will print much faster than the honeycomb design, because, with the honeycomb design, the printhead will have to keep moving and changing direction [62]. Therefore, even though the triangular pattern proved to have a higher EI it may be better for the manufacturer as it is faster to print.

Another consideration is the location of the manufacturer. In Europe 3D printing sourcing is not an issue compared to developing countries. This is due to the lack of access to these techniques on a mass scale. Devices would need to be transported longer distances, largely affecting the EI. Alternatively, a device that can be manufactured using other techniques may be required. If so the material extraction may be also more costly to the environment. In this situation making a reusable device may be more beneficial as the manufacture and transportation only has to happen once per device and then it can be used almost indefinitely. Similarly, a study conducted by Oturu et al. found that reusing the devices is more advantageous to a developing country due to the lower cost barrier of re-purposing single-use devices compared to buying larger medical equipment like scanners [71]. This suggests sending these devices to developing countries could be extremely beneficial to their healthcare and EI.

To measure the EI of the different manufacturing techniques, a manufacturing analysis on the metal right-handle component shown in Table 3.1 has been conducted. The manufacturing methods available in SW have been used, these can be seen in Table 5.1. This part has complex geometry that will likely require a different form of manufacture to milling, especially when it is hollowed out or infilled. Other parts will most likely require other forms of manufacture and it is noted that milling may be slower than casting when it comes to large-scale manufacture. However, due to the lack of available data on all manufacturing techniques, further analysis on components has not been considered. The lack of data arises mainly when changing to Ti. Within SW Sustainability there are only 3 options available for the manufacture of Ti; Milled, Forged and Turned. When it comes to creating some of the more complicated shapes these methods may not be suitable and so a different technique should be used. This is why the SS handle has been chosen. All of the other features of the analysis have been left the same. It is still manufactured within Europe and the SS material and model has been kept the same.

*Table 5.1: Manufacturing Methods analysis shows the effect of using different manufacturing methods. This table shows the data for a SS handle. It also states whether the method is appropriate to fabricate the SS handle.*

| Manufacturing Method | Carbon Footprint (kg of $CO_2$) | Energy Consumption (MJ) | Scrap Rate | Appropriate |
|---|---|---|---|---|
| Milled | 0.040 | 0.754 | 10% | Yes |
| Die Casted | 0.196 | 3.6 | 10% | Yes |
| Extrusion | 0.016 | 0.281 | 5.5% | No |
| Forged | 0.034 | 0.641 | 0% | No |
| Machined Sand Casting | 0.231 | 4.3 | 21% | No |
| Sand Casted | 0.196 | 3.6 | 10% | No |
| Sheetmetal | 0.017 | 0.295 | 4.54% | No |
| Stamped Sheetmetal | 0.021 | 0.370 | 9.67% | No |
| Turned | 0.052 | 0.984 | 10% | Yes |

The results of the study are portrayed in Table 5.1. The results show that milling is one of the better techniques for manufacturing the part in terms of the EI. It is not the best technique, the best technique would be Extrusion or Sheet metal. However, these methods aren't appropriate methods to create such a complex shape, such as the the handle.

Table 5.1 also shows that a method like die casting is more appropriate, especially on a large scale. However, there is a large increase in carbon footprint from the initial manufacturing method of milled. This means the EI of the device would be increased if it was created by die casting. This means that if the devices are being created on a large scale the EI will be higher than if they are created by a method like milling which is slower. For the SS device, as it is made to last forever, this smaller increase in impact at this stage of life should only have a small effect per use as the duration of use is very long. On the other hand, it may not be required to have a quick assembly line as the device will last a long time therefore, it is not as important as it is with the current device to keep reproducing the plastic devices as once the metal device is in circulation it should remain in circulation. Consideration of adding the devices to the economy will be required as they cannot just be reused they must be decontaminated between uses. Because of this several devices will need to be in circulation so die casting may be an appropriate initial set-up method.

The final consideration for metal manufacturing is the complexity of manufacturing the in-fill and the hollow parts. Making these complicated shapes is challenging through all of the techniques offered by SW. A more appropriate method type again would be 3D printing. Using this method is more suitable for the handle component. One example of 3D printing metals is Wire and Arc Additive Manufacturing (WAAM) which when compared to CNC milling and casting showed a promising decrease in environmental impacts [72]. This technique has also been used for 3D printing pure Ti for the medical industry [73]. Therefore, this may be the best method to use for the manufacture of some of the more complicated components.

### 5.6 Business Model

One of the major challenges for companies selling a device that is designed to last forever is the lack of incentive to keep buying. Once a client has enough of these devices, there is no reason for them to buy more, provided the product has no issues. Even though creating a device that lasts forever is a very circular economy approach to design, once the device is in circulation it should never need to be replaced, so the manufacturers will be discouraged from producing and selling this product as it will not make them profits in the long term.

Inevitably some of the components become damaged, the device shouldn't be used at this point. Using a damaged device for surgery could result in serious complications for the patient. So these devices must be replaced when this happens. Clients will also want the product to be replaced if future research improves the device. After this, the clients would want to invest in the new devices. With this in mind, traditional merchandising may not be suitable for this product. It may be more suitable to take another approach and start selling a service. This is also known as servicisation [74]. This way the manufacturer could offer a subscription service stating if anything goes wrong with the device, the device or the failed component will be replaced. Similarly, there would be an agreement that when innovations are made, the old devices will be replaced with the new ones.

This may also be a good business technique for the laparoscopic scissor as a whole and not just for the reusable handle. Clients could pay a subscription and get a delivery of single-use devices as well as an agreement that any failing reusable devices will be replaced. Ultimately, the goal would be to reduce this single-use component and make the laparoscopic scissor entirely reusable, offering to replace broken devices or parts would benefit the manufacturer.

The benefit of this business model would be more effective if the device was made more modular. This entails the individual components of the device to be able to be removed and replaced. For example, a clip could be developed to attach the handles, this would mean that only the handles need to be replaced. If research into a more modular device was conducted the benefits of this could be quantified.

## 6.Conclusion

### 6.1 Achievements

This project combined LCA and eco-design to investigate and improve the EI of the Laparoscopic scissor medical device. A 3D CAD model was created on SW to represent the current laparoscopic scissor. Then using a previous paper, conducting an LCA on laparoscopic scissors, the CAD model and SW Sustainability software were successfully validated. Next by taking the results of the initial LCA changes were made to the CAD model, in problematic areas, which could be representative of physical changes manufacturers could make. Further LCA study was performed on these devices to determine which has the best effect on the device's EIs.

### 6.2 Discussion

First, it was found the key design principles of a circular economy are to reuse a product as many times as possible, remove as much material from the product as possible and at the product's end of life make sure the materials are recycled [21]. These principles can be applied to the design of all products, the focus of this project is on medical devices, more specifically, laparoscopic scissors. It is important to reduce the EI of this area because laparoscopy is a popular surgery and disposable items are one of the largest contributors to the EI of surgery [15]. It was also found that a life cycle analysis is effective in measuring the EI of the device.

Next SW and the Sustainability Add-in were used to create a CAD model of the laparoscopic scissor. Using a previous paper [48] the LCA software was validated and found to be highly accurate. It was also determined the single-use scissor was much worse for the environment than the reusable handle per use. Rizan et al. [48] and López-Muñoz et al. [58] found this to be the case as well. This is because the handle could be used 500 times whereas the scissor only has one use before disposal. As the focus of this project is on a cradle-to-gate analysis the handle was taken forward to try and reduce the EI as the impact of material and manufacture was higher.

Next, it was found that by changing the plastic material of the handle to metal, the lifetime of the device would extend. Consequently, the device's EI per use decreased. However, the impact of one device increased. Two metals were tested: Stainless Steel and Titanium. Titanium was much worse for the environment but it was also significantly lighter than the SS. Weight is an important characteristic of measure for these devices as the weight should be manageable, so the precision is not lost during surgery. When this change was compared to a material reduction design change it was found that per use of the device, a reusable device was better. Material removal still benefited the environment as expected. An important thing to note from this finding is if the components lose some structural integrity and so the lifetime is reduced, this change can be worse for the environment. To maintain the strength an infill pattern was used. This meant less material was removed but the device'slifetime remained the same. It was found this was also beneficial for the environment. Another study on similar surgical scissors showed material removal was the best technique to improve the EI [20]. This study however, did not consider the reusability as a change so it would be expected that this would have a greater impact.

Both of the designs were taken forward and the effect of the combined changes was explored. As expected, combining the new designs significantly reduced the environmental impact, especially compared to the initial metal devices. Similarly, the masses of all of the devices were reduced and a SS device became more realistic with a reduction similar to the initial weight of the Ti device.

Lots of the limitations of this project lie in the SW Software. First making the CAD model was limited by information on the product. There was only material masses and a physical model that could be used to create the representative model. The information that was entered into the SW Sustainability software was also limited to the LCA performed in one paper [48]. Lots of information like manufacturing method, percentage of recycled material used, and scrap rate of the manufacturing technique were not available. A main difficulty was interpreting and understanding the Sustainability Add-ins user interface. It didn't always show the correct values that the calculations were being performed with. Another interesting observation is that when the "Duration of Use" is increased the EI related to transportation appear continuously increased. This is not be expected as the part is still travelling the same distance to reach its use location and further transportation of the product is not being specified in its lifetime, so for the analysis, the transportation of 500 days was used to enable comparison between the results.

This study was also limited to the energy consumption and carbon footprint outputs, as this aligns with the NHS' goal to reach net zero carbon [5]. However, Keil et al. discuss that changing from single-use to reusable devices can have negative impacts on water use [75]. This shows the importance of considering all factors when implementing changes to reduce one environmental impact.

### 6.3 Conclusions

Two different eco-design techniques have been tested here: making the device reusable and removing as much material as possible. Using the techniques three different design changes were created. Having a reusable SS device made from minimal material was found to have the greatest improvement in EI per use of the device. By changing to metals, the device was estimated to last forever. This significantly improved the EI per use of the device. However, one of the negatives of creating the device from metal is the weight increase shown in Figure 5.2. Weight is a key factor for using the laparoscopic scissor as surgeons hold this device for up to an hour at a time. In terms of weight, the next most sustainable device would be the Titanium device made from minimal material as this is much lighter.

Although the metal devices were better for the environment, one of the important things missing from these LCAs is the decontamination of the device. This is a vital process so should be considered. Even more so decontamination is one of the major carbon contributors in the life of this device [48].

After selecting a suitable device it is important to consider the fabrication of this device. Especially when it is going to be made from metals. Different methods have been discussed for the different devices. The best method for the environment was milling, however this LCA was limited to the manufacturing methods that SW offered.

Given the wide use of laparoscopic surgery, optimising laparoscopic instruments and by re-designing single-use devices the environmental impact of the device can be significantly improved. This study focuses on just one particular device that is used in laparoscopic surgery. Several other areas of the surgery could be considered, such as other equipment, any PPE that has to be used as well as the energy that has to go to the surgical room. This study has shown that the application of the design principles across one instrument has improved the EI substantially. The application of all the different instruments used throughout the NHS would also improve their carbon output aiding them on the way to a net zero carbon. Furthermore, although this paper focuses on eco-design for the medical industry it has wider applications over multiple industries. Future research can be conducted with a focus on different industries such as the automotive industry which also have a goal to improve their EI.

### 6.4 Future Work

With more time it would be beneficial to further test the effects of the most optimal designs from this study. For example, testing the hollow device as it was best for carbon footprint. Using more "high-fidelity" software or exporting the data from SW using the GaBi export option and the GaBi software to further examine the EI that the device will have. Using a specially designed LCA software will provide more information on the carbon footprint as well as on other factors such as cost. This is important as cost is vital to manufacturers, then determining if a Ti product is more viable than a SS one will be possible. A different LCA software like SimaPro will also enable more inputs for the analysis to be computed. This, combined with more time to find more information about the end of life, packaging, and decontamination will allow an accurate and detailed analysis of the device's EI. Another benefit of using more accurate software is to fully analyse different manufacturing techniques. First of all to determine the most cost-effective and the least environmentally impactful technique for the different components of the device. The different materials can also be compared directly against each other to determine if it is better to use different manufacturing techniques for different materials.

Further research that could be performed on the designs themselves is trying different optimisations of the infill patterns. Performing a trade-off study between structural stability compared to EI using potentially some form of Finite Element Analysis or physical analysis by manufacturing the model. The models that have been created for this project will also be able to be used for this FEA analysis. Completing this trade-off study will determine which infill pattern allows the device to have the longest lifecycle and the lowest carbon footprint. It may also suggest no infill pattern is required at all. Further study can also be conducted on the different infill percentages and the effect these will have on structure and EI.

As well as optimising the infill, further study on the alternative plastics such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) [76] could be conducted. With these materials it would be worth testing the EI as even a simple change like this could have a large effect. Even a combination of these plastics for different components. The same idea could be incorporated into the metal. The smaller lighter components could be made from SS to reduce EI and cost whereas the larger components from Ti to keep the weight of the produce as low as possible. One of the main findings from studies combining LCA with eco-design is that biopolymers generally improve the EI. However, it is important to assess the impacts resulting from the use of agricultural products such as long transportation distances [60].

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## A.Entire System Boundary

Figures A.2 & A.1 show the full detailed system boundary for the life cycle of the laparoscopic scissor device. Even in this diagram, there are areas of the product's life that are missing such as storage, for example, if a product needed to be kept cool running the refrigerator would be incorporated. However, since this device is packaged it can be left in a warehouse for storage and so this will have a minimal on the overall results of the life of the product.

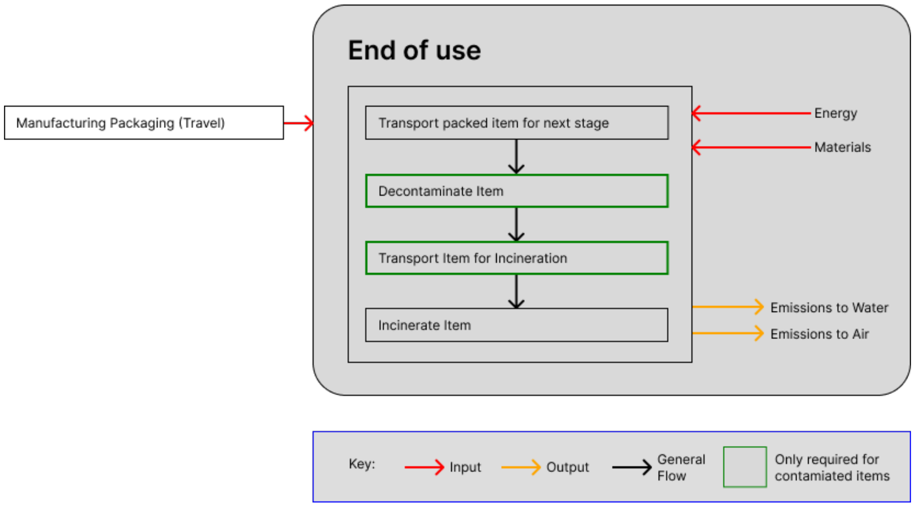



*Figure A.1: Shows the system boundary for the end of life of laparoscopic scissor components and other components such as packaging if required.*

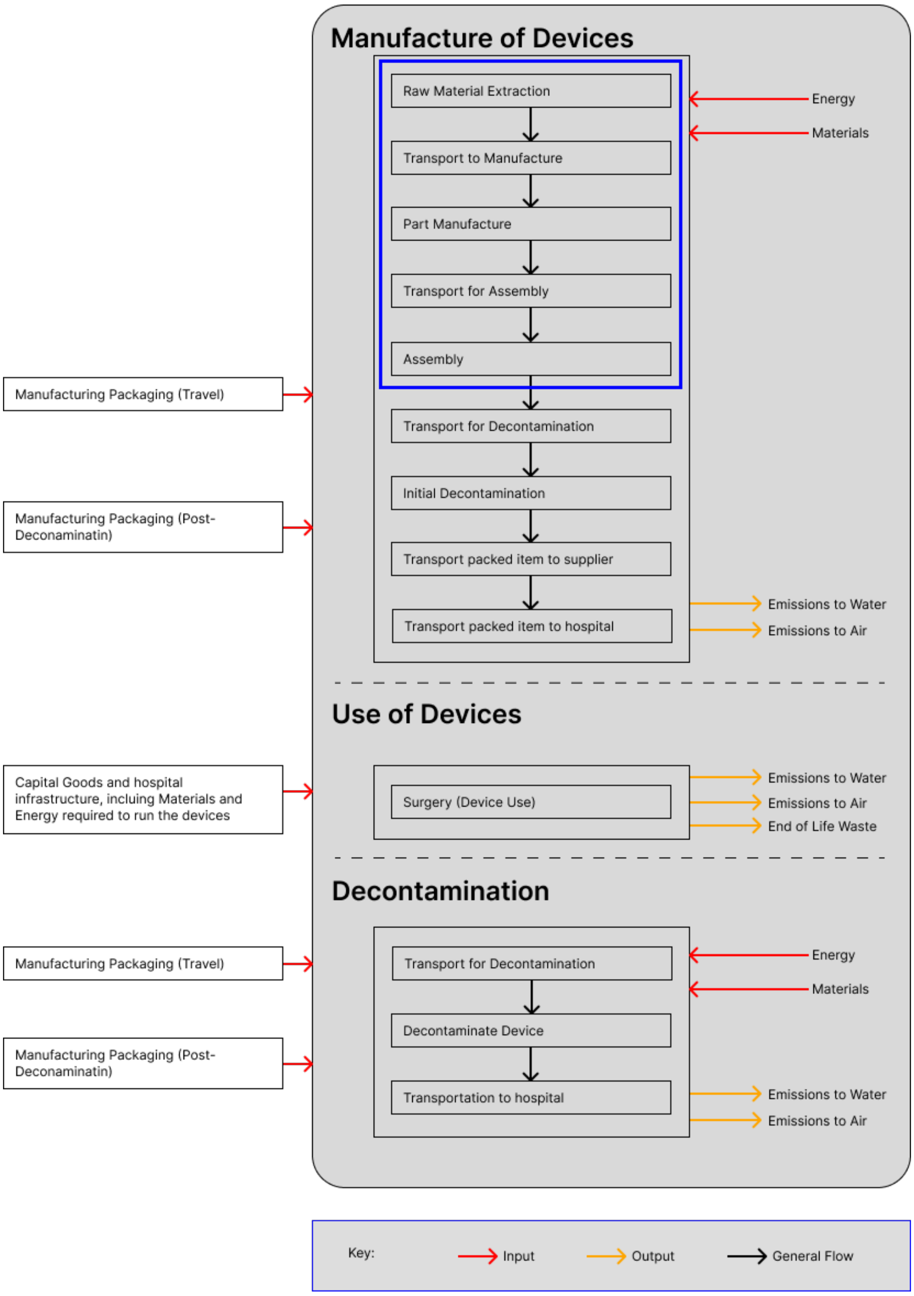



*Figure A.2: Shows the system boundary for the life cycle of laparoscopic scissor components with the blue square being considered in this analysis.*

## B.Handle Images

This appendix contains four different views of the reusable handle that has been used as the baseline to make the SW Model. They are labelled with each of the parts that have been made in SW. The features of the parts can be seen in the Bill of Material in Table 3.1, where the labels correspond to the part number.

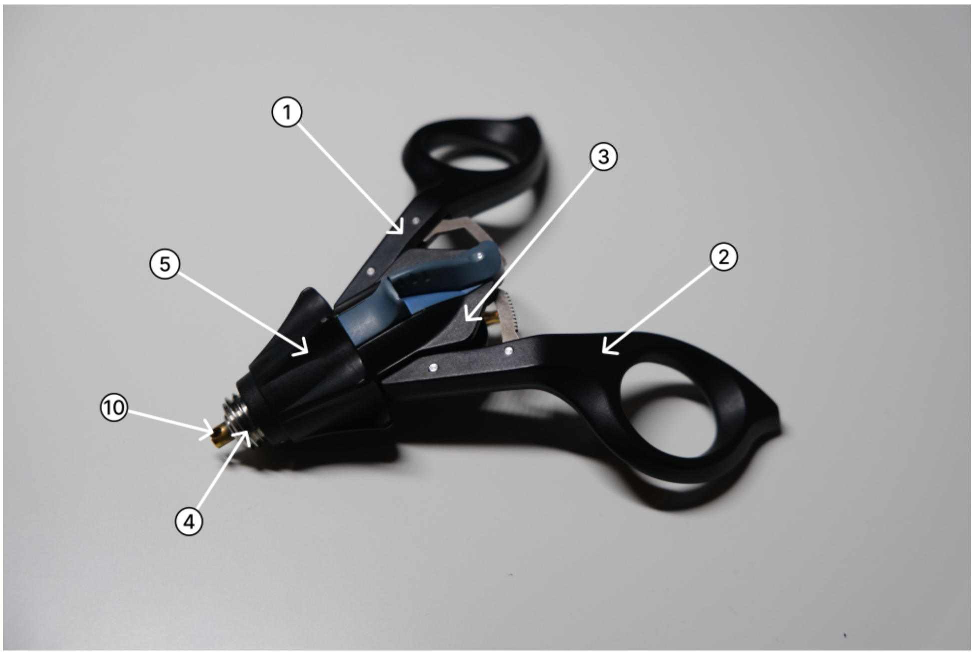



*Figure B.1: Isometric View*

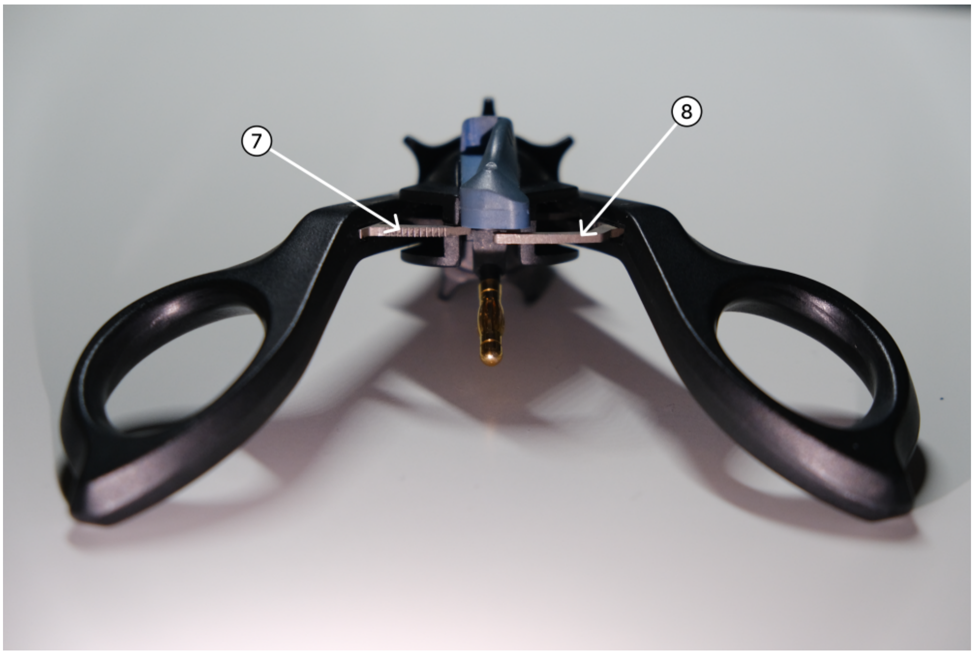



*Figure B.2: Back View*

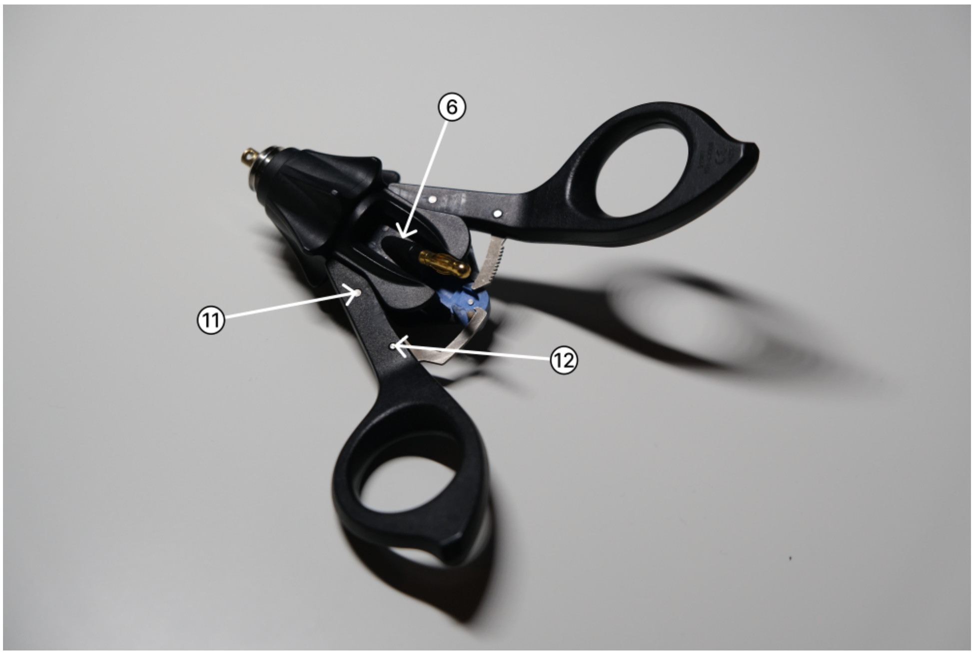



*Figure B.3: Underside View*

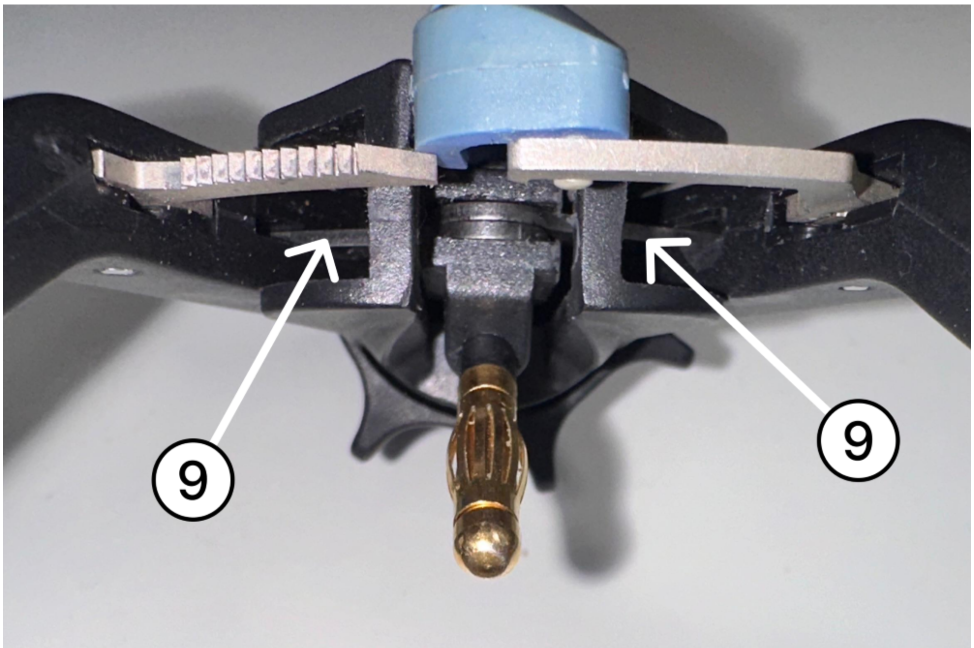



*Figure B.4: Underside Zoom View*

## C.Scissor Creation


*Figure C.1: A top view of the two main sections to the Scissor attachment. It is labelled with each of the parts that have been made in SOLIDWORKS. The features of the parts can be seen in the Bill of Material in Table 3.1*

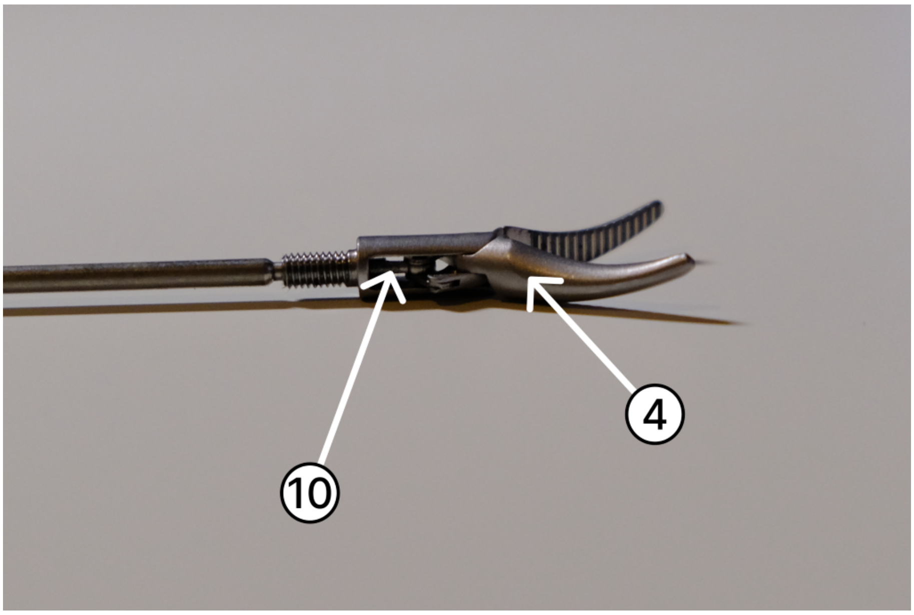



*Figure C.2: A close-up view of the head of the grasper used to create the linkage for the scissor. It is labelled with each of the parts that have been made in SOLIDWORKS. The features of the parts can be seen in the Bill of Material in Table 3.1*

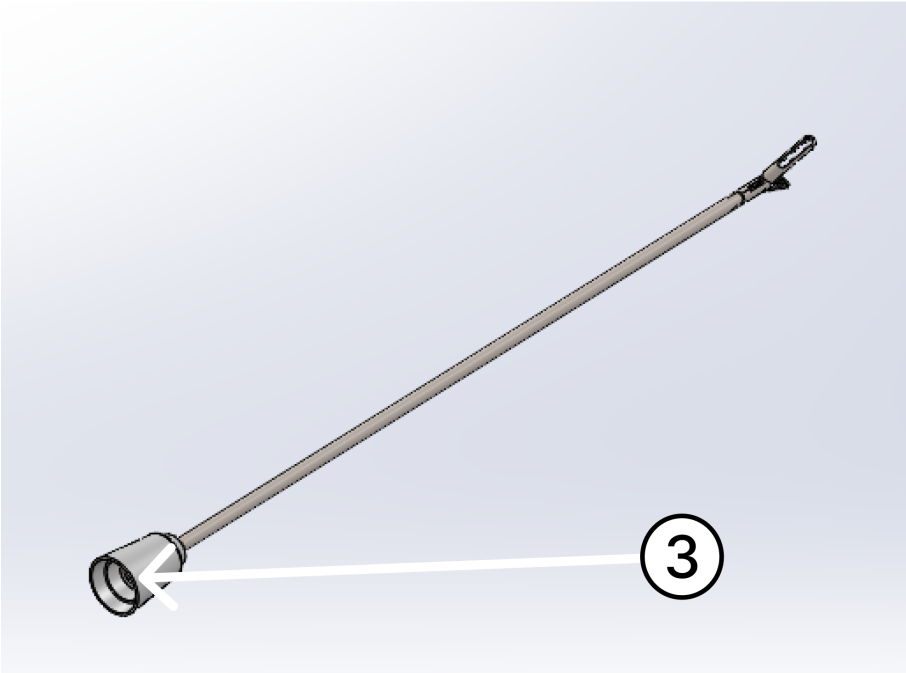



*Figure C.3: An isometric view of the scissor in SOLIDWORKS containing the scissor cap. It is labelled with each of the parts that have been made in SOLIDWORKS. The features of the parts can be seen in the Bill of Material in Table 3.1*

*Table C.1: A Bill of Materials for the Scissor showing each of the parts labelled in Figures C.1,C.2, C.3 & C.4 and the materials and mass' of each part according to SOLIDWORKS*

| Part Number | Part Name | Quantity | Material | Mass per unit (g) |
|---|---|---|---|---|
| 1 | Shaft | 1 | SS | 7.36 |
| 2 | Shaft Cover | 1 | Al | 12.14 |
| 3 | Screw Cover | 1 | PPS | 4.51 |
| 4 | Scissor Blade | 2 | SS | 0.58 |
| 5 | Central Pin | 1 | SS | 0.03 |
| 6 | Holder Pin | 2 | SS | 0.005 |
| 7 | Moving Pin | 1 | SS | 0.02 |
| 8 | Central Holder | 1 | SS | 1.46 |
| 9 | Linkage | 2 | SS | 0.05 |
| 10 | Pusher | 1 | SS | 0.18 |
| 11 | Stem | 1 | SS | 0.48 |
| | Total | 13 | — | 27.45 |

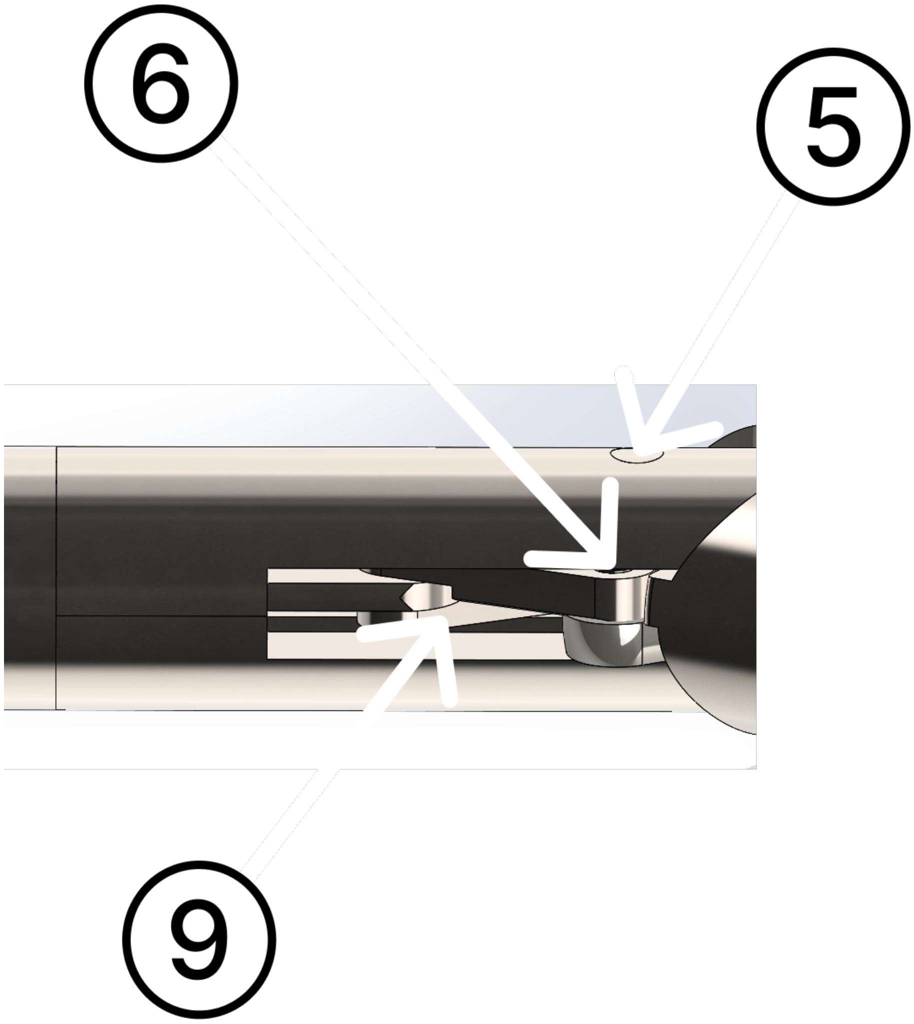
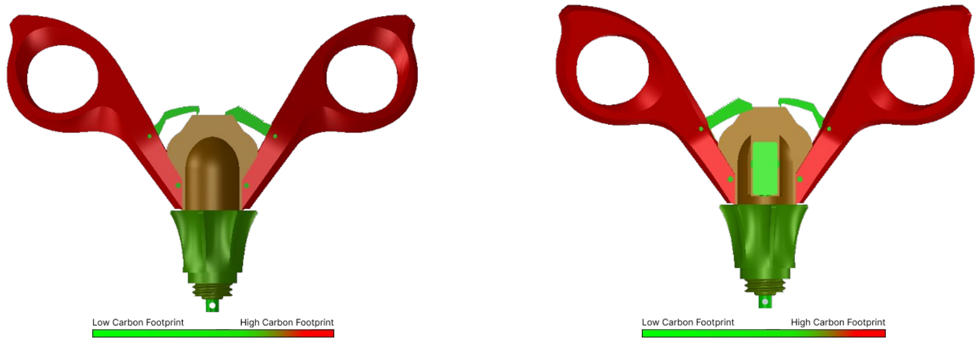



*Figure C.4: A zoomed-in section of the centre linkage of the scissor. It is labelled with each of the parts that have been made in SOLIDWORKS. The features of the parts can be seen in the Bill of Material in Table 3.1*

## D.SOLIDWORKS Visualisation




(a) Top view

(b) Bottom View

*Figure D.1: SOLIDWORKS Model in visualisation mode, showing which parts have the largest carbon footprint across their life cycle.*

## E.LCA Parameters

*Table E.1: Parameters specified for each of the different materials for the laparoscopic scissor [48].*

| | LCA Parameter | Handle | Shaft with Blades |
|---|---|---|---|
| **Materials** | Materials | PPS, SS | PPS, SS, Al |
| **Manufacture Process** | Region | Europe | Europe |
| | Process | IM, Milled | IM, Milled |
| **Assembly Process** | Region | Europe | Europe |
| | Built to last | 500 Days | 1 Day |
| | Fuel | False | False |
| **Transportation** | Truck | 80km | 80km |
| **Use** | Use Region | Europe | Europe |
| | Energy Needed | False | False |
| **End of Life** | Incinerated | 100% | 100% |

*Table E.2: Parameters specified for each of the different life cycle stages, of both the reusable design and the reduced devices for the reusable handle [48].*

| | LCA Parameter | Reusable Design | Reduced Design |
|---|---|---|---|
| **Materials** | Materials | SS/Ti | PPS, SS |
| **Manufacture Process** | Region | Europe | Europe |
| | Process | Milled | IM, Milled |
| **Assembly Process** | Region | Europe | Europe |
| | Built to last | 1000 Years | 500 Days/250 Days |
| | Fuel | False | False |
| **Transportation** | Truck | 80km | 80km |
| **Use** | Use Region | Europe | Europe |
| | Energy Needed | False | False |
| **End of Life** | Incinerated | 100% | 100% |

*Table E.3: Parameters specified for each of the different life cycle stages, of both the reusable design and the reduced devices for the reusable handle [48].*

| | LCA Parameter | Reusable Reduced Design |
|---|---|---|
| **Materials** | Materials | SS/Ti |
| **Manufacture Process** | Region | Europe |
| | Process | Milled |
| **Assembly Process** | Region | Europe |
| | Built to last | 1000 Years |
| | Fuel | False |
| **Transportation** | Truck | 80km |
| **Use** | Use Region | Europe |
| | Energy Needed | False |
| **End of Life** | Incinerated | 100% |

## F.Reusable and reduced Component Masses

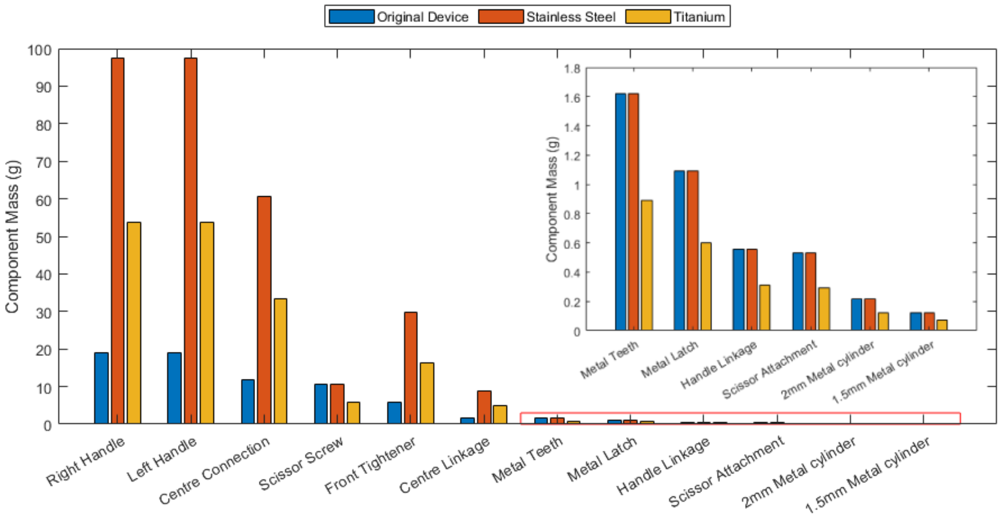



*Figure F.1: Shows the mass of all components of the reusable handle device for each of the reusable design changes.*

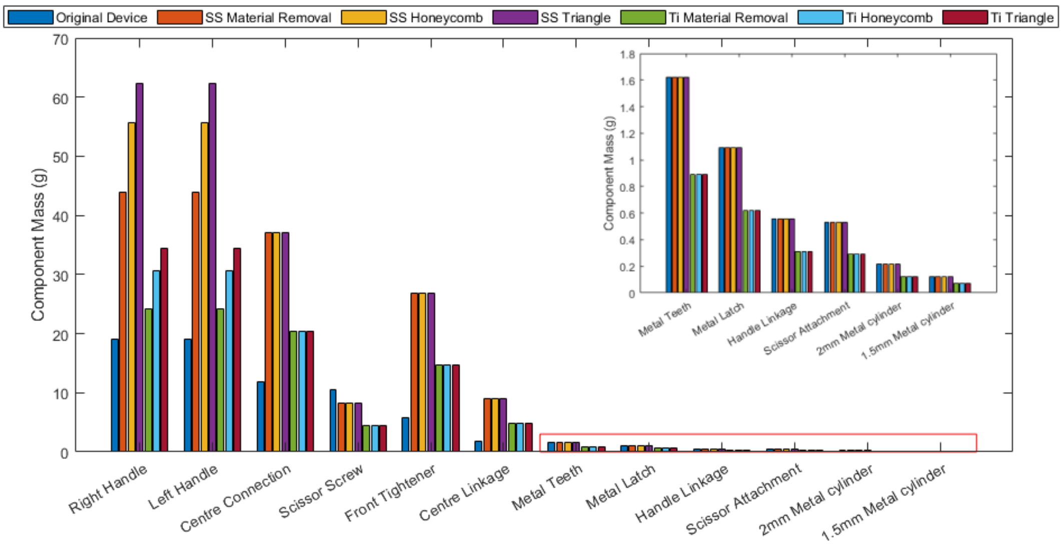



*Figure F.2: Shows the mass of all the parts of the reusable handle device and for each of the reusable, material removal design change.*

## G.Results Per Use

This appendix contains the data when the devices are compared against each other per use of the device. It has been assumed for this graph that all of the metal devices last 10 times longer than the original device.

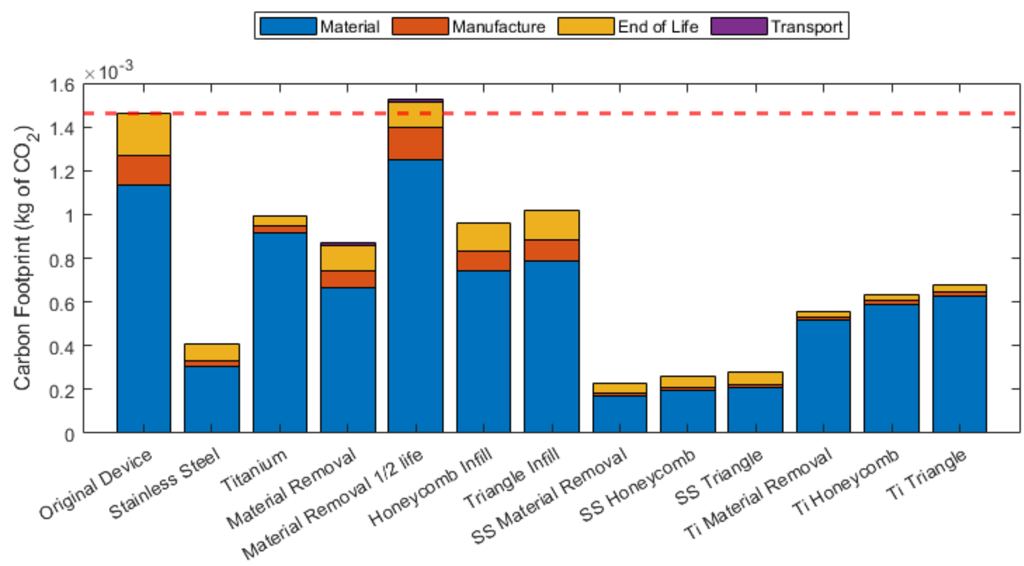



*Figure G.1: All of the tested devices are compared against each other, showing the carbon footprint of each device per use.*

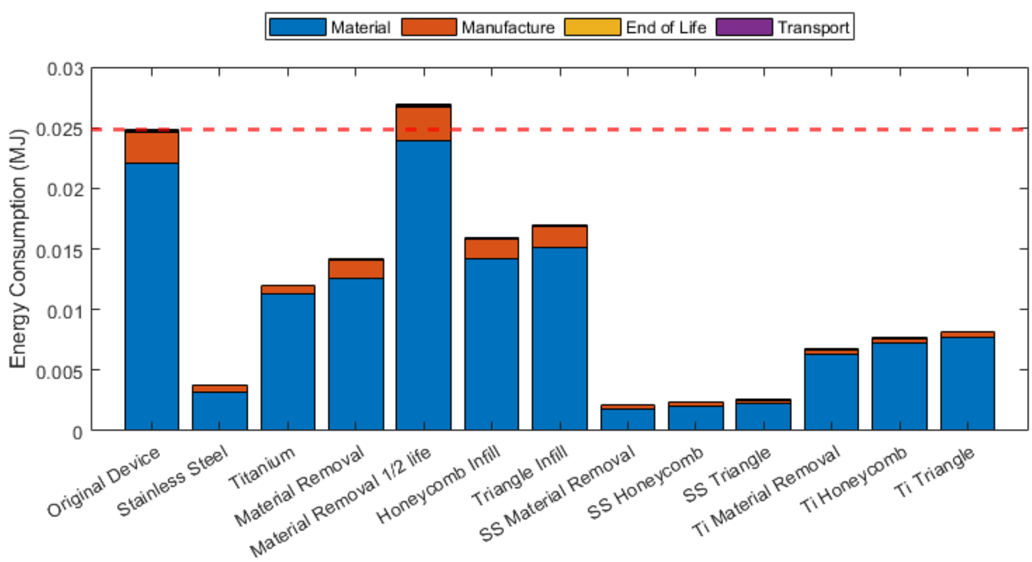



*Figure G.2: All of the tested devices are compared against each other, showing the energy consumption of each device per use.*