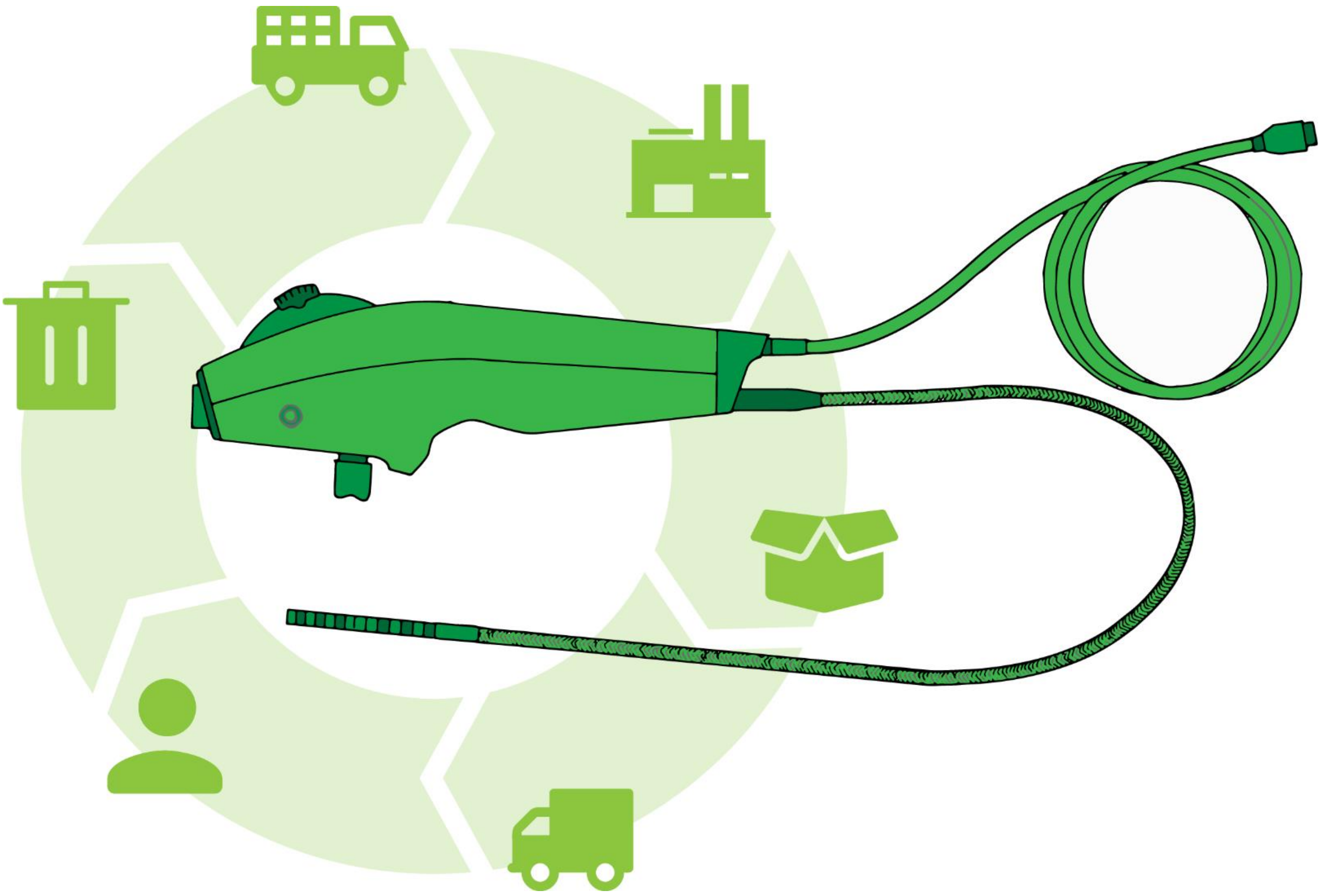
Sustainable device selection for flexible intubation scopes

Comparative environmental impact assessment of disposable and reusable flexible intubation scopes and concept design for sustainable flexible intubation scopes



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Contents

Preface

Dear reader,

Before you lies my thesis about the environmental sustainability of flexible intubation scopes, which is intended to enable development and data-driven selection of sustainable flexible intubation scopes. This thesis has been written to fulfill the graduation requirements of the master program of Biomedical Engineering at the Technical University of Delft. I started this research with enthusiasm for sustainable development of medical devices, although I had limited knowledge of life cycle assessments, and I am proud to present the final outcome.

This research was undertaken at the request of the Leiden University Medical Centre (LUMC), where I was welcomed at the Central Sterilization Department to gather data for my thesis.

I would like to thank my supervisors Anne van der Eijk, Arjo Loeve and Lauran van Oers for their excellent guidance and support throughout this process. There were a couple of obstacles throughout the process, such as working from home due to the corona crisis and the refusal of the manufacturers to participate in the study, but we always managed to find a solution. I want to express my gratitude towards Anne for always giving me good advice during our meetings. I would like to show my appreciation for Arjo, who challenged me by giving constructive and critical feedback. Also, I want to offer great thanks to Lauran for making time to guide me throughout the LCA process. Lastly, I would like to thank J.C. Diehl and J. Dankelman for participating in my graduation committee.

I also would like to thank my family and friends for their support, because they motivated me to keep on track and pursue my goals. We have had a rough couple of years, but this has taught us that you should always stay positive and seize every opportunity you get.

Enjoy your reading!

Kind regards,

Joyce Duijndam

Glossary [1, 2]

Abiotic resource: A natural resource (including energy resources) regarded as non-living, e.g. zinc ore, crude oil, wind energy.

***Acidification potential*:** Impact category for the measure of the decrease in pH-value of rainwater and fog, measured in sulphur dioxide equivalents (kg SO2-eq).

Allocation*:* Method for partitioning the input and/or output of multifunctional unit process to the product system studied.

Alternative *in LCA*: One of a set of product systems studies in a particular LCA (e.g. for comparison).

Background process *in LCA*: A system or process for which secondary data (e.g. databases, public references, estimated data based on input-output analysis) are used in an LCA.

Characterisation *in LCA*: A step of the Impact assessment, in which the environmental interventions assigned qualitatively to a particular impact category are quantified in terms of a common unit for that category.

Characterisation factor *in LCA*: Factor derived from a characterisation model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the impact category indicator.

Classification *in LCA*: A step of Impact assessment, in which environmental interventions are assigned to predefined impact categories on a purely qualitative basis.

Characterisation model *in LCA***:** Mathematical model of the impact of environmental interventions with respect to a particular category indicator.

Climate change: The warming effect of the earth's surface due to release of greenhouse gases into the atmosphere, measured in mass of carbon dioxide equivalents (kg CO2-eq).

Completeness check *in LCA*: A step of the interpretation phase of an LCA to verify whether information yielded by the preceding phases is adequate for drawing conclusions.

Comparative assertion *in LCA*: Environmental claim regarding the superiority or equivalence of one *alternative* of the LCA to a competing product system performing the same function.

Consistency check *in LCA*: A step of the interpretation phase of an LCA to verify whether assumptions, methods and data have been applied consistently throughout the study.

Contribution analysis *in LCA*: A step of the interpretation phase of an LCA to assess the contributions of individual life cycle stages, processes and indicator results to the total LCA result (as a percentage).

Economic flow: A flow of goods, materials, services, energy or waste from one unit process to another.

Elementary flow: Material or energy entering or leaving the product system that has been extracted from or discarded to the environment without previous human transformation.

Environmental impact: A consequence of an environmental intervention in the environment system, defined by the total impact score.

Eutrophication potential: Impact category for the measure of nutrient enrichment in aquatic or terrestrial environments, measured in mass of phosphate equivalents (kg PO4-eq).

Freshwater aquatic ecotoxicity: Impact category for the emissions of toxic substance to the air, water and solid on fresh water and ecosystems, measured in 1,4 dichlorobenzene (kg 1,4 DCB-eq).

Functional flow *in LCA*: The flows of a unit process in an LCA that constitute its goal as a good or waste.

Functional unit *in LCA:* The quantified function provided by the product system(s) studied, for use as a reference basis in an LCA.

Greenhouse gases: The emission into the earth's atmosphere of any of various gases (i.e. carbon dioxide) that contribute to the greenhouse effect.

Human toxicity**:** Impact category for the impact on humans as a results of emissions of toxic substances to air, water and soil, measured in 1,4 dichlorobenzene (kg 1,4 DCB-eq).

Impact assessment family: Group of specific characterisation factors and impact categories.

Impact category: Class representing environmental issue of concern.

Impact category indicator: Quantifiable representation of an impact category.

Indicator result: The numerical value of the characterisation step for a particular impact category.

Inventory analysis: The second phase of an LCA, in which the relevant inputs and outputs of the product system(s) studied throughout the life cycle are compiled and quantified.

Midpoint method: The midpoint method is a characterisation method that provides indicators for comparison of environmental interventions at a level of cause-effect chain between emissions.

Life cycle: The consecutive, interlinked stages of a product system, from raw materials acquisition or natural resource extraction through to final waste disposal.

Life cycle assessment (LCA)*:* Compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle.

Multifunctional process *in LCA*: A unit process yielding more than one functional flow (e.g. co-production, combined waste processing, recycling).

Normalisation: A step of the Impact assessment in which the indicator results are expressed relative to well defined reference information (e.g. for global interventions).

Photochemical oxidation**:** Impact category indicating ‘summer smog’ as the reaction of sunlight with emissions from fossil fuel combustion creating other chemical, measured kg ethylene-equivalents.

Product system *in LCA*: A set of unit processes in an LCA interlinked by material, energy, product, waste or service flows and performing one or more defined functions.

Reference flow *in LCA*: Quantified flow generally connected to the use phase of a product system and representing one way (i.e. by a specific product *alternative*) of obtaining the functional unit.

System boundary *in LCA*: The interface between a product system and the environment system or other product systems.

Stratospheric ozone depletion: Impact category for the measure of gaseous chemicals that react with and destroy stratospheric ozone, measured in mass of chlorofluoromethanes (kg CFC-11 eq).

Terrestrial ecotoxicity**:** Impact category for the effects of a chemical substance to terrestrial organisms and plants, measured in in 1,4 dichlorobenzene (kg 1,4 DCB-eq).

Unit process *in LCA*: The smallest portion of a product system for which data is collected in an LCA.

Abstract

Medical device selection is currently based on criteria including clinical performance, usability, safety and procurement costs. Growing awareness of the negative contribution of the healthcare sector to the total greenhouse gas (GHG) emissions demands environmental sustainability to be taken into account as well. Reusable and disposable flexible intubation scopes are of current interest to anesthesiologists because disposables are often utilized due to their presumed superior sterility, cheaper purchasing price and convenience. Knowledge about the life cycle environmental impact of flexible intubation scopes is limited, so research is required to aid in sustainable device selection. Therefore, the goal of this study is to compare the environmental impact of disposable and reusable flexible intubation scopes and design a sustainable concept to enable data-driven selection of sustainable flexible intubation scopes. A cradle-to-grave comparative life cycle assessment (LCA) was made to quantify the environmental impact of reusable fiberoptic bronchoscopes (FOB) and disposable flexible video endoscopes (FVS) at 450 patient intubations. The largest contributors to the life cycle impact of the flexible intubation scopes were identified and used to generate a sustainable concept. The LCA results suggest that the reusable FOB has a lower life cycle impact in comparison to the disposable FVS, so selecting a reusable FOB is preferable from environmental perspective. Most life cycle emissions of the disposable FVS are caused by the material production of the device and manufacturing of the printed circuit board, while the disinfection process contributes most to the life cycle of the reusable FOB. The final concept of the sustainable flexible intubation scope contains plastic optical fibers and a thicker sleeve around the bending section of the insertion tube to make the device more durable and thus extend its lifetime. In order to minimize the environmental impact of flexible intubation scopes, it is recommended to develop flexible intubation scopes with plastic optical fibers, select low-impact materials for the device and revise the products’ life cycle at the product system level (e.g. disinfection process). Every small contribution towards a more sustainable healthcare system counts.

1. Introduction

Medical device selection is currently based on criteria including clinical performance, usability, safety and procurement costs [3, 4]. Medical disposables were primarily introduced for reducing the risk of infection for patients, but they are often utilized instead of reusable devices due to their cheaper purchasing price, convenience, availability and presumed superior sterility [5]. However, growing awareness of the healthcare sector's negative contribution to the total greenhouse gas (GGH) emissions demands environmental sustainability to be taken into account as well.

Reusable and disposable flexible intubation scopes are of current interest to anesthesiologists. Flexible intubation scopes are mainly used for intubation of patients with anticipated or unanticipated 'difficult to intubate airway' (e.g. presence of head and neck pathological deviations, difficulties in opening the mouth, limited neck extension, morbid obesity, airway tumors or severe facial trauma) [6, 7]. Another function of flexible intubation scopes is performing a bronchoalveolar lavage (BAL) procedure, which is a method to assess the lungs for diseases through administration and suction of fluids in the trachea [8]. There is a concern for the environmental impact of flexible intubation scopes, because disposing a functional device after one use feels counterintuitive and disinfection of reusable devices requires additional resources (e.g. protective clothing, disposable products for cleaning). Therefore, knowledge about the environmental impact of disposable and reusable flexible intubation scopes is required to aid in the sustainable selection of flexible optical scopes.

Research about the life cycle environmental impact of flexible intubation scopes is limited. Studies have suggested that the environmental impact of reusable medical devices is generally lower than of disposable equivalents [3, 9]. However, Sørensen e.a. have documented that the carbon footprint of reusable FOB is higher compared to disposable FVS; the study did not analyze the environmental impact of the complete life cycle of the bronchoscopes, as manufacturing and disposal were excluded [5]. Research on the environmental impact throughout the entire life cycle of flexible intubation scopes is needed to develop more sustainable flexible intubation scopes.

The goal of this study is to compare the environmental impact of disposable and reusable flexible intubation scopes and design a sustainable concept to enable data-driven selection of sustainable flexible intubation scopes. In order to reach the goal, several sub-questions had to be investigated.

1. What are the environmental impacts of reusable and disposable flexible intubation scopes?
2. What life cycle phases of reusable and disposable flexible intubation scopes contribute most to their environmental impact?
3. How can the environmental sustainability of disposable and/or reusable flexible intubation scopes be improved?

Research about the sustainability of medical devices is relevant, because their environmental impact is part of a bigger problem. 7% of the total national greenhouse gas (GHG) emissions are caused by the healthcare sector in the Netherlands [10, 11]. GHG harms the ecosystems of nature and affects human society due to the deterioration of public health and the rise in healthcare expenses [12-14]. Some substantial contributions to the environmental impact of hospitals are the generation of large waste streams due to disposables, using energy-intensive technologies and the contamination of wastewater [15] [16, 17]. In order to reduce GHG emissions, 200 organizations in the Netherlands have agreed on the Green Deal for Sustainable Healthcare to reduce CO_2 emissions by 49% in 2030 [15]. Therefore, this research about the sustainability of flexible intubation scope could make a small contribution towards a more sustainable healthcare system.

1.1 Overview of components flexible intubation scope

Flexible intubation scopes have three sections: the insertion tube, the handpiece and the monitor connector, see Figure 1. The handpiece consists of a mechanical control system with bending cables for deflection of the bending section of the insertion tube. In addition, the handpiece contains the control system for administration and suction of fluids by a suction button and tube connection and endoscope accessories with a working channel port. The insertion tube is flexible and consists of the image transmission system (e.g. optical glass fibers or camera), a light source (e.g. glass fibers or light emitting diode), a channel for fluids and the bending cables. The monitor connector links the flexible intubation scope to the external monitor.

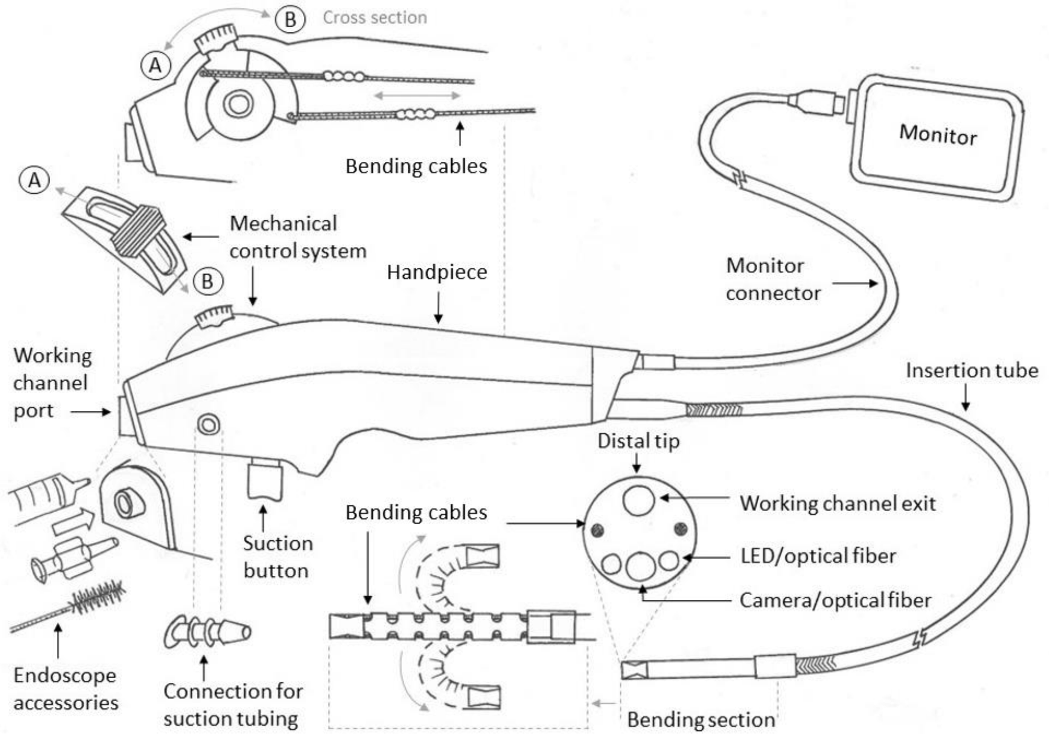


Figure 1: Overview of basic components of flexible intubation scopes with the handpiece, insertion tube and monitor connector

Flexible intubation scopes can be divided into two categories: fiberoptic bronchoscopes (FOB) and flexible video endoscopes (FVS). FOB have glass fibers to transmit images to an external monitor, while FVS contain a camera to transfer the digital image electronically [18, 19].

2. Method

The goal of this study was addressed by investigating the environmental impact of flexible intubation scopes through a Life Cycle Assessment and ideating a concept for a sustainable flexible intubation scope.

2.1 Methodology Life Cycle Assessment

Life Cycle Assessment (LCA) was used to quantify the environmental impact of disposable and a reusable flexible intubation scopes. LCA was the most suitable tool for this study, because LCA is the only tool with the possibility to compare products with a similar function, taking into account a set of different environmental impacts (e.g. climate change, depletion of resources, etc.)[1]. LCA avoids 'shifting of burden' (from one part of the life cycle to another), because the entire life cycle of the product is included in the impact assessment [1].

This LCA study was based on the LCA framework of the methodological standards ISO 14040 and ISO 14044 from the International Organization for Standardization (ISO). The LCA framework has four phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation (Figure 2) [1].

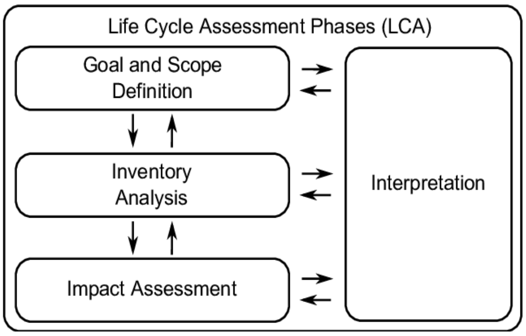


Figure 2: Phases of a Life Cycle Aassessment with (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation [1]

2.1.1 Goal and scope

2.1.1.1 Goal

The goal of this LCA was to compare the life cycle environmental impacts of disposable and reusable flexible intubation scopes. An additional goal was to do a hotspot analysis, i.e. to analyze which processes and/or materials contribute most to the environmental impacts, to aid in sustainable product development of flexible intubation scopes. The results of the LCA study are intended for device selection of flexible intubation scopes at the Leiden University Medical Centre (LUMC) for flexible endoscopes.

The two *alternatives,* meaning the product systems studied in an LCA, that were compared were the disposable FVS (AMBU, aScope 4 Broncho Regular) and the reusable FOB (Storz, Broncho 11301 BNXK), see Figure 3. The main function of the *alternatives* was defined as 'intubation of an endotracheal tube through the nasal or oral cavity in the trachea to restore gas exchange in the respiratory system of the patient with a difficult airway'.

Figure 3: Flexible intubation scopes: disposable flexible video endoscope (AMBU, aScope 4 Broncho Regular) and reusable fiberoptic bronchoscope (Storz, Broncho 11301 BNXK) as alternatives for this LCA study [20, 21]

2.1.1.2 Scope
A simplified cradle-to-grave approach was used as the scope of this LCA, which is a method to assess the environmental impact throughout every phase of the product's life cycle (resource extraction, transport, manufacturing, use and end-of-life scenario). The LCA study was a comparative analysis between the *alternatives* and an attributional approach (distinguish physical flows to and from a products life cycle to depict environmental impacts that can be attributed to a system) was chosen instead of a consequential approach (link hypothetic activities in a product system to identify the consequences a decision has on other processes and systems) [22]. The most recent data for the LCA was collected to represent the present state of technology of flexible intubation scopes (February 2022).

The *functional unit* (the quantified basis of comparison between the *alternatives* studied*)* was 450 patient intubations. For the definition of the functional unit, the clinical performance of the reusable and disposable flexible intubation scope was assumed to be equal. The reusable flexible intubation scope was validated for 450 cleaning and disinfection cycles and the disposable *alternative* is used once [23]. Therefore, the reference flow (the quantified flow of a product system to obtain the functional unit) of the *alternatives* was 450 disposable intubation scopes versus 450 uses of one reusable scope. An overview of the functions, functional unit and reference flows of the *alternatives* is provided in Table 1.

Table 1: Overview of the functions, functional unit and reference flows of the product alternatives

	Disposable FVS	**Reusable FOB**
Function	Intubation of an endotracheal tube through the nasal or oral cavity in the trachea to restore gas exchange in the respiratory system of the patient with a difficult airway	
Functional unit	450 patient intubations	
Reference flow	450 disposable intubation scopes	450 uses of 1 reusable intubation scope

2.1.2 Inventory analysis

The second phase of the LCA study was the inventory analysis, which results in the inventory table listing the quantified inputs from and outputs to the environment; raw materials, energy requirements, emissions and resource uses were quantified for the alternatives. In order to develop the inventory, the product systems of the alternatives were defined in terms of system boundaries, a flow diagram for each alternative, data collection and data modelling.

2.1.2.1 System boundaries
System boundaries were set to define the relevant and irrelevant *unit processes* (the smallest portion of a *product system* for which data is collected) for analysis of the study goal. The *product system* defines the connected *unit processes* that form the product's life cycle. These boundaries were divided into (1) economy-environment system boundaries (2) model simplifications and (3) allocations, which were described below.

The economy-environment system boundaries were established to determine the boundary between the product system and the environmental system (e.g. emitted substances and extracted resources), see Figure 3 [1]. The product system included the economic processes of the system that require human control, such as resource extraction, manufacturing of the endoscope and disposal of the product. The environmental system contained processes that do not need human interaction, such as the growth of raw materials and emissions that are caused by economic processes.

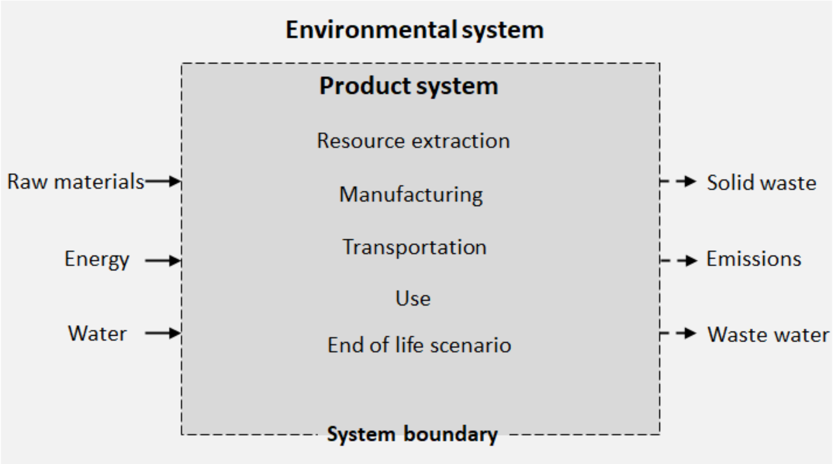


Figure 3: Graphical representation of economy-environment system boundary

Model simplifications (called cut-offs in LCA) were defined to set the boundary between relevant and irrelevant processes of the products system [1]. Capital goods (e.g. machines for manufacturing and incinerators) were not taken into account in this LCA due to the lack of data and because these capital goods are used over long periods of time which leads to depreciation and division of the environmental impact among many uses. The material consumption and production of the external monitors were also not included in this LCA, because the external monitors of the reusable FOB and disposable FVS were assumed to be similar to simplify the LCA.

A *multifunctional process* is a *unit process* that has more than one *functional flow* (a flow that constitutes the goal of that specific *unit process)*. There are two types of functional flows: outflow of a good (flow with economic value ≥ 0) out of a production process and an inflow of a waste (flow with economic value < 0) into a waste treatment process. Figure 4 displays three types of multifunctional processes (A) co-production (a production *unit process* with more than one functional outflow), (B) combined waste processing (a waste treatment *unit process* with more than one functional inflow), (C) recycling (a *unit process* with a functional inflow and functional outflow). Multifunctionality of the *unit processes* was solved by means of *allocation*, because the LCA model only works when there are no *multifunctional processes* present within the system boundary. The allocation method was chosen, so the non-functional flows of the *unit process* were partitioned among the functional flows according to physical allocation (e.g. mass, volume) or economic allocation.

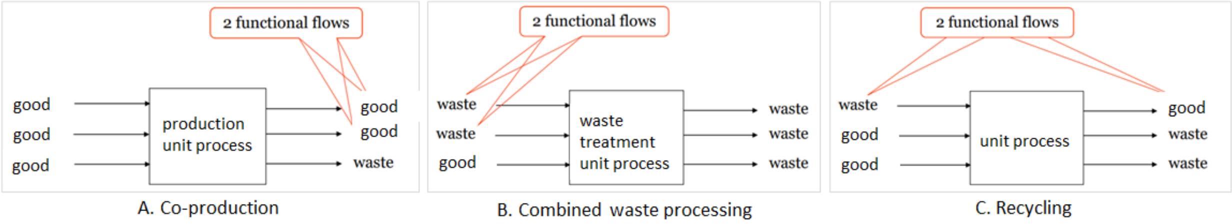


Figure 4: Three types of multifunctional processes within the system boundary of an LCA model: (A) co-production, (B) combined waste processing, (C) recycling. A functional flow is an outflowing good out of a production unit process or an inflowing waste into a waste treatment process

2.1.2.2 Flow diagram

The flows between the *unit processes* of the product system were structured in a flow diagram for both *alternatives* to provide a simplified overview of their life cycle, see Figure 5. The economical flows are displayed through arrows between *unit processes*, which indicates that the output of one process is the input of the subsequent process. The disposable FVS was sterilized with Ethylene Oxide (EtO) gas before use, while the reusable FOB was high-level disinfected with chemicals after use. The flow within the system boundary of the disposable FVS was repeated 450 times and the reusable FOB was disinfected 450 times. The processes of heating tap water, detergent production and disposables production were also taken into account 450 times, because these processes were linked to the disinfection process.

Several *unit processes* were merged into simplified blocks to make the flow diagram uncluttered; the *background unit processes* of the merged blocks were reported in Unit Process Tables, which can be found in Appendix C. The processes for the extraction of resources and production of (raw, semi and final) materials for intubation scope and packaging were merged into the process of 'material production'. Also, the manufacturing processes and assembly of the product were combined in the process ‘manufacturing’. ‘Manufacturing the disposable FVS’s consisted of the *unit processes* for manufacturing of the plastic half products and manufacturing the printed circuit board (PCB) of the image transmission system. The ‘disposables production’ process of the reusable FOB included the material production and manufacturing of every disposable product used during the disinfection of the scope.

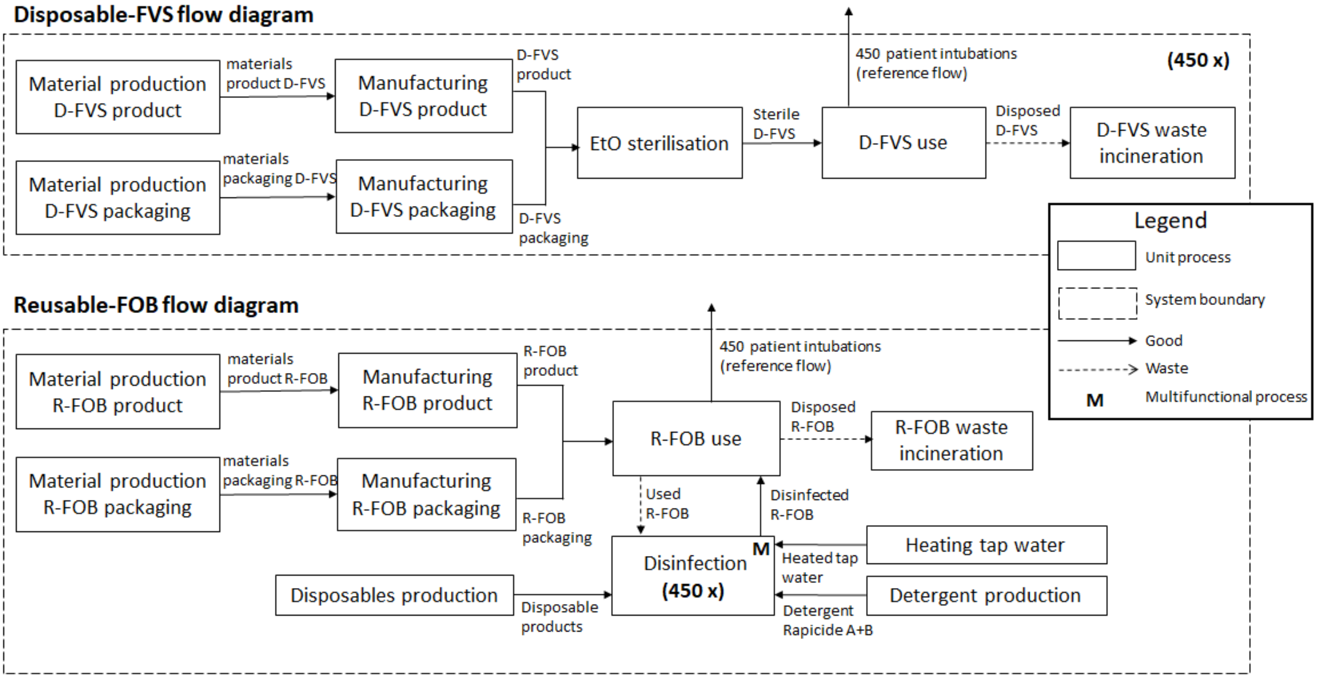


Figure 5: Flow diagram of disposable flexible video endoscope (D-FVS) life cycle and reusable fiberoptic bronchoscope (R-FOB).

2.1.2.3 Data collection and assumptions

Data was collected for each *unit process* of the *alternatives* and reported in Data Collection Tables, in Appendix B, including information about the data sources.

Material production

Data about the material composition of the product and associated packaging were not provided by the manufacturers (AMBU and Storz), despite repeated requests, and the technical files were also confidential. Therefore, the reusable and disposable intubation scope were disassembled and the materials of each part of the alternatives were identified through material analyzing techniques. Metals were identified with X-Ray fluorescence (Panalytical Axios Max WD-XRF spectrometer) and synthetic materials were identified with Fourier-transform infrared spectroscopy (FTIR, Thermoscientific is50). A detailed description of the material identification is included in Appendix A. Each part was weighed using a microgram scale (Mettler PJ360 Deltarange, accuracy of 0,001g). The material composition and weight of each part can be found in Appendix B and the total amount of each material in the flexible intubation scopes is presented in Table 2.

Table 2: Material composition and weight [gram] of the disposable FVS and the reusable FOB

Disposable FVS		Reusable FOB	
Material	**Weight [g]**	**Material**	**Weight [g]**
Acrylonitrile-Butadiene-Styrene [ABS]	55,3	Aluminium sulfide	146,2
Polyvinylchloride [PVC]	63,4	Brass	100,8
Polycarbonate [PC]	8,7	Stainless steel	24,4
Polyethylene, low density [PE, low]	4	Synthetic rubber	16,8
Polypropylene [PP]	2,6	Phenolic resin	67,5
Stainless steel	4,9	Polyurethane [PU]	22,7
Synthetic rubber	1,5	Nickel-iron alloy	17,7
Polyurethane [PU]	10,2	Glass fibers	1,1
Printed Circuit Board	2,2		
Total	155,6	**Total**	398,9

The components of the printed circuit board (PCB) of the disposable FVS were identified by visual observation together with an electrical engineer at the TU Delft [24]. The PCB consisted of a printed wiring board (PWB) with an inductor, a diode, a capacitor, two integrated circuits and four resistors that were labelled (i.e. R1 for a resistor), see Figure 6. The mass of the PCB components was based on assumptions, taking the average weight (kg) or surface area (m^2) of each component from the EcoInvent database [25].

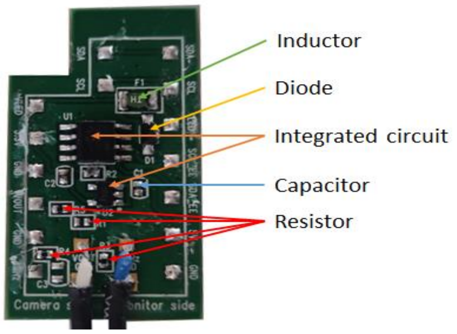


Figure 6: Components of printed circuit board (PCB) of disposable FVS

Manufacturing

Data about the manufacturing processes of the *alternatives* was not provided by the manufacturers (AMBU and Storz). Therefore assumptions were made about the primary production processes (e.g. casting and forming) for transforming the materials into half products. Characteristics of the half products were observed (e.g. shape, material composition, ejection marks, etc.) and affiliated with the associated manufacturing techniques to take their energy and material use into account [26-28]. Data about secondary manufacturing processes (e.g. machining, surface working) and assembly of the half products were not included. The glass optical fibers of the reusable optical fibers were assumed to be manufactured with modified chemical vapor deposition (MCVD), because this is the most common method to produce multimode glass optical fibers [29].

EtO sterilisation

The disposable FVS was EtO sterilized within the associated packaging and data for the amount of ethylene oxide gas and amount of energy used during the sterilization process was obtained through technical files of the Ethylene Oxide Safety Task Group (EOSTG) [23, 30]. The concentration of EtO gas was defined to be approximately 725 mg/L (range: 450 to 1200 mg/L) to achieve a SAL of 10^{-6} and the volume of one disposable FVS was assumed to be 0,2L based on the volume of the aScope 4 packaging.

Use

The light and image transmission of the flexible optical scopes were powered by the external monitors during use: aView for AMBU aScope 4 and C-MAC 8430 ZX for Storz fiberscope. The energy consumption of the external monitors was obtained through their technical files and the duration of use was assumed to be 5 minutes, taking into account the average intubation time of 1 minute [31].

Disinfection

The data of the high-level disinfection process was collected through an observational study at the Central Sterilization Department (CSD) of the LUMC. The disposable products that the CDS employee was wearing (e.g. protecting gloves, plastic gown, mouth mask) were assumed to be replaced after each disinfection process and the material composition of the disposable products was determined through an internet search.

The flexible intubation scope was first cleaned by soaking the device in a sink of 12L water with soap (Intercept, Medivators) of approximately 40^{0} C and by wiping the device with a cleaning brush and a cotton cloth. The energy consumption for heating water was calculated by equation 1, with the change in thermal energy (ΔE_t) in Joules, mass (m) in kg, specific heat capacity (c) in J/kg ^{0}C, and temperature change ($\Delta\theta$) in ^{0}C.

$$\Delta E_t = m \cdot c \cdot \Delta\theta \tag{1}$$

Thereafter, the flexible scope was high-level disinfected in the disinfection machine (Medivators Advantage Plus) for 30 minutes and the amount of water (35 L), the temperature (30 ^{0}C) and the amount of detergent (Rapicide A and B) was displayed on the monitor of the disinfection machine. The ingredients of the detergent (Rapicide part A and part B) were largely confidential, but the hazardous chemicals (e.g. hydrogen peroxide, acidic acid) were found on their safety data sheet [32, 33]. The rest of the ingredients were unknown, so it was assumed that the basis of the detergents was fatty alcohol because this is the primary ingredient in most detergents [34].

After disinfection, the flexible intubation scope was placed in the blow dry machine (Medivators Endodry) for three hours. The energy use of the disinfection and blow dry machine were obtained through their technical manuals at the LUMC.

Waste incineration

Both *alternatives* were discarded in regular municipal solid waste bins and incinerated by waste processing company PreZero at end-of-life.

2.1.2.4 Data modelling

The *unit processes* of the *alternatives* were modelled in Chain Management by Life Cycle Assessment (CMLCA), which is LCA software that was developed by the Institute of Environmental Sciences, Leiden University [35]. The data from the Unit Process Tables (Appendix C) were imported from the EcoInvent database version 3, which is a life cycle inventory database that contains information about the economic and environmental inputs and outputs of the *background processes* [25].

The *unit processes* in the EcoInvent database are called 'activities', which represents a human activity and its exchanges with the environment [1]. The reference product is the reason for carrying out the activity and can either be a good or a waste. There are two types of activities in Ecoinvent: transforming processes (e.g. production or waste treatment processes) and transferring processes ('market' activities are consumption mixes that include transportation) [1]. Transforming processes were selected for the *background processes* for manufacturing and waste treatment processes. Specific waste treatment processes were selected for each material of the product, but some materials were assigned to 'treatment of waste plastic mixture' or 'municipal solid waste incineration' when the specific process did not exist in EcoInvent. Transferring processes were selected for *background processes* of material production and disinfection.

Each activity in the EcoInvent database is associated with a specific geographical location (e.g. average global data, regional data, etc) and the most relevant geographical location must be selected for the *unit processes* in the LCA models [25]. Average global data was chosen for the *background processes* of the raw material production for the product and packaging of both alternatives, because mining of resources and production of materials takes place all over the world. *Background processes* for manufacturing, use and waste treatment processes from Europe were included.

The disinfection process of the reusable intubation scope was considered a multifunctional process, because two functional flows were present: the used FOB is a waste that flows into the disinfection process (waste treatment process) and the disinfected FOB flows out of the disinfection process as a good (production of clean product), see Figure 4. The type of allocation method and allocation details were not important for the results of the LCA, because both functional flows stay part of the product system that is studied (closed loop). The allocation method to resolve the multifunctional process was equal partitioning, so the emissions from the disinfection process were divided equally between the functional flows.

2.1.3 Life Cycle Impact Assessment

In the third phase of the LCA process, the data from the Life Cycle Inventory (LCI) was used as input for the Life Cycle Impact Assessment (LCIA). The LCIA consisted of four steps that were executed in CMLCA: (1) classification, (2) characterisation, (3) normalisation and (4) weighting.

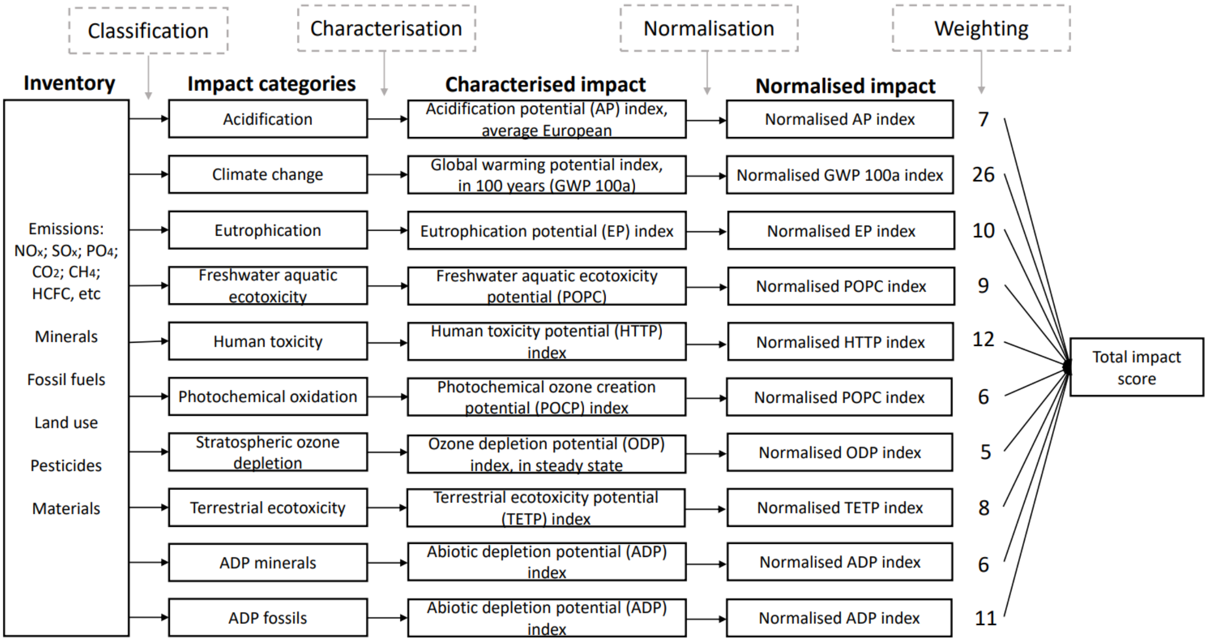


Figure 7: Overview of life cycle impact assessment steps (1) classification, (2) characterisation, (3) normalization and (4) weighting factors

2.1.3.1 Classification

The life cycle inventory results were classified by assigning the elementary flows to selected impact categories according to the substances' ability to contribute to a specific environmental problem, which was described below [36].

Classification of the inventory data was done with the CML2001 impact assessment method, which was developed by the Institute of Environmental Sciences, Leiden University [37, 38]. The CML2001 method was chosen, because the '*method restricts quantitative modelling to early stages in the cause–effect chain to limit uncertainties, with results being grouped in midpoint impact categories according to common mechanisms (e.g. climate change) or commonly accepted groupings (e.g., ecotoxicity)*' [1, 37]. Midpoint impact categories can be used to identify possible trade-offs in the product's life-cycle and between the alternatives, which can support the development of sustainable flexible intubation scopes [39]. Furthermore, the CML2001 method was recommended by the Dutch Handbook on LCA and most impact categories were described in peer-reviewed papers [1, 39].

An impact assessment method with an endpoint-oriented approach was not suitable for this LCIA. Endpoint methods convert the life cycle inventory results into three damage categories (human health, ecosystem quality and resource depletion), resulting in easier interpretation compared to midpoint assessment methods [2, 40]. However, the end-point method provides more general results and the statistical uncertainties are higher, so the end-point method is not suitable to identify possible trade-offs for sustainable development of flexible intubation scopes.

The included midpoint impact categories, measured in equivalents (Eq) of their respective reference compound, were: *acidification, climate change, eutrophication, freshwater aquatic ecotoxicity, human toxicity, photochemical oxidation, stratospheric ozone depletion, terrestrial ecotoxicity, Abiotic Depletion Potential (ADP) minerals, ADP fossils*, see Table 3.

Table 3: Definitions of midpoint impact categories of the CML2001 impact assessment method

Impact category	Definition
Acidification	The measure of the decrease in pH-value of rainwater and fog, measured in sulphur dioxide equivalents (kg SO_2-Eq)
Climate change	The warming effect of the earth's surface due to release of greenhouse gases into the atmosphere, measured in mass of carbon dioxide equivalents (kg CO_2-eq)
Eutrophication	The measure of nutrient enrichment in aquatic or terrestrial environments, measured in mass of phosphate equivalents (kg PO_4-Eq)
Freshwater aquatic ecotoxicity	The emissions of toxic substance to the air, water and solid on fresh water and ecosystems, measured in 1,4 dichlorobenzene (kg 1,4-DCG-Eq)
Human toxicity	The impact on humans as a results of emissions of toxic substances to air, water and soil, measured in 1,4 dichlorobenzene equivalents (kg 1,4-DCB-Eq)
Photochemical oxidation	'Summer smog', the reaction of sunlight with emissions from fossil fuel combustion creating other chemicals, measured in kg ethylene-equivalents (kg ethylene-Eq)
Stratospheric ozone depletion	The measure of anthropogenic emissions that react with and destroy the stratospheric ozone, measured in mass of chlorofluoromethanes (kg CFC-11-Eq)
Terrestrial ecotoxicity	The effects of a chemical substance to terrestrial organisms and plants, measured in in 1,4 dichlorobenzene (kg 1,4-DCB-Eq)
ADP minerals	The measure of the extraction of minerals, measured in stibium equivalents (kg Sb-Eq)
ADP fossils	The measure of the extraction of fossil fuels (megajoule)

2.1.3.2 Characterization

The classified LCI data were characterized by assigning the environmental interventions quantitively to the midpoint impact categories according to the underlying environmental mechanism [1]. The environmental substances that contribute to a specific impact category were multiplied by a characterization factor (see Figure 7) that defines the relative contribution of the substance to the common unit of the impact category (i.e. kg CO_2- equivalents for climate change) [1, 39]. For example, methane ($\mathrm{CH_4}$) and carbon dioxide ($\mathrm{CO_2}$) both contribute to climate change, but their relative contribution to climate change differs; the characterization factor of $\mathrm{CH_4}$ and $\mathrm{CO_2}$ is 25 and one respectively, which means that the release of 1 kg of $\mathrm{CH_4}$ has approximately the same effect on climate change as 25 kg of $\mathrm{CO_2}$ [41].

The category indicators results were calculated in CMLCA and compared between the *alternatives*. The category indicator results cannot be compared between the different impact categories because each impact category impact represents another environmental concern and has a different unit.

2.1.3.3 Normalization

The category indicator results were normalized to global reference information in CMLCA to give insight into the magnitude of the category indicator results. Another aim of normalization is to prepare the category indicator results for additional procedures (e.g. weighting, described in Section 2.1.3.4) [1]. The reference information was chosen to be the total annual world interventions, calculated by baseline global normalization factors for 1999, because this was the most up-to-date reference information available in CMLCA [42].

The unit for the normalized category indicator results is year. Impact categories with a high value indicate that the *alternative* has a relatively high contribution to the global world problem, but it does not imply that it is the most significant impact category.

Toxicity related categories (e.g. human toxicity, freshwater aquatic toxicity and terrestrial ecotoxicity) were not normalized, because normalization of these impact categories is unreliable as complete global inventory results are missing adequate reference information [1].

2.1.3.4 Weighting

The normalized category indicators results were weighted to derive a single total impact score to compare the impact of the *alternatives.* The total impact score is the measure of the environmental impact.

The CML2001 impact assessment method did not provide a baseline method for weighting, so the baseline from the International Reference Life Cycle Data System (ILCD) was used to determine the relative importance of the impacts categories [39]. ILCD was devised by the European Union to harmonize LCIA on a European level and was suitable for weighting, because the method has a set of weighting factors that was composed of three expert panel sets (EPA science advisory board, BEES stakeholder panel and NOGEPA additional factors) and the ILCD factors are similar to the impact categories and characterisation factors of CML2001 [43]. The weight factors for each impact category of ILCD are displayed in Figure 7 [39, 43].

2.1.4 Interpretation

In the last phase of the LCA framework, the life cycle impact assessment results were interpreted through two numerical methods: (1) contribution analysis and (2) sensitivity analysis.

2.1.4.1 Contribution analysis

The contribution analysis was executed to decompose the LCA results into life cycle phases and constituent elements of individual processes to provide an overview of specific contributing factors. The contributions within each impact category were expressed as percentages of the total impact, which were visualized in stacked bar diagrams. The contribution analysis was performed at characterization level and three items were analyzed for both *alternatives* separately.

1. Contribution between life-cycle phases: the foreground *unit processes* were categorized into five life cycle stages: (a) material production, (b) manufacturing, (c) use of the product (d) sterilization/disinfection and (e) disposal, see Appendix D. The life-cycle stages with the largest environmental impact were identified to investigate which phases should be analyzed in more detail.

2. Contributions of different background *unit processes* within the life cycle phase with the largest environmental impact for both *alternatives* to investigate opportunities for a sustainable redesign of the device or redesign of the product system (e.g. disinfection process).

3. Contribution of product materials: the contribution of the production of materials in the flexible intubation scopes was analyzed to investigate which materials had the largest impact relative to their weight.

2.1.4.2 Sensitivity Analysis

The sensitivity analysis was executed to determine the robustness of the outcome of the LCA model to uncertain input data, model choices and assumptions. The sensitivity of the results was analyzed with a local sensitivity analysis and a scenario analysis.

Local sensitivity analysis

In the local sensitivity analysis, nominal values of the initial input variable of the LCA model were increased by 100% to study the response of uncertain data to the output value. The initial input values were changed one-at-a-time (OAT) and the sensitivity factor of that parameter was calculated with equation 2. The multiplier (δ) was calculated by dividing the change in output variable (Δy) by the change in input variable (Δx_i).

$$\delta \approx \frac{\Delta y}{\Delta x_i} \tag{2}$$

The multiplier (δ) provides information on how the model output y responds to a small change of x_i from its nominal value $\tilde{x}_i$. However, different multipliers cannot be compared due to differences in scale and/or unit [44]. Proportional sensitivity (ε) were calculated with equation 3 to be able to compare the response of the variables relative to each other.

$$\varepsilon = \frac{\tilde{x}_i}{\tilde{y}} \delta \tag{3}$$

The input variables that needed to be assessed were the weight of the PCB components, the amount of water, electricity and soap used during the disinfection process, the weight of the materials of the flexible intubation scopes and their primary manufacturing processes. The sensitivity of these variables was analyzed, because they were based on assumptions, observations or measurements and therefore were expected to have the highest uncertainty among the collected data in this LCA.

Scenario analysis

In the scenario analysis, several initial input variables were changed simultaneously to study the influence of model choices and assumptions in a different scenario on the results of the LCA.

The functional unit of the product system was assumed to be the intubation of 450 patients, but often medical devices are discarded before their intended lifetime. The functional unit of the *alternatives* was reduced by 15% to observe if the outcome of the climate change impact category changed, because climate change is perceived as the most important impact category. Furthermore, the break-even point of the functional unit between the category indicator results of the *alternatives* was calculated for each impact category. The break-even point was estimated by calculating the category indicator results for the functional unit of 1 to 400 with steps of 100. The slope of the category indicator results of the *alternatives* was calculated and compared to define when the *alternatives* have the same impact within each impact category.

The impact assessment method CML2001 was chosen for the interpretation of the inventory data of this LCA study. Two other impact assessment methods, ReCiPe midpoint and ILCD midpoint, were also available in CMLCA and they were applied to determine if the outcome was influenced by the choice of impact assessment method. Each impact assessment method consists of a different set of characterisation factors and impact categories, so the environmental interventions of the product systems are classified and characterised differently [39]. The ReCiPe method is a midpoint method that has been developed in collaboration between the Dutch National Institute for Public Health and the Environment (RIVM); the ReCiPe method is a follow-up of the CML method, so the impact categories have been redeveloped and updated [39, 45]. The ILCD midpoint was also applied, because ILCD factors are similar to the impact categories and characterisation factors of CML2001 [43]. The categorized indicator results of the ReCiPe and ILCD methods were compared with the CML2001 method by coupling impact categories of the methods, based on similar aspects.

2.2 Concept ideation

A sustainable concept for flexible intubation scopes was developed by listing the requirements, generating concepts, selecting one concept with the most potential and evaluating the final concept.

2.2.1 Requirements

The requirements were based on specifications of the studied flexible intubation scopes and interviews with anesthesiologists and the contract and supplier manager of the LUMC [46, 47]. The requirements were divided into functional requirements, user requirements, specifications and constraints [48].

Functional requirements

1. The device must be able to insert an endotracheal tube through the nasal or oral cavity in the trachea to secure the airway of a patient with a difficult airway within 5 minutes [49, 50].
2. The device must have a minimal sterility assurance level of 10^{-3} before use [51, 52].

User requirements [47]

The device must

3. visualize the airway of the patient.
4. have the flexibility to glide along the airway of the patient with a difficult airway.
5. enable administering fluids and suction fluids from the airway.
6. allow inserting endoscopic accessories (i.e. for lung biopsy) in the airway.
7. be portable.
8. not damage the mucous membrane of the patient.
9. allow the user to adjust the angle of the distal tip of the device with one hand.

Specifications

10. The distal tip of the device must be able to bend 120° over a length of 4cm [21].
11. The pixel size of the image transmission system must be smaller than 300µm [53, 54].
12. The device must withstand temperatures between -20 to 40 °C [23].
13. The device must have a maximum weight of 0,5 kg [50].
14. The length of the insertion tube must be 60 ± 1 cm [20].
15. The outer diameter of the insertion tube must be 5 ± 0,2 mm [21].
16. The diameter of the working channel must be 1,2 + 0,1 mm [21].

Constraints

17. The total costs of the flexible intubation scope per procedure must not exceed €200 [46].
18. The total impact score of the life cycle of the device must not exceed $4{,}0 \cdot 10^{-8}$ year.

2.2.2 Concept generation

Concepts were generated with the results of the contribution analysis and the use of the EcoDesign Strategy Wheel, which is a tool to select and communicate Ecodesign strategies [55]. The eight Ecodesign strategies are (1) new concept development, (2) selection of low-impact materials, (3) reduction of material usage, (4) optimization of production techniques, (5) optimization of distribution system, (6) reduction of impact during use, (7) optimization of initial lifetime and (8) optimization of end-of-life system [55]. The focus of the concepts was chosen to be the product system level (Ecodesign strategy 7 and 8) and product component level (Ecodesign strategy 2 and 3). The concepts were not directed towards improving the product structure level (e.g. Ecodesign strategy 4, 5 and 6), as this was out of the scope of this research. Recommendations to improve the disinfection process of the reusable FOB were included in the discussion. The clinical performance of the studied flexible intubation scopes was assumed to be adequate, so Ecodesign strategy 1 was not the primary focus of the concepts. Solutions for the EcoDesign Strategies were explored through a mind map and possible combinations were highlighted to support the generation of ideas for sustainable concepts, see Appendix G.

2.2.3 Concept selection

Four concepts were evaluated based on five selection criteria (performance, usability, complexity, affordability and circularity) to choose the concept with the most potential. The selection criteria were based on the requirements and were ranked with a weighting factor between one to three, based on the importance of the selection criterion for the goal of this study. Environmental sustainability was not chosen as a distinct selection criterium, as the environmental impact cannot be defined easily; the selection criteria that directly influence the environmental impact of the device were ranked higher to ensure that the sustainability of the device is taken into account during concept selection.

2.2.3.1 Selection criteria

The *performance* of the device indicates the quality of the image transmission system, defined by the transmission efficiency and pixel size of the device. An interview with two anesthesiologists from the LUMC revealed that the user (anesthesiologist or OR assistant) prefers to have the best image quality for the device, although an image with a maximum pixel size of 300μm is adequate for visualization of the airway[47]. Therefore, the *performance* criterium received a weighting factor of one.

The *usability* was determined by the efficiency of using the device by measuring the number of actions the user (anesthesiologist or OR assistant) has to take before and after use of the device. The weighting factor of the *usability* was ranked as two, because the number of actions defines the amount of time that is required for handling the device and the time of the user is limited.

The *complexity* of the device indicates the difficulty of manufacturing and assembling the device, which was determined by the number of components of the device and the connections between the components. The additional manufacturing processes contribute to the environmental impact and the manufacturing costs of the device. The weight of the *complexity* was three, because the environmental-friendliness and costs were considered important for the goal of this study.

The *affordability* of the device per procedure is important, because medical device-selection is often driven by procurement costs of the device. A simple costs analysis was made, taking into account the costs of the complete life cycle (e.g. costs for procurement, maintenance, repair, disinfection and waste treatment) and excluding capital equipment acquisition and transport costs. The total costs indicates the costs of the device per procedure. Furthermore, the contract and supplier manager of the LUMC was interviewed to get more insight into the importance of the *affordability* for device selection, who stated that hospitals have a limited budget and have to make a cost-benefit analysis for purchasing devices [46]. Therefore, the *affordability* was given a weight factor of three.

The *circularity* indicates if the concept enables a way to reduce, reuse, remanufacture or recycle components of the flexible intubation scope to take into account the end-of-life scenario. The weighting factor of the *circularity* was one, because it promotes circular innovation and thinking outside the box for creative concepts but does not necessarily decrease the environmental impact.

2.2.4 Concept evaluation

The selected concept was developed further regarding the material composition and primary manufacturing processes of the device. In order to evaluate the final concept, the environmental impact of the final design was estimated by making alterations to the input of the LCA model. The steps of the life-cycle impact assessment phase (Section 2.4; classification, characterization, normalization and weighting) were repeated to calculate the category indicator results and total impact score of the final design. The category indicator results of the final concept were compared to the category indicator results of the studied flexible intubation scope.

Furthermore, the number of patient intubations (functional unit of this LCA) was calculated at which the environmental impact of the studied flexible intubation scope and the final design are the same.

3. Results

In this section, the results from the Life Cycle Assessment and concept ideation for a sustainable flexible intubation scope are described.

3.1 Impact assessment results

The results from the Life Cycle Impact Assessment phase of this LCA are presented through the characterized impact, normalized impact and weighted impact.

3.1.1 Characterized impact

The category indicator results of the disposable FVS and reusable FOB are reported in Table 4 and the table indicates whether the category indicator results were higher (red) or lower (green) for the *alternatives* in each impact category. The category indicator results were higher for the disposable FVS in eight out of ten of the impact categories at 450 patient intubations: the difference between the category indicator results of the *alternatives* was bigger than 15% for acidification, eutrophication, freshwater aquatic ecotoxicity, human toxicity and ADP minerals. The category indicator results of climate change, photochemical oxidation and ADP fossils were comparable between the *alternatives*, because the difference between the category indicator results was smaller than 15%. The impact on the stratospheric ozone depletion and the terrestrial ecotoxicity was lower for disposable FVS compared to the reusable FOB. The comparative analysis with normalized category indicator results is shown in Appendix E. It must be noted that the category indicator results cannot be compared between the impact categories.

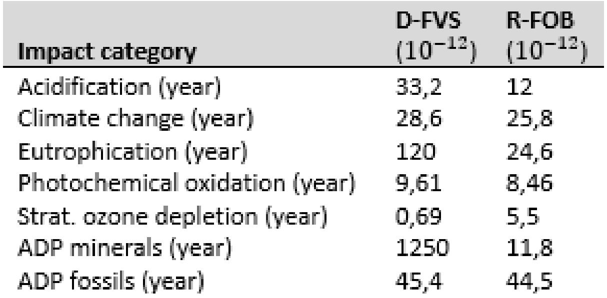
Table 4: Environmental comparison among the reusable FOB and disposable FVS of the absolute category indicator results at 450 patient intubations (note: do not compare between impact categories)

Impact category	Disposable FVS	Reusable FOB	Difference (%)
Acidification (kg SO2-Eq)	7,91	2,92	63,1
Climate change (kg CO2-Eq)	1230	1120	8,9
Eutrophication (kg PO4-Eq)	9,59	1,98	79,4
Freshwater aquatic ecotoxicity (kg 1,4-DCB-Eq)	2610	1040	60,2
Human toxicity (kg 1,4-DCB-Eq)	5090	906	82,2
Photochemical oxidation (kg ethylene-Eq)	0,353	0,312	11,6
Stratospheric ozone depletion (kg CFC-11-Eq)	8,32E-05	6,62E-04	87,4
Terrestrial ecotoxicity (kg 1,4-DCB-Eq)	14,4	202	92,9
ADP minerals (kg Sb-Eq)	6,86	0,0644	99,1
ADP fossils (megajoule)	17200	17000	1,2

3.1.2 Normalized impact

The normalized category indicator results are shown in Table 5. The category indicators results of eutrophication and the depletion of minerals were high in their category, compared to the other impact categories, relative to the total annual world interventions in 1995 (year).

Table 5: Normalized category indicator results (10^{-12}) of the impact categories relative to the annual world interventions



Impact category	D-FVS (10^{-12})	R-FOB (10^{-12})
Acidification (year)	33,2	12
Climate change (year)	28,6	25,8
Eutrophication (year)	120	24,6
Photochemical oxidation (year)	9,61	8,46
Strat. ozone depletion (year)	0,69	5,5
ADP minerals (year)	1250	11,8
ADP fossils (year)	45,4	44,5

3.1.3 Weighted impact

The total impact score relative to the total annual world interventions of the disposable FVS and reusable FOB were $7{,}92 \cdot 10^{-8}$ and $2{,}48 \cdot 10^{-8}$, respectively; the total impact score of the reusable FOB is approximately 69% smaller compared to the disposable FVS after weighting.

3.2 Interpretation results

The results from the interpretation phase of this LCA are shown through the contribution analysis of three distinct items of the product's life cycle and the sensitivity analysis, comprised of the local sensitivity analysis and the scenario analysis.

3.2.1 Contribution analysis

The contribution of the life cycle phases of the flexible intubation scopes is displayed in Figure 9. The graph 9A of the disposable FVS suggests that the life-cycle phase with the highest environmental impact is the manufacturing of the device, followed by the material production. Another contribution analysis of the D-FVS manufacturing phase revealed that the impact is mostly due to manufacturing of the printed circuit board (PCB) of the FVS, so the hot-spots of the PCB components were investigated in the second item of the contribution analysis. Sterilization had the lowest contribution in every impact category among the life cycle phases of the disposable FVS.

The graph of the reusable FOB in Figure 9B implies that the life cycle phase with the highest environmental impact was the disinfection process. The contribution of the material production, manufacturing, use and disposal phase of the reusable FOB was lower than 30% of the total impact in every impact category.

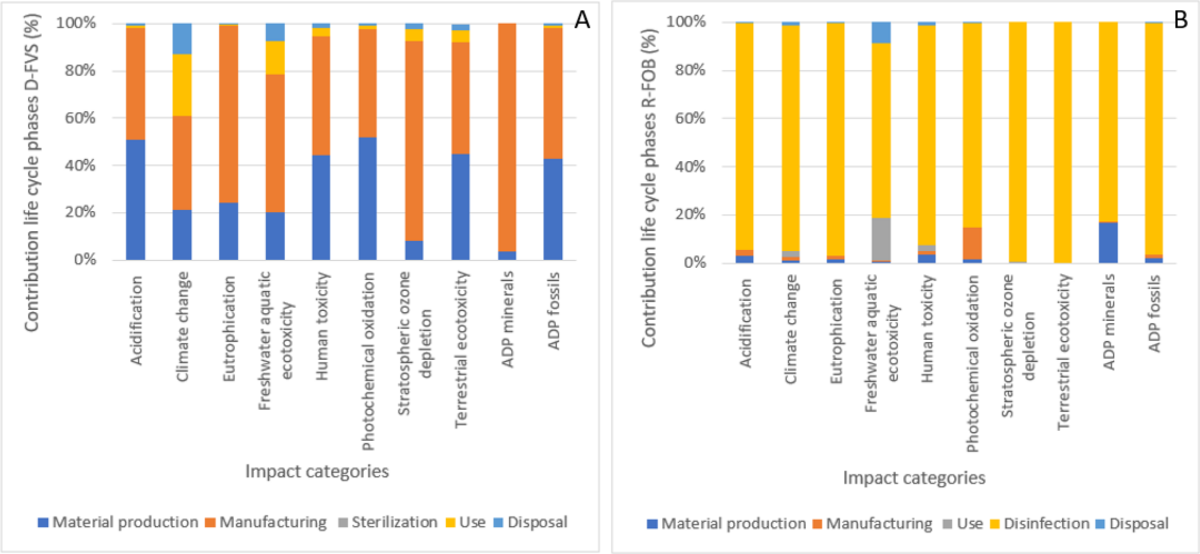


Figure 9: Contribution analysis of life cycle phases of (A) 450 disposable flexible video endoscopes and (B) 450 patient intubations of the reusable fiberoptic bronchoscope

The contributions of the different background *unit processes* within the life-cycle phase with the highest environmental impact are displayed in Figure 10. The components of the PCB of the disposable FVS with the highest impact were the integrated circuit (IC) and the connecting copper wires, see Figure 10A. The main attributions to eutrophication and freshwater ecotoxicity of the disposable FVS were the treatment of sulphide tailing (e.g. copper and gold of the PCB). The impact on the depletion of minerals was substantial due to the production of silver and gold in the PCBs integrated circuit.

The contributions of the inputs of the disinfection process of the reusable FOB were distributed more evenly throughout most impact categories, see Figure 10B. The disposable products had the largest contribution to the stratospheric ozone depletion, which was due to the consumption of nitrile gloves. The impact on the terrestrial ecotoxicity was high for reusable FOB due to the production of soap.

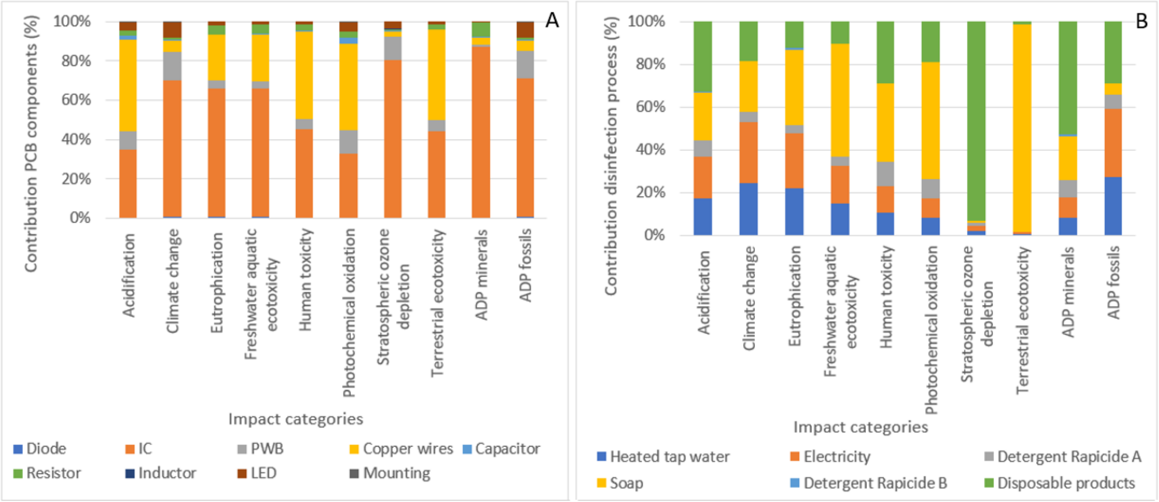


Figure 10: Contribution analysis of life-cycle phase with highest impact: (A) manufacturing of electronic components of the disposable flexible video endoscope and (B) the disinfection process of the reusable FOB

The contribution of the production of the materials within the flexible intubation scopes concerning their weight is displayed in Figure 11. The disposable FVS mainly consisted of plastic materials, but the production of a small amount of stainless steel had a large contribution to the toxicity related impact categories and ADP minerals. The production of ABS had a high contribution to the total impact in several impact categories compared to the weight of ABS in the product. Figure 11B implies that the production of materials of the reusable FOB with the highest contributions were aluminium alloy and brass.

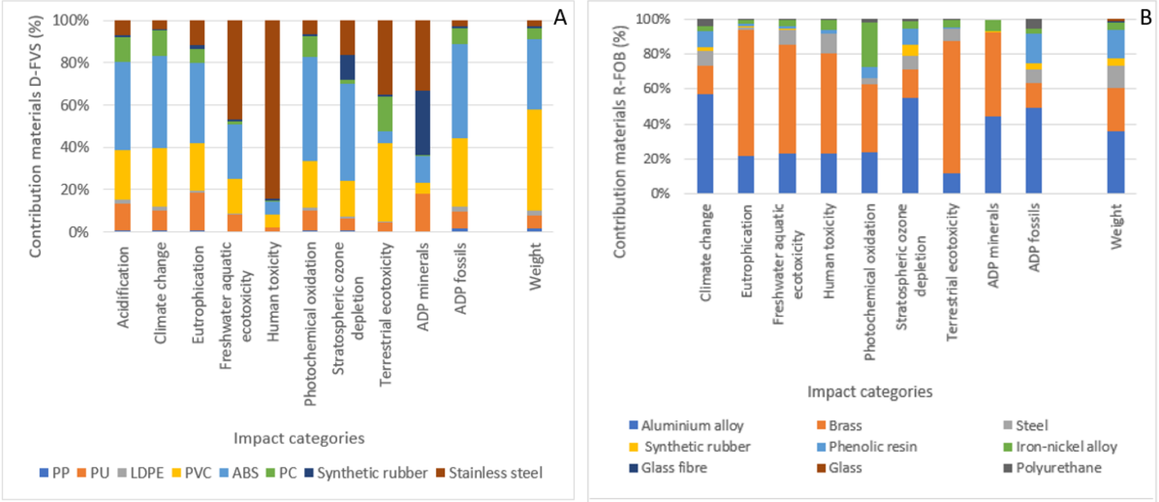


Figure 11: Contribution analysis of production of materials in the product of (A) disposable flexible video endoscope and (B) reusable fiberoptic bronchoscope, relative to their weight

The category indicator results of the alternatives were comparable in the categories of climate change, ADP fossils and photochemical oxidation, which can be clarified through the results of the contribution analysis. The main contributing factors of the disposable FVS to climate change were electricity production for the manufacturing of the PCB, the material production and the treatment of waste; the impact of the reusable FOB on climate change was mainly due to the material production for disposable products and production of electricity for the disinfection process. The impact on ADP fossils fuels and photochemical oxidation was defined by the use and combustion of brown coal, hard coal, gas and crude oil; the disposable FVS used fossil fuels for the manufacturing of the integrated circuit and extraction of ABS and PVC, while the largest contributing factor to the impact of the reusable FOB was the production of electricity (i.e. for heating of tap water, energy use of disinfection machines and production of PP).

3.2.2 Sensitivity analysis

Local sensitivity analysis

The sensitivity of the LCA models for several local input parameters was analyzed: weight of the PCB components, amount of material in the device, primary manufacturing processes and main supplies for the disinfection process. The proportional sensitivity (ε: the proportional change of the output variable over the change of the input parameter) of the total impact score of the input variables are shown in Tables 6-11 to compare the local sensitivity for the variables relative to each other. The underlying category indicator results and the calculated multipliers of each impact category of the varied input data were reported in Appendix F.

The proportional sensitivity of the PCB components is displayed in Table 6; the LCA model of the disposable FVS was most sensitive to the integrated circuit (0,5404) and the copper wires (0,2576).

Table 6: Proportional sensitivity of total impact score of PCB components of the disposable FVS

	Diode	IC	PWB	Inductor	LED	Copper	Capacitor	Resistor
$\boldsymbol{\varepsilon_i}$	0,0025	0,5404	0,0354	0,000	0,0114	0,2576	0,0013	0,0391

Tables 7 and 8 show the proportional sensitivity of the materials' production of the disposable FVS and reusable FOB, respectively. The product materials of the studied flexible intubation scopes barely influence the outcome of the LCA model, because the proportional sensitivity is smaller than 0,1. Polycarbonate (PC), polyethylene (PE), stainless steel, synthetic rubber and phenolic resin had the least influence on the LCA models.

Table 7: Proportional sensitivity of total impact score of disposable FVS product materials

	ABS	PVC	PC	PE	Steel	Copper	Rubber	PU
$\boldsymbol{\varepsilon_i}$	0,0063	0,0038	0,000	0,000	0,000	0,0177	0,0000	0,0013

Table 8: Proportional sensitivity of total impact score of reusable FOB product materials

	Aluminium	Brass	Steel	Rubber	Phenolic resin	Nickel-iron	Glass fibers
$\boldsymbol{\varepsilon_i}$	0,0063	0,0038	0,000	0,000	0,000	0,0177	0,0000

The influence of the primary manufacturing processes of the flexible intubation scopes on the LCA model was small, see Tables 9 and 10. The LCA model of the reusable FOB was most sensitive to aluminium casting (0,008) compared to the other manufacturing processes. Injection moulding had the largest influence on the LCA model of the disposable FVS.

Table 9: Proportional sensitivity of total impact score of reusable FOB manufacturing processes

	Wire drawing	Casting, brass	Casting, aluminium	Injection moulding	Sheet rolling
$\boldsymbol{\varepsilon_i}$	0,0000	0,0000	0,0080	0,0000	0,0000

Table 10: Proportional sensitivity of total impact score of disposable FOB manufacturing processes

	Extrusion	Injection moulding	Wire drawing
$\boldsymbol{\varepsilon_i}$	0,0013	0,0051	0,000

The category indicator results of the LCA model would be affected by the input variables of water, electricity and soaps used during the disinfection process, see Table 11.

Table 11: Proportional sensitivity of total impact score of disinfection process of the reusable FOB

	Water	Electricity	Soap
$\boldsymbol{\varepsilon_i}$	0,1245	0,1446	0,4578

Scenario analysis

Several input parameters were altered simultaneously to analyze the influence of model choices on the outcome of this LCA.

The reduction of the functional unit by 15% for the *alternatives* showed that the category indicator results had similar outcomes: the environmental impact throughout the lifetime of the reusable FOB was lower compared to the disposable FVS (952 kg CO2-eq vs 1040 kg CO2-eq for climate change) when the device was discarded after 380 patient intubations. The break-even point for impact on climate change between the two *alternatives* was at approximately 124 patient intubations, see Figure 12.

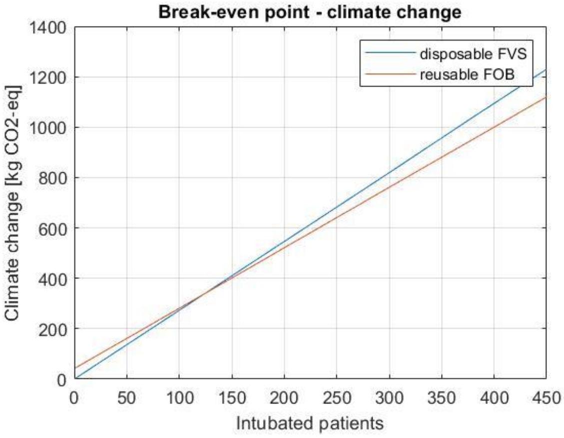


Figure 12: Break-even analysis of climate change for disposable FVS and reusable FOB with intersection at 124

The break-even points and impact equations of the other impact categories are reported in Appendix F.5, which showed that the break-even point ranged between 4 and 295 depending on the impact category. The total environmental impact between the disposable FVS and reusable FOB was equal at 84 patient intubations.

The ReciPe and ILCD method were applied to the LCA models to determine if the outcome was influenced by the choice of impact assessment method. The impact (I(%)) between the disposable FVS and reusable FOB is displayed in Table 12 to compare the results of the impact assessment methods. The ReCiPe and ILCD method consist of more impact categories than the CML2001 method, so multiple impact categories of the ReCiPe and ILCD method were coupled to a singular CML2001 category (i.e. eutrophication of CML2001 was coupled to freshwater and marine eutrophication of ReciPe). The CML2001 method was considered the benchmark and the impact difference (ΔI(%)) between the benchmark and the ReCiPe and ILCD method was reported in Table 12.

Table 12: The impact (I(%)) between the category indicator results of the CML2001, ReCiPe and ILCD method and the impact difference (ΔI(%)) between the benchmark (CML2001) and the ReCiPe and ILCD method

CML2001 (benchmark)	**I(%)**	**ReCiPe impact category**	I(%)	ΔI(%)	**ILCD impact category**	I(%)	ΔI(%)
Acidification	63,7	Terrestrial acidification	58,3	-5,4	Freshwater and terrestrial acidification	58,8	-4,9
Climate change	9,2	Climate change	9,3	-0,4	Climate change	9,2	-0,5
Eutrophication	97,5	Freshw. eutrophication Marine eutrophication	87,5 8,4	+8	Freshw. eutrophication Marine eutrophication Terrest. eutrophication	87,5 8,5 30,2	+8 -49,3
Freshwater ecotoxicity	60,3	Freshwater ecotoxicity Marine ecotoxicity	64,2 70,6	+3,9 +10,3	Freshwater ecotoxicity	84,7	+24,4
Human toxicity	82,3	Human toxicity	93,0	+10,7	Carcinogenic effect Non-carcinogenic	71,6 96,0	-10,7 +13,7
Photoch. oxidation	12,1	Photochemical oxidant formation	47,5	+35,4	Photoch. ozone creation	48	+35,9
Strat. ozone depletion	87,4	Ozone depletion	85,8	-1,6	Ozone layer depletion	87,4	0
Terrestrial ecotoxicity	92,8	Terrestrial ecotoxicity	99,0	+6,2	N.A	-	-
ADP minerals	99,1	Metal depletion	92,9	-6,2	Resources	84,5	-14,6
ADP fossils	2,0	Fossil depletion	4,1	+2,1			
N.A.	-	Part. matter formation	57,9		Respiratory effects	55,8	

The impact differences between the CML2001 method and the two other impact assessment methods were comparable (< ±10%) for the studied flexible intubations scopes for the impact categories of acidification, climate change, eutrophication, stratospheric ozone depletion, ADP minerals and ADP fossils. The outcome differences of the toxicity related impact categories were more diverse (> ±10%) between the different methods; the impact difference between the impact assessment methods was bigger for freshwater ecotoxicity (+24,4% for ILCD), human toxicity (+11,1% for ReCiPe) and photochemical oxidation (+36% for both ReCiPe and ILCD).

The environmental impact of the disposable FVS was higher than the reusable FOB in most impact categories for the ReCiPe and ILCD method, except for ozone depletion and terrestrial ecotoxicity, which is similar to the results of the CML2001 method. The impact on marine eutrophication, an additional impact category of the ReCiPe and ILCD method, was slightly higher for the reusable FOB than the disposable FVS.

3.4 Sustainable concept

Four sustainable concepts were described with complementary drawings, whereafter one concept with the most potential was selected. The final concept was described and evaluated.

3.4.1 Concept description

The concepts were described and illustrated to bring across the core idea of several solutions paths for a sustainable flexible intubation scopes; the concepts indicate the main working principle of the design, so the illustrations do not show the definite mechanisms. The four concepts were (1) disposable fiberoptic bronchoscope, (2) fiberoptic bronchoscope for disassembly, (3) reusable plastic fiber bronchoscope, and (4) hybrid flexible intubation scope.

The LCA suggested that the electronic components of the disposable FVS contributed most to the total environmental impact of the device. Therefore, the electronic components (PCB and copper wires) were replaced by optical fibers in every concept to reduce the environmental impact. Optical fibers use differing refractive indexes (ratio of the velocity of light in a vacuum to the velocity of light in the material) between the core and cladding layer for internal reflection and light propagation and use an objective and relay lens to produce the image.

Optical fibers can be divided into glass optical fibers (GOF) and plastic optical fibers (POF) [29]. GOFs are typically made of pure glass ($SiO2$), are able to transmit light and images in the spectrum of 200-2200 nm (ultraviolet to infrared light spectrum) and can withstand extreme temperatures and corrosive environments without degrading, but they are prone to breaking if not handled carefully (see Figure 14). POFs are generally made from polymethyl methacrylate (PMMA) and operate in the visible wavelength range of 400 to 760nm [56]. In comparison to GOFs, POFs have superior flexibility and resilience to bending, shock, and vibration, are less expensive (due to production set-up and alignment costs) and are more lightweight. However, the loss of transmitted light is 150 dB/km for PMMA and 3 dB/km for glass fibers, so the image quality of GOFs is much better [54].

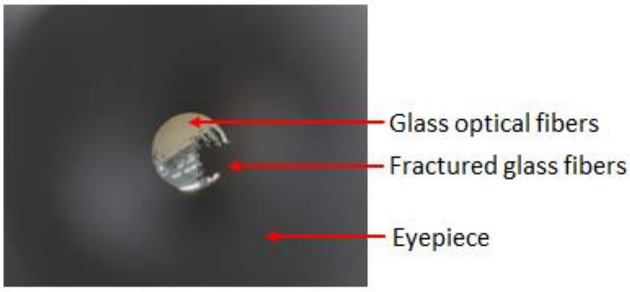


Figure 14: Defects of reusable FOB with fractured optical fibers

Concept 1: disposable fiberoptic bronchoscope

The first concept consists of POF instead of printed circuit board to produce and transmit the image inside the insertion tube of the flexible intubation scope in order to reduce the environmental impact of the device, see Figure 15. The flexible intubation scope can be connected to an external monitor to view the image, which is reused during multiple intubations.
Furthermore, low-impact materials were chosen to replace the ABS and stainless steel in the device, because these materials had the highest contribution to the total environmental impact of the product.

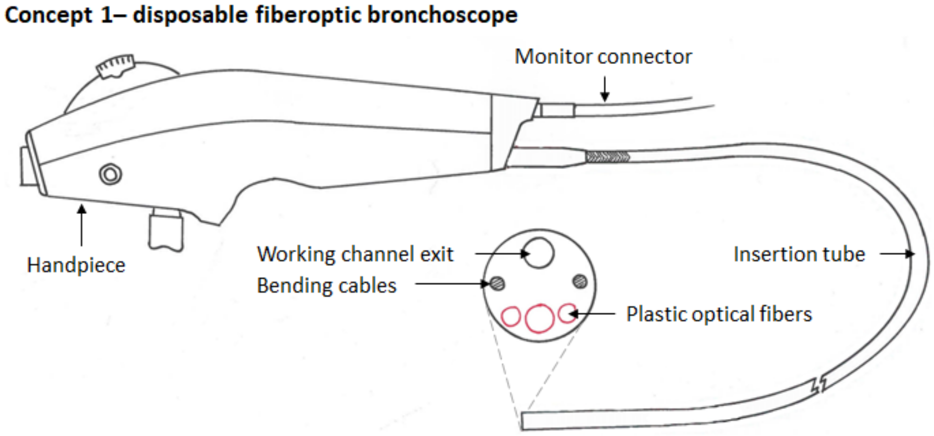


Figure 15: Concept of disposable fiberoptic bronchoscope with glass optical fibers and low-impact materials

Concept 2: fiberoptic bronchoscope for disassembly

The second concept was created to enable disassembly of the device at end-of-life, as displayed in Figure 16. The studied flexible intubation scopes cannot be disassembled easily, see Appendix A. The fiberoptic bronchoscope can be disassembled within a few steps, so parts of the device can be recycled and/or refurbished as the production of materials was responsible for a large proportion of the environmental impact. The main parts of the handpiece are connected by click fit connections and the cables of the external monitor and insertion tube are coupled to the handpiece with a squeeze connector. The ABS parts of the device can be refurbished (collecting and refinishing the parts to serve their original function) and scraps of stainless steel can be recycled instead of incinerated. Furthermore, the image transmission system with the electronic circuit is replaced with POF.

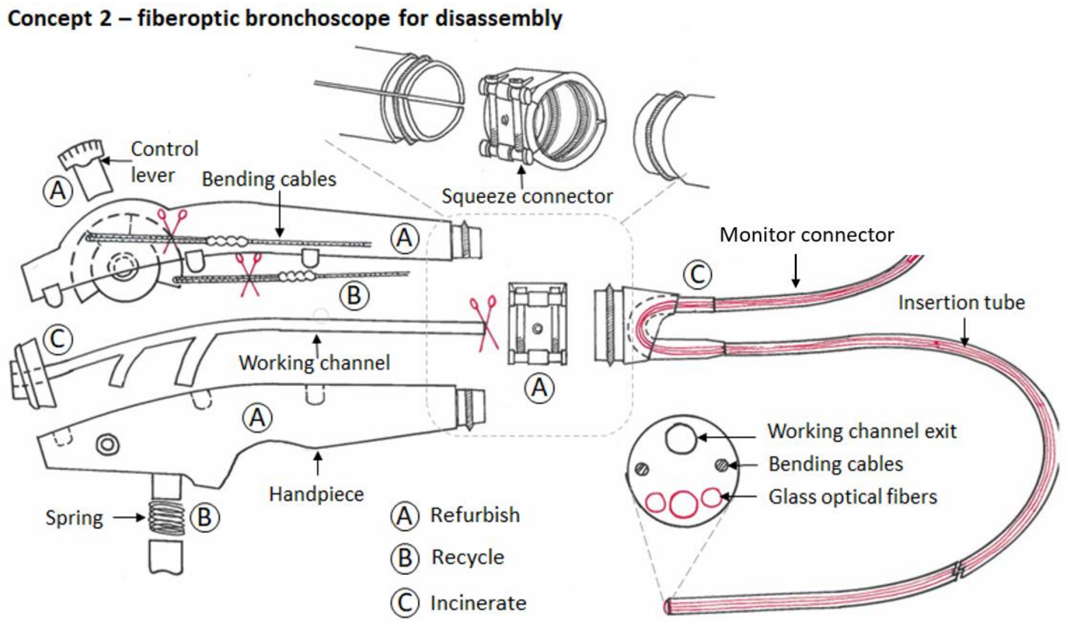


Figure 16: Concept of disposable fiberoptic bronchoscope for easy disassembly to be able to remanufacture/recycle parts

Concept 3: reusable plastic fiber bronchoscope

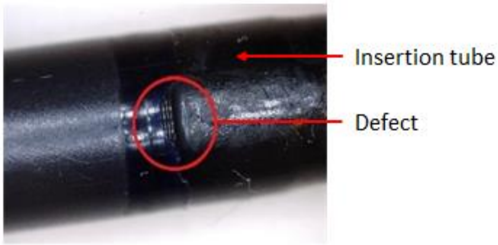


Figure 17: Defects of reusable FOB deflection tip of the insertion tube

The third concept was created to enhance the durability of the reusable intubation scope, see Figure 18. The lifetime of the original reusable FOB is limited due to the durability of the glass fibers and the fragility of the bending section of the insertion tube. The image quality of the glass fibers gradually decreases after multiple reuses due to fracturing of the fragile glass fibers, see Figure 14 [57]. In the concept, the glass fibers are replaced by POF to increase the resilience to bending, shock, and vibration. Secondly, the original reusable FOB was fractured at the cardans of the bending section most often, which resulted in failure of the leak test of the device, see Figure 17. In order to make the bending section of the insertion tube more shock resistant to external forces, the polyurethane sleeve was made slightly thicker at the most fragile part of the bending section.

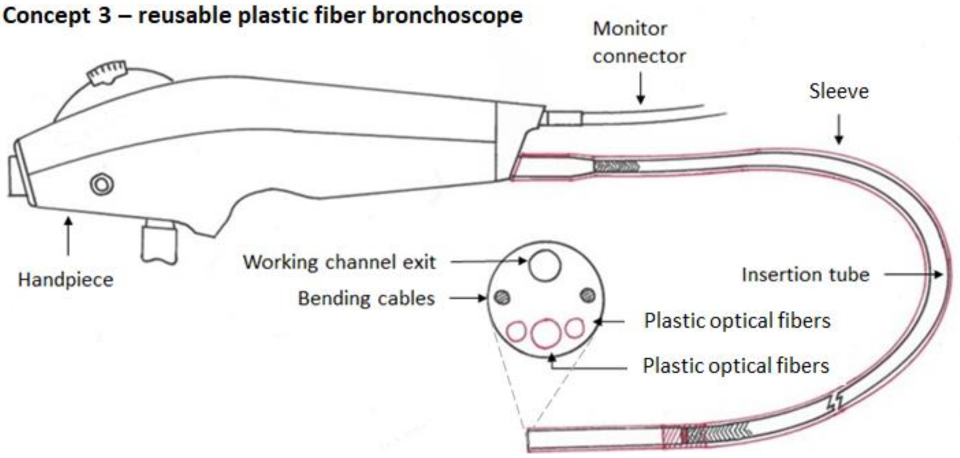


Figure 18: Concept of reusable flexible video endoscope with plastic optical fibers and a robust bending section

Concept 4: hybrid flexible intubation scope

The fourth concept was created to optimize the initial lifetime of the reusable device, so the flexible intubation scope can be used for more than 450 patient intubations. Figure 19 displays the hybrid flexible intubation scope with a reusable handpiece and a separate insertion tube that is intended to be reused until the image quality of the glass fibers diminishes, which was inspired by an electric toothbrush. The insertion tube is connected before use (by rotational force with a bayonet locking mechanism) and consists of glass fiberoptic bundles, a channel for fluids and two deflection cables. Insertion tubes with various diameters could be made to enable patient specific choice of tube diameter. The reusable handpiece consists of the control mechanism for tip deflection and fluid irrigation. The parts are connected through a mechanism that ensures that the bending cables are coupled for proper bending of the distal tip and the fluid channel is linked sufficiently to avoid leakage, but this connection mechanism is not designed yet.

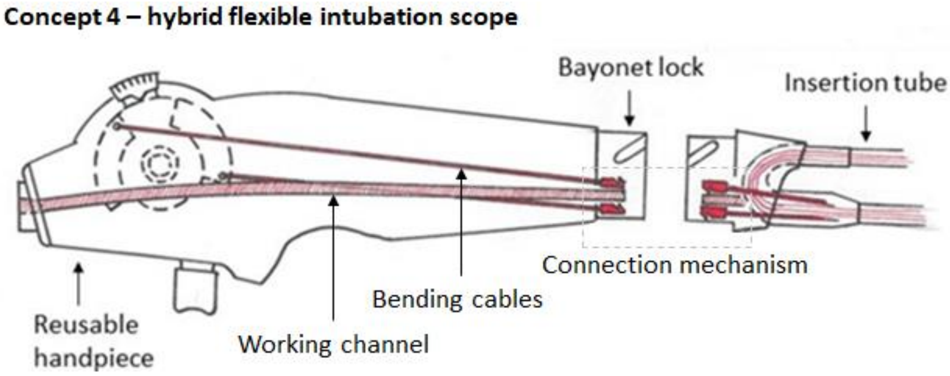


Figure 19: Concept of hybrid flexible intubation scope with reusable handpiece and separate insertion tube

3.4.2 Concept selection

The four concepts were evaluated based on five selection criteria (performance, usability, complexity, affordability and circularity) with the concept evaluation matrix to choose the concept with the most potential, see Table 13. Each concept is scored based on how well it fulfills the criterion; exceeds (green, multiplication of 2), meets (yellow, multiplication of 1), or does not meet (orange, multiplication of 0).

Table 13: Concept evaluation matrix for concept selection [plastic optical fibers (POF) and glass optical fibers (GOF)]

Criterium	**Weight**	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**
Performance	1	POF	POF	POF	GOF
Usability	2	No actions	Disassembly	Disinfection	Detach, disinfection
Complexity	3	Not complex	More connections	Not complex	Complex mechanism
Affordability	3	Purchasing price	Purchasing price	Affordable	Costs insertion tube
Circularity	1	Not circular	Refurbish, recycle	Reuse	Reuse
Total		14	10	19	8

The *performance* criterion is met for concepts 1, 2 and 3, because the image quality of the POF is adequate; the pixel size of the POFs ranges between 250µm and 1000µm and the transmission loss of light is low due to the short length of the fibers (≈ 200cm). The image quality of the glass fibers of concept 4 exceeds the *performance* criterion, because the transmission loss is very low (3 dB/km) and the pixel size of the GOF ranges from 15µm to125µm.

The *usability* of concept 1 exceeds the criterion, because no additional actions need to be taken by the user before or after use of the device (except for disposal of the device). Concepts 2, 3 and 4 meet the *usability* criterion, because less than 10 additional actions are required; concept 2 needs to be disassembled after use, concept 3 must be disinfected after use and the handpiece and separate insertion tube of concept 4 need to be attached before and detached after use.

Furthermore, concepts 1 and 3 exceed the *complexity* criterion, because the number of components and connections of the device are not increased compared to the studied flexible intubation scopes. Concept 2 is more complex to manufacture and assemble, because the device consists of more connections between the parts to enable disassembly and a squeeze connector is added. The *complexity* criterion is not met by concept 4, because the connection mechanisms between the handpiece and separate insertion tube is very complex; the connection mechanism must form a reliable connection between the parts during use, enable fast attachment and detachment of the parts when required, ensure tightening of the bending cables and provide a leak tight connection between the working channels.

In order to estimate the *affordability* of the concepts, the total costs per device per procedure were calculated for the disposable FVS and reusable FOB, see Appendix G. The cost analysis revealed that there is a break-even point between the costs of the disposable FVS and reusable FOB at 209 patient intubations, see Figure 20. The unit costs of a disposable FVS are approximately 30% higher than the unit costs of one of a reusable FOB (€187,- vs €144,-) at the intended lifetime of 450 uses.

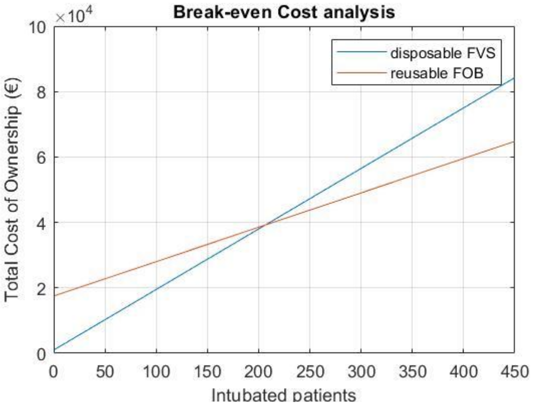


Figure 20: Break-even analysis total costs per procedure for disposable FVS and reusable FOB with intersection at 209 intubated patients

Concepts 1, 2 are expected to meet the *affordability* criterion due to the low costs of the POF, but the total costs per procedure for the disposable intubation scopes are higher at 450 patient intubations compared to the reusable options. The total cost per procedure of concept 4 is likely to be higher than the reusable FOB, because the insertion tube with glass optical fibers is replaced when the image quality of the fibers diminishes after a number of reuses, thus increasing the manufacturing costs. Concept 3 is presumably less expensive than the reusable FOB, because the production set-up and alignment costs are less expensive for POF than GOF and therefore exceeds the criterion.

Finally, concepts 2, 3 and 4 consist of a circular component as the devices are reused, recycled or refurbished after use, so they meet the *circularity* criterion. Concept 1 is disposed immediately after use, which indicates a linear product, so the concept does not meet the criterion.

The concept evaluation matrix suggests that concept 3 has the most potential, because concept 3 has the highest total score compared to the other concepts.

3.4.3 Final concept

The final concept is the reusable plastic fiber bronchoscope, displayed in Figure 21. The final concept consists of a description of the material composition of the parts and the primary manufacturing processes of the device that were altered compared to the reusable FOB.

The image transmission system consists of POF made from PMMA as the core material and fluorinated polymer as fiber cladding material with a refractive index of approximately 1.49 and 1.35, respectively. The medical grade multimode fiber (Toray Raytela, Fiberfin) has a fiber diameter of 250µm [54, 58]. Light-emitting diodes (LED) are integrated in the external monitor as data transmitters and receivers, because LEDs generally operate at the wavelength of 650 nm at which the fiber core is most transparent [58]. The primary manufacturing process for synthetic optical fibers is extrusion, where the polymeric liquid is extruded through fine holes. Thereafter, the fibers are drawn out to the desired diameter and length to increase the crystallinity and the strength of the fibers [59].

The polyurethane layer around the insertion tube was made thicker at the most fragile part of the bending section. The thickness of the polyurethane sleeve is 0,4 mm at the insertion tube and 0,6 mm at the bending section of the insertion tube to avoid fracturing of the cardans. Extrusion is used as the primary method for manufacturing the polyurethane sleeve with multiple thicknesses [60].

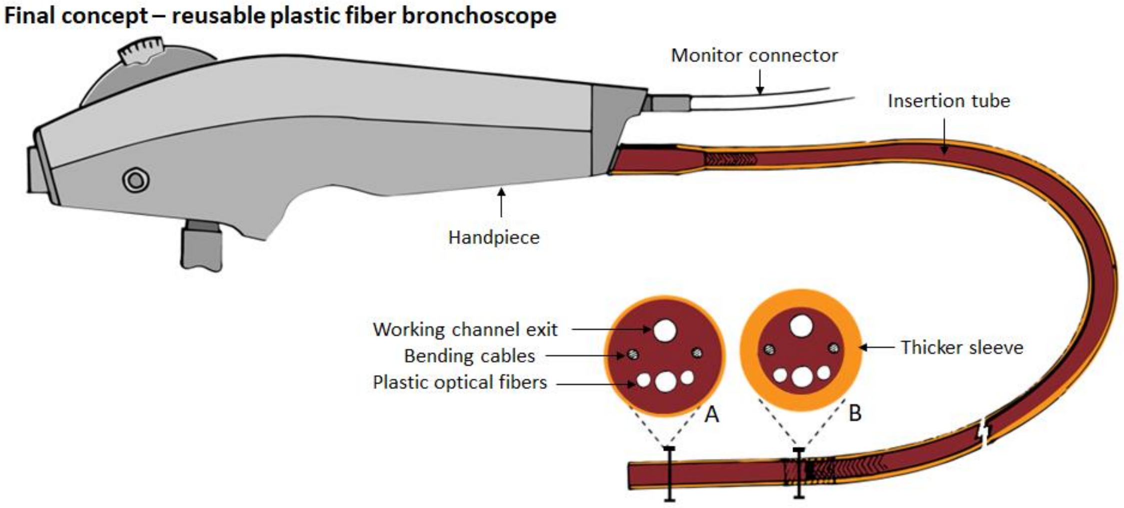


Figure 21: Final concept – Reusable plastic fiber bronchoscope with plastic optical fibers as image transmission system and a polyurethane sleeve at the (A) the insertion tube and (B) fragile part of the bending section

3.4.4 Concept evaluation

The alterations of the LCA model for the final concept are reported in Appendix I. The category indicator results and total impact score of the R-FOB and final concept at 450 patient intubations are shown in Table 14, including the percental difference between the results. The final concept had a slightly higher environmental impact on the categories of eutrophication (+0,4%) and ADP fossils (+0,5%), due to the production and manufacturing of the plastic optical fibers. Most impact categories were not affected by the alteration of the input parameters of the final concept. The functional unit at which the environmental impact of the reusable FOB and the final design is the same is at approximately 464 patient intubations.

Table 14: Category indicator results and total impact score of R-FOB and final concept, with the percental difference

Impact category	**Category indicator result**		
	R-FOB	Final concept	Difference (%)
Acidification	2,92	2,93	+0,2
Climate change	1,12E+03	1,12E+03	0,0
Eutrophication	1,98	1,99	+0,4
Freshwater aquatic ecotoxicity	1,04E+03	1,04E+03	0,0
Human toxicity	906	907	+0,1
Photochemical oxidation	0,312	0,313	+0,2
Stratospheric ozone depletion	0,000662	0,000662	0,0
Terrestrial ecotoxicity	202	202	0,0
ADP minerals	0,0644	0,0644	0,0
ADP fossils	1,70E+04	1,71E+04	+0,4
Total impact score	2,48E-08	2,49E-08	+0,3

4. Discussion

The goal of this study was to compare the environmental impact of disposable and reusable flexible intubation scopes and design a sustainable concept to enable data-driven selection of sustainable flexible intubation scopes. The results from the life cycle assessment suggest that the reusable fiberoptic bronchoscope has a lower life cycle impact in comparison to the disposable flexible video endoscope, which reflects the equivalence between 450 disposable devices and 450 uses of the reusable *alternative*. Therefore, the reusable FOB is preferable from an environmental perspective. The final concept of the sustainable flexible intubation scope is a reusable plastic fiber bronchoscope with plastic optical fibers and a thicker sleeve at the bending section of the insertion tube to enhance the durability and thereby elongate its lifespan.

Life cycle assessment

The category indicator results of this LCA showed that the disposable FVS has a higher environmental impact (> 60%) compared to the reusable FVS in most impact categories, including acidification, eutrophication, freshwater aquatic ecotoxicity, human toxicity and ADP minerals. The material production and manufacturing of the PCB components contributed most to the impact of the disposable FVS, because the components had to be made 450 times. The studied flexible intubation scopes had similar category indicator results for the impact category of climate change and photochemical oxidation and the reusable FOB has a higher environmental impact (> 90%) compared to the disposable FVS in the categories of stratospheric ozone depletion and terrestrial ecotoxicity. The disinfection process contributed most to environmental impact of the reusable FVS's life cycle, because the device has to be high-level disinfected after each use.

The normalized impact assessment results demonstrated that the flexible intubation scopes have a high contribution to eutrophication and ADP minerals relative to the total annual world interventions. The impact on eutrophication of the disposable FVS can be explained by the amount of sulfidic tailing, which is the waste materials after mining, resulting from the production of copper that causes nutrient enrichment in terrestrial environments. The depletion of minerals is also relatively high, because the PCB components contain gold and silver material, which are rare minerals on earth. The toxicity related impact categories were not taken into account during normalization, because the normalization results are often largely overestimated [61]. The number of environmental flows of toxic related impact categories is incomplete in currently available normalization references as there is an extensive number of toxic substances in the world.

The total impact score relative to the total annual world interventions of the disposable FVS and reusable FOB were $7{,}92 \cdot 10^{-8}$ and $2{,}48 \cdot 10^{-8}$, respectively, which implies that overall the reusable FOB is more environmentally friendly. However, weighting of the impact categories is a subjective step, because the relative importance of the impact categories is determined through value judgement. There are different approaches to determine the weighting factors, including policy targets, scientific targets, monetary value or panel weighting. Climate change is often considered the most important impact category and therefore receives the highest weighting factor [43]. The weighting factors of this LCA were based on three expert panel sets to reduce potential bias. The total impact score allows for easy comparison and communication of the impact between the alternatives in an LCA, but the outcome should be treated with caution [1].

The influence of the model choices was analyzed by the scenario analysis, which showed that the overall outcome of the LCA would not change if the flexible intubation scope was discarded after 380 patient intubations or if another impact assessment model was chosen. The total impact score of the disposable FVS and reusable FOB would be equal at approximately 84 patient intubations, so the reusable flexible intubation scope should be reused minimally 84 times to maintain a lower environmental impact. The ReCiPe and ILCD method suggested that the disposable FVS has a higher environmental impact compared to the reusable FOB in most impact categories, which was similar to the category indicator results of the CML2001 method. The impact difference between the alternatives was even considerably bigger in three impact categories of the ILCD and ReCiPe method (freshwater ecotoxicity, human toxicity and photochemical oxidation), which is probably due to the differences in categorization factors between the impact assessment methods.

The method and outcomes of another LCA study, investigating the environmental impact of bronchoscopes, were compared to this LCA study to inspect if the results were consistent [5]. The study of Sorenson e.a. compared the use and disposal of one single-use bronchoscope and materials for the disinfection process of one reusable bronchoscope, so the basis of comparison was different from this LCA study [5]. The outcome of the LCA study was that CO2-equivalent emissions and resource consumption of the reusable bronchoscope were higher than the single-use bronchoscope when using one set of protective wear per disinfection process, while the environmental impact was comparable when using the equipment twice or more. Other life-cycle stages (e.g. material production, manufacturing) were not considered in the impact assessment of Sorenson e.a., so the LCA study '*could not conclude which type of bronchoscope affects the environmental factors the* most' [5]. The current LCA included all life-cycle stages of flexible intubation scopes, so this LCA provides a more complete outline of the environmental impact.

Concept ideation

The concept evaluation showed that the environmental impact of the final concept was slightly higher (+0,3%) compared to the reusable FOB, so the final concept is not more sustainable than the studied flexible intubation scopes at 450 patient intubations. The final concept was designed to be more durable and thus extend the lifetime of the device, which would presumably lower the environmental impact of the device per procedure if the device is used more than 464 times. A fatigue test of the device is required to determine the number of times the final concept can be reused. In successive research, performance and usability tests should be performed on a prototype of the final concept to evaluate the other requirements of the flexible intubation scopes and to develop the final concept into a successful product.

Concept selection suggested that the final concept (reusable plastic fiber bronchoscope) has more potential compared to the other concepts, but the disposable fiberoptic bronchoscope (concept 1) would reach a similar outcome in the concept selection table when the device is more affordable. Advancement of the POF technology could decrease the costs of manufacturing and alignment. Also, the total costs per procedure are only higher for the disposable FVS if the intubation scope is used for more than 209 patient intubations, but flexible intubation scopes are not used frequently due to the small target patient group (patients with a difficult airway) and due to the introduction of video laryngoscopes [31]. The disposable fiberoptic bronchoscope probably has a lower environmental impact than the final concept, because the components with the highest contribution to the impact (e.g. PCB board) were replaced and the disposable device does not need to be high-level disinfected. Therefore, it is recommended to produce the disposable fiberoptic bronchoscope (concept 1) for the replacement of disposable FVS if the total costs per procedure are equal to the reusable flexible intubation scopes.

The environmental impact of the concepts could be decreased further by selecting low-impact materials (e.g. renewable materials, recyclable materials) for the device. The contribution analysis showed that the brass components had the highest environmental impact of the R-FOB materials relative to the weight of the components, so brass could be replaced by a low-impact material. The material choice depends on the material properties and environmental impact for material production, manufacturing of the parts and disposal of the material. Aluminium-magnesium alloy seems to be a good alternative for brass due to their similar mechanical properties and lower impact regarding the material's production, however casting of aluminium alloy causes a much higher impact compared to brass casting, see Appendix J. More extensive research about low-impact materials would be valuable to reduce the environmental impact of flexible intubation scopes.

Furthermore, the LCA demonstrated that the disinfection process has the largest contribution to the environmental impact of the life cycle of the reusable FOB. In this study, concept generation was not directed towards improving the product system level, but it is recommended to revise the disinfection process to make the life cycle of the reusable flexible intubation scopes more sustainable. Disposable products (e.g. gloves, mouth masks and gowns) could be worn during multiple disinfection procedures instead of one to reduce the environmental impact of the disinfection process, although the risk of infection must be considered carefully. Also, the amount of electricity for blow-drying the intubation scope could be decreased by drying more flexible endoscopes at once in the machine, because eight flexible endoscopes can be blow-dried at the same time in the Medivators Endodry [62].

Flexible intubation scopes with plastic optical fibers are currently not on the market yet. Glass fibers have dominated the market due to their excellent image quality over short and long distances, causing plastic optical fibers to be over-shadowed [54]. Also, the minimal outer diameter of POF used to be 1000 µm, while multimode GOFs have an outer diameter of approximately 125 µm [58]. Recent developments in POF technology have resulted in POFs with an outer diameter of 250µm, making them applicable to devices with small diameter sizes such as flexible intubation scopes. POF have the advantage of being cost-effective, lightweight and flexible compared to GOF. The loss of light transmittance is higher for POF (150 dB/km) compared to GOF (3 dB/km) at 650nm due to absorption or scatting of light, but this is low (< 0,1 dB) for both optical fibers at short distances; the dB loss is 0,075 dB and 0,0015 dB at 0,5m for the POF and GOF, respectively. In order to be able to implement POF in the design of flexible optical scopes, some disadvantages have to be overcome; there is a lack of standards for POF and a limited number of producers and suppliers, so more research and resources are required to reach the full potential of POF [54]. Another advancement in optical fiber technology is the development of biopolymer based optical fibers for short distance applications, which could be a sustainable option for the image transmission system of flexible intubation scopes in the future [63].

Besides the reusable FOB and the disposable FVS studied, there are also other models of flexible intubation scopes on the market. Storz has introduced the CMOS Five 6.5, which is a reusable flexible video endoscope (FVS) with a CMOS (Complementary metal oxide semiconductor) camera [64]. The CMOS camera has superior image quality compared to optical fibers, but the high resolution of the image is not required for sufficient performance of the device. The reusable FVS was not studied in this LCA, because the model was not available for material identification for the inventory analysis. The environmental impact of reusable FVS is expected to be slightly higher than the reusable FOB due to the electronic components, but the total impact score is probably lower compared to the disposable FVS, because the PCB components have to be manufactured once instead of 450 times. Therefore, the reusable FVS could also be considered when replacing the disposable FVS with a more sustainable flexible intubation scope.

Limitations

There are several limitations to this study. First of all, the inventory data for the LCA are incomplete, resulting in potential underestimation of the environmental impact of the flexible intubation scopes. The material composition of the *alternatives* was obtained through material identification techniques (XRF and FTIR), but the composition of small metal parts could not be identified because the sample needed to be flat and the sample size was required to be bigger than $1\ cm^2$ for identification with XRF. However, the sensitivity analysis suggested that the influence of the product materials on the outcome was small, so it is not critical to gather more accurate data for the amount of material in the flexible intubation scope. Furthermore, the inventory results only contained data about the primary manufacturing processes (e.g. casting and forming) of the product and packaging, but data about secondary manufacturing processes (e.g. machining, surface working) and assembly of the half products were not included. The impact related to the disposable FVS could have been underestimated in this LCA study due to incompleteness of manufacturing data, because the manufacturing stage is incorporated 449 times more compared to the reusable alternative. On the other hand, the secondary manufacturing processes and assembly steps of the reusable FOB are more complex due to sophisticated end parts and connections (Appendix A), which could also have led to an underestimation of the environmental impact. Also, transport of the product from the manufacturer to the hospital was not taken into account, because of lack of information. However, the environmental impact of a product's life cycle also depends on the transport distances and type of transport, so the impact of the flexible optical scopes could have been underestimated. In order to avoid potential bias and asses the exact environmental impact of the alternatives, more data should be gathered for the LCA inventory.

Secondly, assumptions had to be made during data collection of the inventory results, which could have led to uncertainty of the data. Similar studies also mentioned the difficulty of obtaining LCI data from medical device manufacturers due to confidentiality of the product or unwillingness of participating in LCA studies [65]. Assumptions were made for the weight of the PCB components and the local sensitivity analysis suggested that the LCA model was sensitive to the input of the integrated circuit and copper wires of the disposable FVS, so these variables can change the results considerably. The value of the integrated circuit is very small (6,92E-04 kg), so accurate data for the input variable is required to make the outcome of the LCA more robust. The PCB components could be soldered off the printed wiring board and weighed for more accurate data. Furthermore, the protective clothes of the CSD employee were assumed to be replaced after one disinfection process, but the protective clothes are often worn during multiple procedures so the environmental impact is probably overestimated. Assumptions were also made about the primary production processes of the flexible intubation scopes, but the local sensitivity analysis showed that the input variables of the manufacturing processes had almost no influence on the LCA model. The sensitivity analysis also showed that the amount of water, electricity and soap for disinfection had a large influence on the LCA model, so the observational study should be repeated several times to obtain more accurate data.

Lastly, the local sensitivity analysis was performed to investigate the robustness of the model to various uncertain input parameters. However, local sensitivity analysis does not take into account '*interaction effects between parameters, does not assess all model parameters and assumes all parameters have strictly linear effects.*'[66]. Some sensitive parameters might have been overlooked, although the input parameters with the highest uncertainty were analyzed. In order to analyze the sensitivity of every parameter of the model (≈ 14.000) and consider their probability distribution, it is recommended to use a sampling based approach, such as a Monte Carlo simulation or a global sensitivity analysis.

Recommendations

In order to select a sustainable flexible intubation scope at present, it is recommended to replace the disposable flexible video endoscopes with a reusable alternative due to the higher environmental impact of the disposable flexible video endoscope. Another option is to design and produce a flexible intubation scope without PCB due to the high environmental impact of PCB manufacturing. The current shortage of semiconductor chips, a component of the integrated circuit, emphasized the need to select devices with a limited number of electronic components. Furthermore, in order to reduce the environmental impact of reusable flexible optical scopes, the durability of the device should be enhanced. More research is required about plastic optical fibers to be able to implement them in the design of flexible intubation scopes and develop the final concept (reusable plastic fiber bronchoscope) into a successful product. Also, the selection of low-impact materials for the product and optimizing the disinfection process could potentially make the intubation scopes more sustainable.

This study enables data-drive selection of sustainable flexible intubation scopes, so it makes a small contribution towards a more sustainable healthcare system. However, there are numerous medical devices that have a large impact on the environment. Approximately 10% of the total environmental impact of Dutch hospitals is associated with medical device manufacturing [67]. Therefore, this study should be perceived as a case study to reduce the environmental impact of medical devices and stimulate more research about the sustainability of medical devices.

5. Conclusion

The selection of medical devices should be based on the clinical performance, usability, safety and procurement costs, but also on the environmental sustainability of the device. This study has demonstrated that the environmental impact and total costs per procedure are higher for disposable flexible video endoscopes, therefore selecting a reusable fiberoptic bronchoscope is preferred. Manufacturing of the printed circuit board contributed most to the environmental impact of the disposable video endoscopes, hence the electronic components should be replaced by another image transmission system. The disinfection process has the highest contribution to the impact of the reusable FOB, so it is recommended to revise its life cycle at product system level to reduce the environmental of the reusable flexible intubation scopes. The sustainability of reusable flexible intubation scopes can be improved further by developing a device that is more durable and contains low-impact materials. Data-driven selection and development of sustainable flexible intubation scopes can make a contribution towards a more sustainable healthcare sector, so let’s make a change!

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Appendix A: Material identification

The flexible intubation scopes were disassembled, see Figure 22 and 23. Disassembly of AMBU aScope was done within one hour, while taking apart the reusable fiberscope lasted four hours. The reusable FOB contained several sophisticated connections with screws or glue connections that were difficult to dismantle.

Figure 22: Picture of demounted AMBU aScope 4

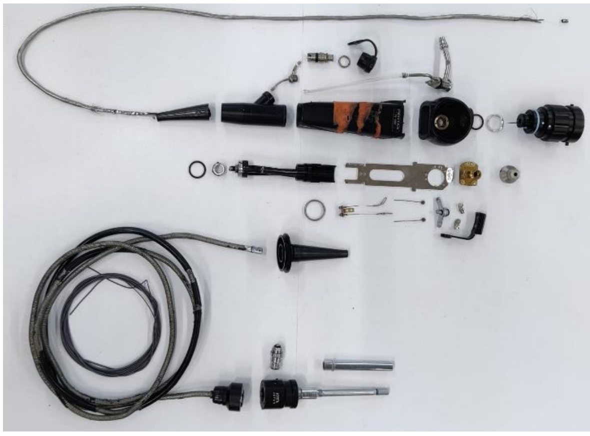

Figure 23: Picture of demounted Storz Bronchoscope BNX

A.1 Synthetic material identification

Samples were made for identification of the synthetic material and and metal parts of the flexible intubation scopes. Synthetic materials were identified with Fourier-transform infrared spectroscopy (FTIR, Thermoscientific is50). The results of the FTIR are displayed in Figure 24 and compared to FTIR graphs of synthetic polymers to identify the material of the sample.

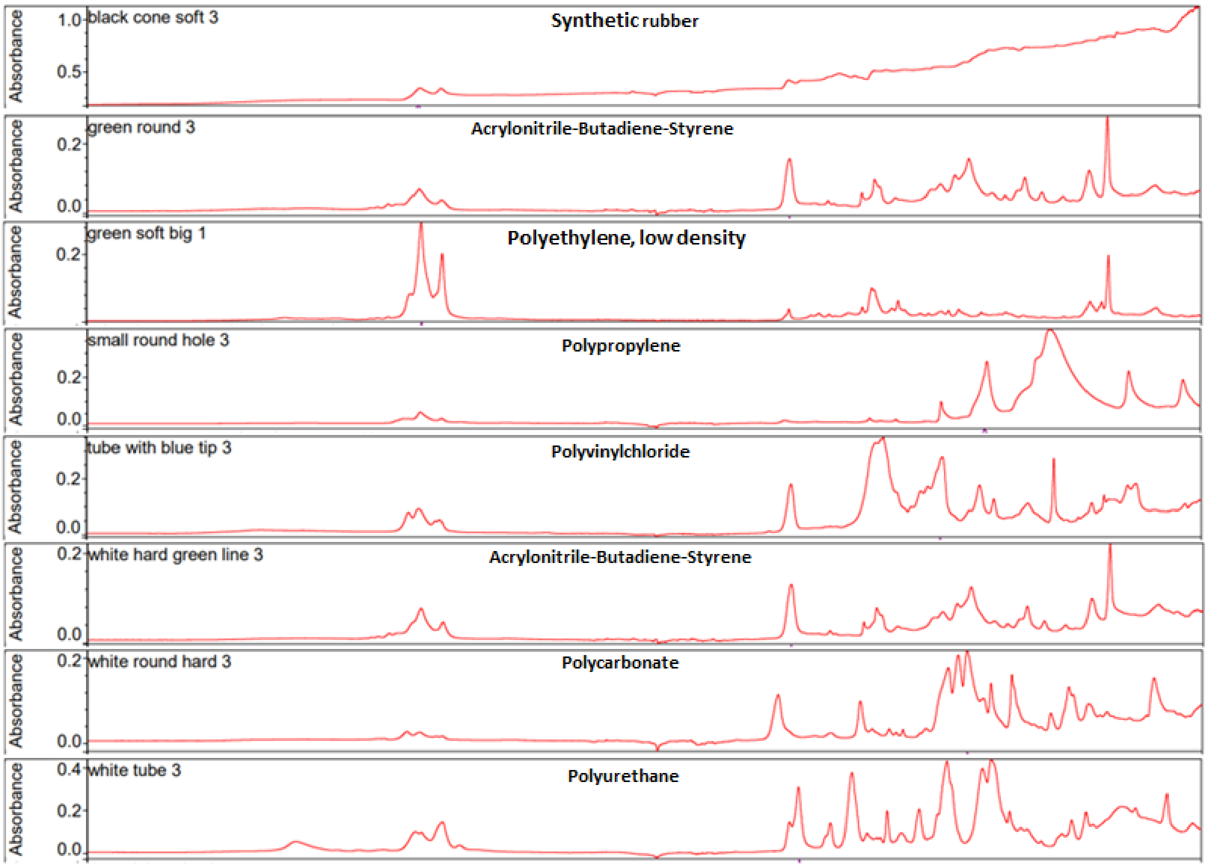

Figure 24: Fourier transformed Infrared Spectroscopy(FTIR) graphs of eight material samples of flexible intubation scopes

A.2 Metal material identification

Metal parts were meaured with X-Ray fluorescence (Panalytical Axios Max WD-XRF spectrometer) and evaluated with SuperQ5.0i/Omnian software. Eight metal samples was presented in Figure 20 and results of the metal identification are displayed in Table 13-20 with the five most abundant compounds of each sample. The concentration of each compound and their absolute error were reported as weight percentages (wt%). The absolute error was calculated at normalization of the weight percentage to 100%, after the dispersion around the calibration line of the compound was determined as the relative error. The metal identification results are shown in Table 21.

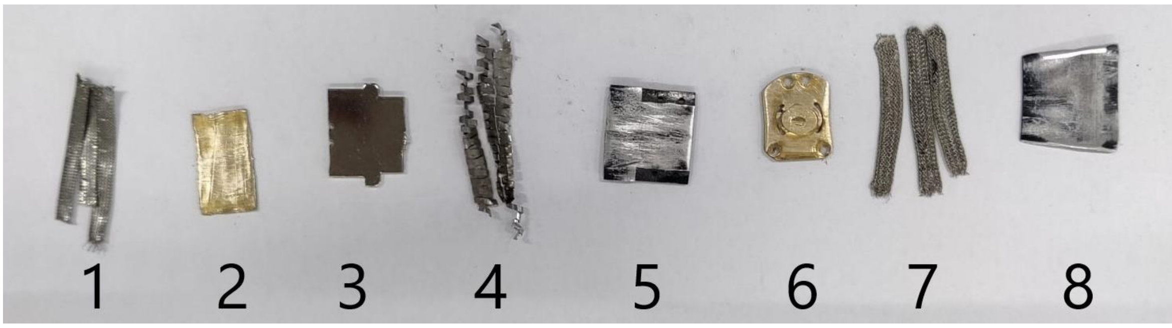

Figure 25: Metal samples of the flexible intubation scopes for identification of the material with X-Ray fluorescence

Table 13: XRF results sample 1

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Fe	64.167	0.5
2	Cr	16.187	0.2
3	Ni	12.535	0.3
4	Mo	2.278	0.04
5	Mn	1.847	0.07

Table 14: XRF results sample 2

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Cu	61.862	0.3
2	Zn	35.02	0.2
3	Pb	2.243	0.07
4	Sn	0.231	0.02
5	Al	0.222	0.01

Figure 15: XRF results sample 3

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Ni	88.809	0.2
2	Fe	8.986	0.09
3	Cu	1.754	0.04
4	Al	0.146	0.01
5	Cl	0.118	0.01

Table 16: XRF results sample 4

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Fe	72.111	0.6
2	Cr	15.937	0.2
3	Ni	8.68	0.3
4	Mn	1.164	0.06
5	Al	0.503	0.02

Table 17: XRF results sample 5

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Al	88.855	0.09
2	S	5.324	0.07
3	Mg	3.998	0.06
4	Cl	0.436	0.02
5	Cu	0.332	0.02

Table 18: XRF results sample 5

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Cu	57.225	0.1
2	Zn	36.132	0.1
3	Al	2.429	0.05
4	Pb	2.34	0.05
5	Cl	0.742	0.03

Table 19: XRF results sample 7

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Fe	61.802	0.3
2	Cr	18.124	0.1
3	Ni	11.644	0.2
4	Mo	2.344	0.05
5	Mn	1.5	0.04

Table 20: XRF results sample 8

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Al	86.631	0.1
2	S	7.203	0.08
3	Mg	3.372	0.05
4	Cl	1.289	0.03
5	Na	0.328	0.02

Table 21: metal identification results

Sample	Material
1	Stainless steel
2	Brass
3	Nickel-iron alloy
4	Stainless steel
5	Aluminum sulphide
6	Brass
7	Stainless steel
8	Aluminum sulphide

Appendix B: Data Collection Table

B.1 Data collection table for disposable FVS

Table 22: Data Collection Table for disposable FVS

Unit	Product parts FVS	Material	Amount	Production process
gram	White casing part 1	Acrylonitrile-Butadiene-Styrene [ABS]	20,6	Injection moulding
gram	White casing part 2	Acrylonitrile-Butadiene-Styrene [ABS]	25,1	Injection moulding
gram	White structured cable long	Polyurethane [PU]	8,2	Extrusion
gram	White soft cone with blue arrow	Polyvinylchloride [PVC]	5,6	Polymer Casting
gram	Luer lock	Polycarbonate [PC]	0,7	Injection moulding
gram	White large round part	Polycarbonate [PC]	5,1	Injection moulding
gram	Green soft bottom casing	Polyethylene, low density [PE, low]	4,0	Polymer Casting
gram	White small hose	Polyurethane [PU]	0,5	Extrusion
gram	White part for fluids	Acrylonitrile-Butadiene-Styrene [ABS]	3,5	Injection moulding
gram	Green cap	Acrylonitrile-Butadiene-Styrene [ABS]	0,5	Injection moulding
gram	Green handle	Acrylonitrile-Butadiene-Styrene [ABS]	1,3	Injection moulding
gram	White rod with connection to wires	Polycarbonate [PC]	2,9	Polymer Casting
gram	Metal elastic wire	Stainless steel	4,0	Drawing
gram	White part with hose for fluids	Acrylonitrile-Butadiene-Styrene [ABS]	3,3	Polymer Casting
gram	White part with multiple diameters	Acrylonitrile-Butadiene-Styrene [ABS]	1,0	Polymer Casting
gram	Blue wire	Synthetic rubber	1,5	Extrusion
gram	Spring	Stainless steel	0,6	Drawing
gram	White small round part (2x)	Polypropylene [PP]	0,6	Injection moulding
gram	Metal wire	Stainless steel	0,3	Drawing
gram	White hose	Polyurethane [PU]	1,5	Extrusion
gram	Electricity cable	Polyvinylchloride [PVC]	42,2	Drawing
gram	Copper wires	Copper	17,9	Drawing
	Printed circuit board components			
kg	Diode	Diode, glass for surface mounting	3,20E-05	
kg	Integrated circuit (2x)	Integrated circuit, logic tyoe	6,92E-04	
m2	Printed wiring board	Printed wiring board, surface mounting	4,64E-04	
kg	Capacitor	Capacitor, for surface mounting	8,60E-05	
kg	Resistors (4x)	Resistor, for surface mounting	9,40E-05	
kg	Inductor	Inductor, low value multilayer chip	8,16E-06	
kg	Light emitting diode	Light emitting diode	3,50E-04	
m2	Mounting	Mounting, surface mount technology, pb free	4,64E-04	
	Packaging materials			
gram	Paper packaging around scope	Bleached kraft paper	4,9	Corrugation
gram	Packaging box transportation	Unbleached kraft paper	28,76	Corrugation
gram	Synthetic cover handle scope	Polypropylene [PP]	43,8	Injection moulding
gram	Synthetic packaging around scope	Polyethylene, high density [HDPE]	2,4	Extrusion, plastic fil
	Pre-sterilization			
kWh	Electricity consumption	Elecricity, low voltage	0.62	
mg/L	Ethylene oxide (EtO) gas		725	
	Use			
kWh	Energy monitor	Electricity, low voltage	0,0063	

B.2. Data Collection Table for reusable FOB

Table 23: Data Collection Table for reusable FOB (materials-use)

unit	Part R-FOB	Materials	Amount	Production process
gram	Black synthetic casing	Phenolic resin	26,8	Injection moulding
gram	Black synthetic round casing	Phenolic resin	23,4	Injection moulding
gram	Black metal case for fluids	Aluminium sulphide	37,7	Casting, lost wax, aluminium
gram	Silver bar in casing	NIckel-iron alloy	17,7	Sheet rolling, copper
gram	Black metal cover for wires	Aluminium sulphide	15	Casting, lost wax, aluminium
gram	Optical piece	Aluminium sulphide	57,8	Casting, lost wax, aluminium
gram	Golden part	Brass	6,6	Casting, brass
gram	Silver rod with different diameters	Brass	5,8	Wire drawing, copper
gram	Black soft cone (3x)	Synthetic rubber	3,3	Extrusion, plastic pipes
gram	Silver rod casing	Brass	10,6	Wire drawing, copper
gram	Silver small rod with screw thread	Brass	0,1	Wire drawing, copper
gram	Silver small rod with two diameters	Brass	8,9	Wire drawing, copper
gram	Cap	Synthetic rubber	3	Polymer casting
gram	Silver long rod on synthetic case	Brass	36,5	Wire drawing, copper
gram	Black rubber band large	Synthetic rubber	0,4	Extrusion, plastic pipes
gram	Black rubber band small	Synthetic rubber	0,1	Extrusion, plastic pipes
gram	Silver ring large	Aluminium sulphide	1,3	Sheet rolling, aluminium
gram	Silver ring middle	Aluminium sulphide	0,3	Sheet rolling, aluminium
gram	Silver ring small	Aluminium sulphide	0,5	Sheet rolling, aluminium
gram	Silver rotating piece with two threads	Brass	3,7	Wire drawing, copper
gram	Grey wire	Synthetic rubber	3,4	Extrusion, plastic pipes
gram	Silver kidney piece (2x)	Brass	0,7	Casting, brass
gram	Golden part with two wires	Brass	1	Sheet rolling, copper
gram	Silver part in case for fluids small	Brass	2,1	Wire drawing, copper
gram	Handle	Aluminium sulphide	5,7	Casting, lost wax, aluminium
gram	Silver screw thread	Brass	1,7	Wire drawing, copper
gram	Silver part for fluids large	Brass	13,2	Wire drawing, copper
gram	Black round part	Aluminium sulphide	10,6	Casting, lost wax, aluminium
gram	Black synthetic part on wire	Aluminium sulphide	17,3	Casting, lost wax, aluminium
gram	Large outer wire	Stainless steel	20,4	Wire drawing, steel
gram	Large inner wire	Stainless steel	20,4	Wire drawing, steel
gram	Small outer wire	Stainless steel	4,9	Wire drawing, steel
gram	Small inner wire	Stainless steel	4	Wire drawing, steel
gram	Glass fibers	Glass fibers	1	Glass fibre production
gram	Magnifying glass	Glass	5,2	Glass production
	Packaging materials			
gran	Foam inlay	Polyethylene, high density foam	3020	Polymer foaming
gram	Plastic bag	Polyethylene, low density	0,2	Extrusion, plastic film
gram	Case	Polypropylene	1453	Extrusion of plastic sheets
	Use			
kWh	Electricity monitor C- 8403 ZX	Electricity, low voltage	0,007	

Table 24: Data Collection Table for reusable FOB (disinfection process)

Unit	High-level disinfection	Materials/process	Amount	Production process
kWh	Electricity	Heating water (1L)	0,02	
kWh	Electricity (Medivators Advantage Plus	Disinfection	0,9	
kWh	Electricity (medivators Endodry)	Drying	0,225	
L	Water	Water cleaning	12,00	
L	Water	Water disinfection	34,56	
mL	Soap	Soap cleaning	650	
mL	Soap	Soap disinfection	250	
mL	Detergent Rapicide A	Fatty alcohol	128	
mL	Detergent Rapicide A	Hydrogen peroxide	44	
mL	Detergent Rapicide A	Acetic acid	18	
mL	Detergent Rapicide A	Peroxyacetic acid	1	
mL	Detergent Rapicide B	Fatty alcohol	178	
mL	Detergent Rapicide B	Oxirane [ethylene oxide]	10	
mL	Detergent Rapicide B	Trisodium phosphate	9	
mL	Detergent Rapicide B	1H Benzotriazole	3	
	Disposables			
gram	Cleaning brush, double	Stainless steel	3	Wire drawing
gram	Cleaning brush, double	Polypropylene [PP]	3	Injection moulding
gram	Cleaning cloth	Cotton fibre	2	Spinning
gram	Tooth brush	Polyethylene [PE]	18	Injection moulding
gram	Hookup Casette	Stainless steel	2	Sheet rolling, steel
gram	Bouffant hair covers	Polypropylene [PP]	3	Spinning
gram	Gloves	Nitrile	8	Dipping mold
gram	Gown	Polypropylene [PP]	71	Extrusion, plastic film
gram	Mouthmask	Polypropylene [PP]	8	Spinning

Appendix C: Unit Process Data Tables

C.1 Disposable FVS

Table 25: Unit process data of material production disposable FVS product

Material production D-FVS product					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
0,0553	kg	Market for Acrylonitrile-Butadiene-Styrene [ABS]	GLO	FTIR measurement	G4490
0,0808	kg	Market for Polyvinylchloride [PVC]	GLO	FTIR measurement	G2651
0,0087	kg	Market for Polycarbonate [PC]	GLO	FTIR measurement	G4727
0,004	kg	Market for Polyethylene, low density [PE, low]	GLO	FTIR measurement	G3102
0,0026	kg	Market for Polypropylene [PP]	GLO	FTIR measurement	G1240
0,0049	kg	Market for Stainless steel [chromium 18/8]	GLO	XRF measurement	G14012
0,0015	kg	Market for Synthetic rubber	GLO	FTIR measurement	G11853
0,0102	kg	Market for Polyurethane, flexible foam [PU]	GLO	FTIR measurement	G2509
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	D-FVS materials product			G14916

Table 26: Unit process data of manufacturing the plastic parts of the disposable FVS

Manufacturing D-FVS: plastic parts					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
0,0574	kg	Injection moulding	Europe [RER]	Guide to manufacturing processes for plastics [28]	G1052
0,0049	kg	Wire drawing	Europe [RER]	Guide to manufacturing metal parts [30]	G9186
0,083	kg	Extrusion, plastic pipes	Europe [RER]	Guide to manufacturing processes for plastics [28]	G232
0,0168	kg	Polymer casting	Europe [RER]	Guide to manufacturing processes for plastics [28]	G1052
1	unit	D-FVS Materials product			G14916
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	D-FVS product			G14900

Table 27 Unit process data of manufacturing the electronic components of the disposable FVS

Manufacturing D-FVS: electronics					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
3,20E-05	kg	Diode, glass for surface mounting	GLO	EcoInvent database	G13958
6,92E-04	kg	Integrated circuit, logic type	GLO	EcoInvent database	G6875
4,64E-04	m2	Printed wiring board, surface mounting	GLO	EcoInvent database	G12675
8,60E-05	kg	Capacitor, for surface mounting	GLO	EcoInvent database	G11376
9,40E-05	kg	Resistor, for surface mounting	GLO	EcoInvent database	G10069
8,16E-06	kg	Inductor, low value multilayer chip	GLO	EcoInvent database	G13084
3,50E-04	kg	Light emitting diode	GLO	EcoInvent database	G10951
4,64E-04	m2	Mounting, surface mount technology, pb free	GLO	EcoInvent database	G506
0,0179	kg	Market for Copper	GLO	Mettler PJ360 Deltarange	G5949
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	D-FVS Printed Circuit Board			G14920

Table 28: Unit process data for material production of the packaging disposable FVS

Materials production D-FVS Packaging					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
0,0049	kg	Market for Bleached kraft paper	GLO	Article: Sorenson e.a.[8]	G748
0,0228	kg	Market for Unbleached kraft paper	GLO	Article: Sorenson e.a.[8]	G13271
0,0438	kg	Market for Polypropylene [PP]	GLO	FTIR measurement	G1240
0,0024	kg	Market for Polyethylene, high density [HDPE]	GLO	Guide to manufacturing processes for plastics [28]	G3952
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	D-FVS materials packaging			G14917

Table 29: Unit process data for manufacturing of disposable FVS packaging

Manufacturing D-FVS packaging					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
0,0024	kg	Extrusion, plastic film	Europe [RER]	Guide to manufacturing processes for plastics [28]	G3893
0,0438	kg	Injection moulding	Europe [RER]	Guide to manufacturing processes for plastics [28]	G1052
0,0336	kg	Corrugated board box	Europe [RER]	Ecoinvent database	G1218
1	unit	D-FVS materials packaging			G14917
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	D-FVS packaging			G14901

Table 30: Unit process data for ethylene oxide gas sterilization of disposable FVS

EtO sterilisation					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	D-FVS Product			G14900
1	unit	D-FVS Packaging			G14901
1	unit	D-FVS electronic circuit/PCB			G14920
0,0062	kWh	Electricity, low voltage	NL	Ethylene Oxide Safety Task Group	G2907
0,000725	mg/L	Ethylene oxide (EtO)	GLO	Ethylene Oxide Safety Task Group	G782
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	D-FVS sterile			G14902

Table 31: Unit process data for use of the disposable FVS

D-FVS use					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	D-FVS sterile			G14902
0,0063	kWh	Electricity, low voltage	NL	Technical file: aView	G2907
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	Intubated patient (reference flow)			G14903
1	unit	D-FVS disposed			W14904

Table 32: Unit process data for waste incineration of disposable FVS

D-FVS waste incineration					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	D-FVS disposed			W14904
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
0,064	kg	Treatment of waste Plastic mixture [MABS, PC]	Europe [RER]	Ecoinvent database	W7930
0,0769	kg	Treatment of waste Polyvinylchloride [PVC]	Europe [RER]	Ecoinvent database	W1877
0,0064	kg	Treatment of waste Polyethylene	Europe [RER]	Ecoinvent database	W709
0,0464	kg	Treatment of waste Polypropylene [PP]	Europe [RER]	Ecoinvent database	W5964
0,0049	kg	Treatment of waste Stainless steel	Europe [RER]	Ecoinvent database	W651
0,0015	kg	Treatment of waste Rubber, unspecified	Europe [RER]	Ecoinvent database	W6940
0,0102	kg	Treatment of waste Polyurethane [PU]	Europe [RER]	Ecoinvent database	W4107
0,1487	kg	Waste for paper	Europe [RER]	Ecoinvent database	W8412
0,00219	kg	Used Printed Circuit Board	GLO	Ecoinvent database	W10995

C.2 Reusable FOB

Table 33: Unit process data for material production of reusable FOB product

Materials production R-FOB product					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
0,1462	kg	Market for Aluminium sulphide [al-s-mg]	GLO	XRF measurement	G241
0,1008	kg	Market for Free-cutting brass [copper-zinc alloy]	GLO	XRF measurement	G110
0,0497	kg	Market for (Duplex) Stainless steel [fe-cr-ni]	GLO	XRF measurement	G14012
0,0168	kg	Market for Synthetic rubber	GLO	FTIR measurement	G11853
0,0227	kg	Market for polyurethane, rigid foam [PU]	GLO	FTIR measurement	G9680
0,0675	kg	Market for Phenolic resin	GLO	FTIR measurement	G9042
0,0177	kg	Market for Nickel-iron alloy	GLO	XRF measurement	G6179
0,001	kg	Market for Glass fibers	GLO	Ecoinvent database	G6812
0,0052	kg	Market for Glass	GLO	Ecoinvent database	G14716
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	R-FOB Product materials			G14918

Table 34: Unit process data for manufacturing of reusable FOB device

Manufacturing R-FOB product					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
0,0072	kg	Extrusion, plastic pipes	Europe [RER]	Guide plastic parts [28]	G232
0,1441	kg	Casting, lost wax, aluminium	Europe [RER]	Guide metal parts [30]	G10889
0,0497	kg	Wire drawing, steel	Europe [RER]	Guide metal parts [30]	G9186
0,0073	kg	Casting, brass	Europe [RER]	Guide metal parts [30]	G6890
0,0187	kg	Sheet rolling, copper	Europe [RER]	Guide metal parts [30]	G1856
0,003	kg	Polymer casting	Europe [RER]	Guide plastic parts [28]	G2466
0,0021	kg	Sheet rolling, aluminium	Europe [RER]	Guide metal parts [30]	G32
0,0925	kg	Wire drawing, copper	Europe [RER]	Guide metal parts [30]	G13130
0,0502	kg	Injection moulding	Europe [RER]	Guide plastic parts [28]	G1052
1	unit	R-FOB Product materials			G14918
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1		R-FOB product			G14905

Table 35: Unit process data for material production of reusable FOB packaging

Materials production R-FOB packaging					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
3,02	kg	Market for Polyethylene, high density foam	GLO	Article: Sorensen [8]	G3952
0,0002	kg	Market for Polyethylene, low density	GLO	Article: Sorensen [8]	G11485
1,453	kg	Market for Polypropylene	GLO	Article: Sorensen [8]	G1240
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	R-FOB Packaging materials			G14919

Table 36: Unit process data for manufacturing of reusable FOB packaging

Manufacturing packaging R-FOB					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
3,02	kg	Polymer foaming	Europe [RER]	Guide plastic parts [28]	G8923
0,0002	kg	Extrusion, plastic film	Europe [RER]	Guide plastic parts [28]	G3893
1,453	kg	Extrusion of plastic sheets and thermoforming	Europe [RER]	Guide plastic parts [28]	G8195
1	unit	R-FOB Packaging materials			G14919
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1		R-FOB Packaging			G14906

Table 37: Unit process data for use of reusable FVS

R-FOB Use					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	R-FOB assembly			G14907
450	unit	R-FOB disinfected			G14908
0,007	kWh	Electricity, low voltage	NL	Technical file: C-MAC 8430	G2907
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
450	unit	Intubated patient (reference flow)			G14909
1	unit	R-FOB disposed			W14910
450	unit	R-FOB used			W14911

Table 38: Unit process data for heating of tap water for the disinfection process of the reusable FOB

Disinfection: heating tap water					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
1	kg	Market for Tap Water	Europe [RER]	Ecoinvent database	G3289
0,02	kWh	Electricity, low voltage	NL	Change in thermal energy	G2907
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	kg	Heated Tap Water			G14912

Table 39: Unit process data for production of Rapicide A for the disinfection process of the reusable FOB

Disinfection: detergent Racipide A production					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
0,64	kg	Market for fatty alcohol	GLO	Assumption - primary ingredient detergents	G3169
0,22	kg	Market for Hydrogen peroxide	GLO	Safety data sheet, Rapicide A	G5197
0,14	kg	Market for Acetic acid	GLO	Safety data sheet, Rapicide A	G1185
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	kg	Detergent Rapicide A			G14913

Table 40: Unit process data for production of Rapicide B for the disinfection process of the reusable FOB

Disinfection: detergent Racipide B production					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
0,89	kg	Market for fatty alcohol	GLO	Assumption - primary ingredient detergents	G640
0,006	kg	Market for Oxirane [ethylene oxide]	GLO	Safety data sheet, Rapicide B	G782
0,005	kg	Market for Trisodium phosphate	GLO	Safety data sheet, Rapicide B	G5075
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	kg	Detergent Rapicide B			G14914

Table 41: Unit process data for production and manufacturing of disposable products for the disinfection process

Manufacturing R-FOB product					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
0,0072	kg	Extrusion, plastic pipes	Europe [RER]	Guide plastic parts [28]	G232
0,1441	kg	Casting, lost wax, aluminium	Europe [RER]	Guide metal parts [30]	G10889
0,0497	kg	Wire drawing, steel	Europe [RER]	Guide metal parts [30]	G9186
0,0073	kg	Casting, brass	Europe [RER]	Guide metal parts [30]	G6890
0,0187	kg	Sheet rolling, copper	Europe [RER]	Guide metal parts [30]	G1856
0,003	kg	Polymer casting	Europe [RER]	Guide plastic parts [28]	G2466
0,0021	kg	Sheet rolling, aluminium	Europe [RER]	Guide metal parts [30]	G32
0,0925	kg	Wire drawing, copper	Europe [RER]	Guide metal parts [30]	G13130
0,0502	kg	Injection moulding	Europe [RER]	Guide plastic parts [28]	G1052
0,001	kg	Glass fibre production	Europe [RER]	Internet search	G9931
1	unit	R-FOB Product materials			G14918
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1		R-FOB product			G14905

Table 42: Unit process data for the disinfection process of the reusable FOB

Disinfection					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
46,56	kg	Heated tap water		Observational study CSD	G14912
1,125	kWh	Electricity, low voltage	NL	Observational study CSD	G2907
0,09	kg	Market for Soap	GLO	Observational study CSD	G9746
0,2	kg	Detergent Rapicide A		Observational study CSD	G14913
0,2	kg	Detergent Rapicide B		Observational study CSD	G14914
1	unit	Disposable products disinfection			G14915
1	unit	R-FOB used			W14911
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	R-FOB Disinfected			G14908

Table 43: Unit process data for the waste incineration of the reusable FOB

R-FOB Waste incineration					
Economic flow in:					
Amount	Unit	Activity	Location	Data source	Number
1	unit	R-FOB disposed			G14910
Economic flow out:					
Amount	Unit	Activity	Location	Data source	Number
0,1462	kg	Treatment of waste scrap Aluminium, incineration	GLO	Ecoinvent database	W1051
0,1008	kg	Treatment of waste scrap Copper, incineration	GLO	Ecoinvent database	W2199
0,0497	kg	Treatment of waste scrap Steel	GLO	Ecoinvent database	W8053
0,0168	kg	Treatment of waste Rubber, unspecified	Europe [RER]	Ecoinvent database	W6940
0,1004	kg	Mucinipal solid waste	NL	Ecoinvent database	W7702
1,538	kg	Treatment of waste Polypropylene [PP]	GLO	Ecoinvent database	W5473
3,0382	kg	Treatment of Waste Polyethylene	Europe [RER]	Ecoinvent database	W709

Appendix D: Classification of life cycle stages

The *unit processes* of the *alternatives* were classified into five life cycle stages. The classification of the *unit processes* of the disposable FVS and reusable R-FOB are displayed in Table 44 and Table 45, respectively. The life cycle stages were used during the contribution analysis for the life cycle phases of the *alternatives.*

Table 44: Classification of the disposable FVS unit processes into five life cycle stages

Life cycle stage	Unit processes D-FVS
Material production	Material production D-FVS product Material production D-FVS packaging
Manufacturing	Manufacturing D-FVS: plastic parts Manufacturing D-FVS: electronics Manufacturing D-FVS packaging
Sterilization	EtO sterilisation
Use	D-FVS use
Disposal	D-FVS waste incineration

Table 45: Classification of the reusable FOB unit processes into five life cycle stages

Life cycle stage	Unit processes R-FOB
Material production	Material production R-FOB product Material production R-FOB packaging
Manufacturing	Manufacturing R-FOB product Manufacturing R-FOB packaging
Use	R-FOB use
Disinfection	Disinfection Heating tap water Disinfection: detergent Rapicide A production Disinfection: detergent Rapicide B production Disinfection: disposable products production
Disposal	R-FOB waste incineration

Appendix E: Comparative analysis

E.1 Comparative analysis of CML2001

The category indicator results were compared between the *alternatives* in a clustered-column bar chart to visualize the difference between the *alternatives* in each impact category simultaneously. The largest value of each impact category was normalized to 1 and the smallest value was represented relative to the largest value. The relation between the impact categories was not displayed in the bar chart, because category indicator results cannot be compared between the impact categories, see Figure 26.

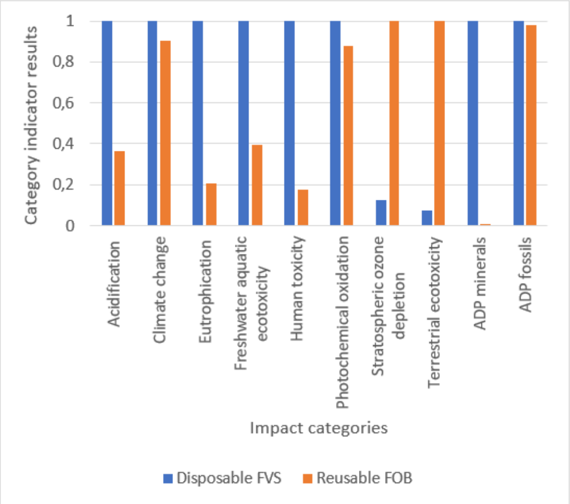

Figure 26: Comparative analysis of the environmental impact of the disposable FVS and reusable FOB for 450 patient intubations in ten impact categories

E.2 Comparative analysis of ReCiPe and ILCD

The category indicator results between the *alternatives* through the ReCiPe and ILCD impact assessment method were compared in a clustered-column bar chart, see Figure 27. The environmental impact of the disposable FVS was higher than the reusable FOB in most impact categories for the ReCiPe and ILCD method, except for ozone depletion and terrestrial ecotoxicity, which is similar to the results of the CML2001 method. The impact on marine eutrophication, an additional impact category of the ReCiPe and ILCD method, was slightly higher for the reusable FOB than the disposable FVS.

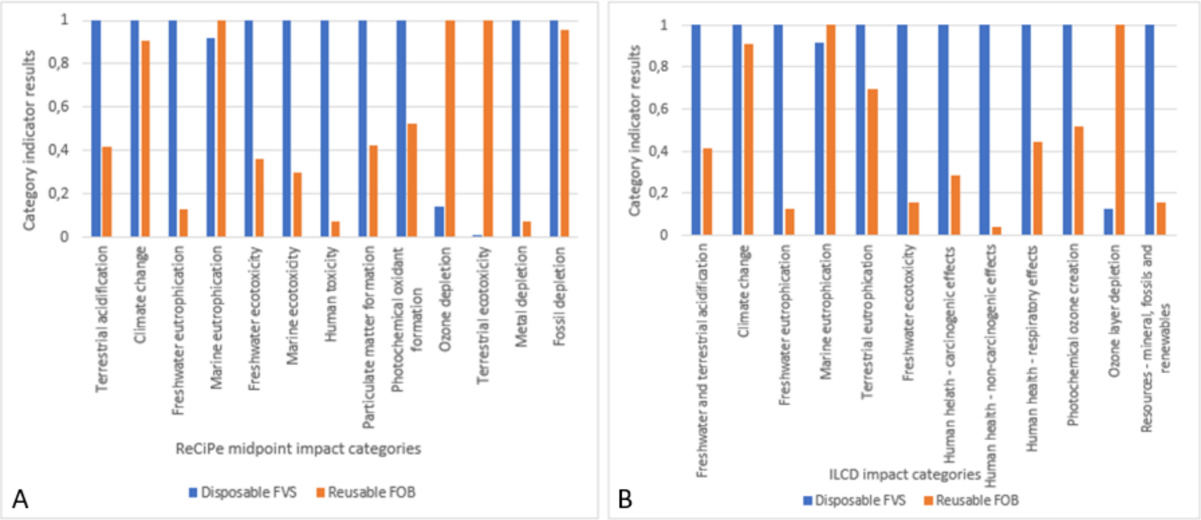

Figure 27: Comparative category indicator results between the disposable FVS and reusable FOB for the ReCiPe and ILCD method

Appendix F: Sensitivity analysis

In order to calculate the sensitivity of certain input variables of the LCA model, the input was doubled one at the time (OAT). The category indicator results and proportional sensitivity for each impact category of the altered input variables is displayed in the tables below.

F.1 PCB components

Table 46: Category indicator results of the PCB components when their weight is increased with 100% OAT

Impact category	Diode	IC	PWB	Inductor	Capacitor	Resistor	Copper	LED
Acidification	7,94E+00	10,1	8,51	7,92	8,05	8,1	1,09E+01	8,18E+00
Climate change	1,23E+03	1,65E+03	1,32E+03	1,23E+03	1,23E+03	1,24E+03	1,26E+03	1,28E+03
Eutrophication	9,63E+00	15,6	9,97	9,6	9,61	10	1,17E+01	9,74E+00
Freshwater aquatic ecot.	2,62E+03	4,08E+03	2,69E+03	2,61E+03	2,61E+03	2,72E+03	3,15E+03	2,64E+03
Human toxicity	5,10E+03	7,20E+03	5,32E+03	5,09E+03	5,09E+03	5,24E+03	7,20E+03	5,15E+03
Photochemical oxidation	0,354	0,437	0,384	0,353	0,361	0,36	4,67E-01	3,65E-01
Stratospheric ozone depl.	8,34E-05	0,000135	9,10E-05	8,32E-05	8,33E-05	8,37E-05	8,50E-05	8,55E-05
Terrestrial ecotoxicity	14,4	19,9	15,1	14,4	14,4	14,7	2,02E+01	1,46E+01
ADP minerals	6,86E+00	12,8	6,94	6,88	6,89	7,35	7,11	6,87
ADP fossils	1,73E+04	2,33E+04	1,84E+04	1,72E+04	1,73E+04	1,73E+04	1,77E+04	1,79E+04
Total impact score	7,94E-08	1,22E-07	8,20E-08	7,92E-08	8,01E-08	9,96E-08	7,93E-08	8,23E-08

Table 47: Proportional sensitivity (10^{-3}) *of the PCB components when their weight is increased with 100% OAT*

Impact category	Diode	IC	PWB	Inductor	Capacitor	Resistor	Copper	LED
Acidification	37,9	2768,6	758,5	12,6	341,3	3780,0	177,0	240,2
Climate change	0,0	3414,6	731,7	0,0	406,5	243,9	0,0	81,3
Eutrophication	41,7	6266,9	396,2	10,4	156,4	2200,2	20,9	427,5
Freshwater aquatic ecot.	38,3	5632,2	306,5	0,0	114,9	2069,0	0,0	421,5
Human toxicity	19,6	4145,4	451,9	0,0	117,9	4145,4	0,0	294,7
Photochemical oxidation	28,3	2379,6	878,2	0,0	339,9	3229,5	226,6	198,3
Stratospheric ozone depl.	24,0	6226,0	937,5	0,0	276,4	216,3	12,0	60,1
Terrestrial ecotoxicity	0,0	3819,4	486,1	0,0	138,9	4027,8	0,0	208,3
ADP minerals	0,0	8658,9	116,6	29,2	14,6	364,4	43,7	714,3
ADP fossils	58,1	3546,5	697,7	0,0	407,0	290,7	58,1	58,1
Total impact score	25,3	5404,0	353,5	0,0	113,6	2575,8	12,6	391,4

F.2 Materials product disposable FVS

Table 48: Category indicator results of the disposable FVS product materials when the weight is increased with 100% OAT

Impact category	ABS	PVC	PC	PE	PP	Steel	Rubber	PU
Acidification	8,27	8,11	8,01	7,93	7,92	7,97	7,92	8,02
Climate change	1,34E+03	1,30E+03	1,26E+03	1,23E+03	1,23E+03	1,24E+03	1,23E+03	1,25E+03
Eutrophication	9,64	9,62	9,6	9,59	9,59	9,61	9,59	9,61
Freshwater aquatic ecot.	2,63E+03	2,62E+03	2,61E+03	2,61E+03	2,61E+03	2,64E+03	2,61E+03	2,62E+03
Human toxicity	5,10E+03	5,10E+03	5,09E+03	5,09E+03	5,09E+03	5,26E+03	5,09E+03	5,09E+03
Photochemical oxidation	0,38	0,365	0,358	0,354	0,353	0,356	0,353	0,358
Stratospheric ozone depl.	8,46E-05	8,37E-05	8,32E-05	8,32E-05	8,32E-05	8,37E-05	8,35E-05	8,33E-05
Terrestrial ecotoxicity	14,4	14,7	14,5	14,4	14,4	14,6	14,4	14,4
ADP minerals	6,86	6,86	6,86	6,86	6,86	6,86	6,86	6,86
ADP fossils	1,96E+04	1,90E+04	1,76E+04	1,74E+04	1,73E+04	1,74E+04	1,73E+04	1,77E+04
Total impact score	7,97E-08	7,95E-08	7,92E-08	7,92E-08	7,92E-08	8,06E-08	7,92E-08	7,93E-08

Table 49: Proportional sensitivity (10^{-3}) *of the disposable FVS product materials when the weight is increased with 100% OAT*

Impact category	**ABS**	**PVC**	**PC**	**PE**	**PP**	**Steel**	**Rubber**	**PU**
Acidification	45,5	25,3	12,6	2,5	1,3	7,6	1,3	13,9
Climate change	89,4	56,9	24,4	0,0	0,0	8,1	0,0	16,3
Eutrophication	5,2	3,1	1,0	0,0	0,0	2,1	0,0	2,1
Freshwater aquatic ecot.	7,7	3,8	0,0	0,0	0,0	11,5	0,0	3,8
Human toxicity	2,0	2,0	0,0	0,0	0,0	33,4	0,0	0,0
Photochemical oxidation	76,5	34,0	14,2	2,8	0,0	8,5	0,0	14,2
Stratospheric ozone depl.	16,8	6,0	0,0	0,0	0,0	6,0	3,6	1,2
Terrestrial ecotoxicity	0,0	20,8	6,9	0,0	0,0	13,9	0,0	0,0
ADP minerals	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
ADP fossils	139,5	104,7	23,3	11,6	5,8	11,6	5,8	29,1
Total impact score	6,3	3,8	0,0	0,0	0,0	17,7	0,0	1,3

F.3 Materials product reusable FOB

Table 50: Category indicator results of the reusable FOB product materials when the weight is increased with 100% OAT

Impact category	Aluminium	Brass	Steel	Rubber	Phenolic resin	Nickel-ion	Glass fibers
Acidification	2,94	2,95	2,93	2,92	2,93	2,94	2,92
Climate change	1,12E+03	1,12E+03	1,12E+03	1,12E+03	1,12E+03	1,12E+03	1,12E+03
Eutrophication	1,99	2,01	1,99	1,99	1,99	1,99	1,99
Freshwater aquatic ecot.	1,04E+03	1,04E+03	1,04E+03	1,04E+03	1,04E+03	1,04E+03	1,04E+03
Human toxicity	914	926	911	907	908	909	907
Photochemical oxidation	0,313	0,314	0,313	0,313	0,313	0,313	0,313
Stratospheric ozone depl.	0,000662	0,000662	0,000662	0,000662	0,000662	0,000662	0,000662
Terrestrial ecotoxicity	202	202	202	202	202	202	202
ADP minerals	0,0691	0,0695	0,0644	0,0644	0,0644	0,0651	0,0644
ADP fossils	1,71E+04	1,71E+04	1,71E+04	1,71E+04	1,71E+04	1,71E+04	1,71E+04
Total impact score	2,50E-08	2,51E-08	2,50E-08	2,49E-08	2,49E-08	2,50E-08	2,49E-08

Table 51: Proportional sensitivity (10^{-3}) *of the reusable FOB product material when the weight is increased with 100% OAT*

Impact category	Aluminium	Brass	Steel	Rubber	Phenolic resin	Nickel-ion	Glass fibers
Acidification	68,5	102,7	34,2	0,0	34,2	68,5	0,0
Climate change	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Eutrophication	50,5	151,5	50,5	50,5	50,5	50,5	50,5
Freshwater aquatic ecot.	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Human toxicity	88,3	220,8	55,2	11,0	22,1	33,1	11,0
Photochemical oxidation	32,1	64,1	32,1	32,1	32,1	32,1	32,1
Stratospheric ozone depl.	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Terrestrial ecotoxicity	0,0	0,0	0,0	0,0	0,0	0,0	0,0
ADP minerals	729,8	791,9	0,0	0,0	0,0	108,7	0,0
ADP fossils	58,8	58,8	58,8	58,8	58,8	58,8	58,8
Total impact score	40,2	80,3	40,2	0,0	0,0	40,2	0,0

F.4 Disinfection process supplies

Table 52: Category indicator results of the reusable FOB disinfection supplies when the value is increased with 100% OAT

Impact category	Water	Electricity	Soap
Acidification	3,4	3,46	3,54
Climate change	1,38E+03	1,43E+03	1,38E+03
Eutrophication	2,41	2,48	2,66
Freshwater aquatic ecotoxicity	1,18E+03	1,20E+03	1,52E+03
Human toxicity	998	1,01E+03	1,21E+03
Photochemical oxidation	0,335	0,336	0,458
Stratospheric ozone depletion	0,000676	0,000679	0,00067
Terrestrial ecotoxicity	204	204	398
ADP minerals	0,0689	0,0693	0,0754
ADP fossils	2,15E+04	2,23E+04	1,78E+04
Total impact score	2,80E-08	2,85E-08	3,63E-08

Table 53: Proportional sensitivity $(10^{-3})$of disinfection supplies when the weight is increased with 100% OAT

Impact category	Water	Electricity	Soap
Acidification	1643,8	1849,3	2123,3
Climate change	2321,4	2767,9	2321,4
Eutrophication	2171,7	2525,3	3434,3
Freshwater aquatic ecotoxicity	1346,2	1538,5	4615,4
Human toxicity	1015,5	1147,9	3355,4
Photochemical oxidation	737,2	769,2	4679,5
Stratospheric ozone depletion	211,5	256,8	120,8
Terrestrial ecotoxicity	99,0	99,0	9703,0
ADP minerals	698,8	760,9	1708,1
ADP fossils	2647,1	3117,6	470,6
Total impact score	1245,0	1445,8	4578,3

F.5 Manufacturing processes disposable FVS

Table 54: Category indicator results of disposable FVS manufacturing processes when the value is increased with 100% OAT

Impact category	Extrusion	Injection moulding	Wire drawing
Acidification	7,97	8,06	7,92
Climate change	1,24E+03	1,26E+03	1,23E+03
Eutrophication	9,62	9,67	9,59
Freshwater aquatic ecotoxicity	2,62E+03	2,63E+03	2,61E+03
Human toxicity	5,10E+03	5,11E+03	5,09E+03
Photochemical oxidation	0,355	0,362	0,353
Stratospheric ozone depletion	8,42E-05	8,80E-05	8,32E-05
Terrestrial ecotoxicity	14,5	14,5	14,4
ADP minerals	6,86	6,86	6,86
ADP fossils	1,74E+04	1,79E+04	1,72E+04
Total impact score	7,93E-08	7,96E-08	7,92E-08

Table 55: Proportional sensitivity (10^{-3}) *of disposable FVS manufacturing processes when the weight is increased with 100%*

Impact category	Extrusion	Injection moulding	Wire drawing
Acidification	75,9	189,6	12,6
Climate change	81,3	243,9	0,0
Eutrophication	31,3	83,4	0,0
Freshwater aquatic ecotoxicity	38,3	76,6	0,0
Human toxicity	19,6	39,3	0,0
Photochemical oxidation	56,7	255,0	0,0
Stratospheric ozone depletion	120,2	576,9	0,0
Terrestrial ecotoxicity	69,4	69,4	0,0
ADP minerals	0,0	0,0	0,0
ADP fossils	116,3	407,0	0,0
Total impact score	12,6	50,5	0,0

F.6 Manufacturing processes reusable FOB

Table 56: Category indicator results of reusable FOB manufacturing processes when the value is increased with 100% OAT

Impact category	Sheet rolling	Injection moulding	Casting, brass	Casting, aluinium	Wire drawing
Acidification	2,92	2,92	2,92	2,98	2,92
Climate change	1,12E+03	1,12E+03	1,12E+03	1,13E+03	1,12E+03
Eutrophication	1,98	1,98	1,98	2,01	1,98
Freshwater aquatic ecot.	1,04E+03	1,04E+03	1,04E+03	1,04E+03	1,04E+03
Human toxicity	906	906	906	916	906
Photochemical oxidation	0,312	0,312	0,312	0,336	0,312
Stratospheric ozone depl.	0,000662	0,000662	0,000662	0,000663	0,000662
Terrestrial ecotoxicity	202	202	202	202	202
ADP minerals	0,0644	0,0644	0,0644	0,0646	0,0644
ADP fossils	1,70E+04	1,70E+04	1,70E+04	1,72E+04	1,70E+04
Total impact score	2,49E-08	2,49E-08	2,49E-08	2,51E-08	2,49E-08

Table 57: Proportional sensitivity (10^{-3}) *of reusable FOB manufacturing processes when the weight is increased with 100%*

Impact category	Sheet rolling	Injection moulding	Casting, brass	Casting, aluinium	Wire drawing
Acidification	0,0	0,0	0,0	205,5	0,0
Climate change	0,0	0,0	0,0	89,3	0,0
Eutrophication	0,0	0,0	0,0	151,5	0,0
Freshwater aquatic ecot.	0,0	0,0	0,0	0,0	0,0
Human toxicity	0,0	0,0	0,0	110,4	11,0
Photochemical oxidation	0,0	0,0	0,0	769,2	0,0
Stratospheric ozone depl.	0,0	0,0	0,0	15,1	0,0
Terrestrial ecotoxicity	0,0	0,0	0,0	0,0	0,0
ADP minerals	0,0	0,0	0,0	31,1	15,5
ADP fossils	0,0	0,0	0,0	117,6	0,0
Total impact score	0,0	0,0	0,0	80,3	0,0

F.7 Scenario analysis: reduction of functional unit

Table 58 shows the number of patient intubations (functional unit) at which the environmental impact of each impact category is equal. The break-even point (BEP) between the impact of the disposable FVS and reusable was determined by comparing the impact equations, which consisted of a the slope of the environmental impact and the functional unit (FU).

Table 58: The break-even point (BEP) of the number of patient intubations (functional unit) between the impact of the disposable FVS and reusable FOB for ten impact categories, with FU being the functional unit

Impact category	**Impact equation disposable FVS**	**Impact equation reusable FOB**	**BEP**	**Highest impact > BEP**
Acidification (kg SO2-eq)	$0{,}0176 \cdot FU$	$0{,}0606 \cdot FU + 0{,}172$	15	Disposable FVS
Climate change (kg CO2-eq)	$2{,}73 \cdot FU$	$2{,}369 \cdot FU + 44{,}1$	122	Disposable FVS
Eutrophication (kg PO4-eq)	$2{,}13\mathrm{e}^{-2} \cdot FU$	$4{,}23\mathrm{e}^{-3} \cdot FU + 0{,}067$	4	Disposable FVS
Freshwater aquatic ecotoxicity	$5{,}8 \cdot FU$	$2{,}01 \cdot FU + 126$	33	Disposable FVS
Human toxicity (kg 1,4DCB-eq)	$11{,}3 \cdot FU$	$1{,}87 \cdot FU + 58$	6	Disposable FVS
Photochemical oxidation (kg ethylene)	$7{,}8\mathrm{e}^{-4} \cdot FU$	$5{,}9\ \mathrm{e}^{-4} \cdot FU + 0{,}0475$	239	Disposable FVS
Stratospheric ozone depletion (kg CFC)	$1{,}8\mathrm{e}^{-7} \cdot FU$	$1{,}5\mathrm{e}^{-6} \cdot FU + 2{,}9\mathrm{e}^{-6}$	2	Reusable FOB
Terrestrial ecotoxicity (kg 1,4 DCB-eq)	$0{,}032 \cdot FU$	$0{,}443 \cdot FU + 0{,}615$	1	Reusable FOB
ADP minerals (kg Sb-eq)	$1{,}52\mathrm{e}^{-2} \cdot FU$	$1{,}2\mathrm{e}^{-4} \cdot FU + 0{,}0111$	1	Disposable FVS
ADP fossils (megajoule)	$y = 38{,}3 \cdot a$	$36{,}15 \cdot FU + 635$	295	Disposable FVS

Appendix G: Concept generation

Figure 28 displays the mind map that was made during the concept generation of the sustainable flexible intubation scope.

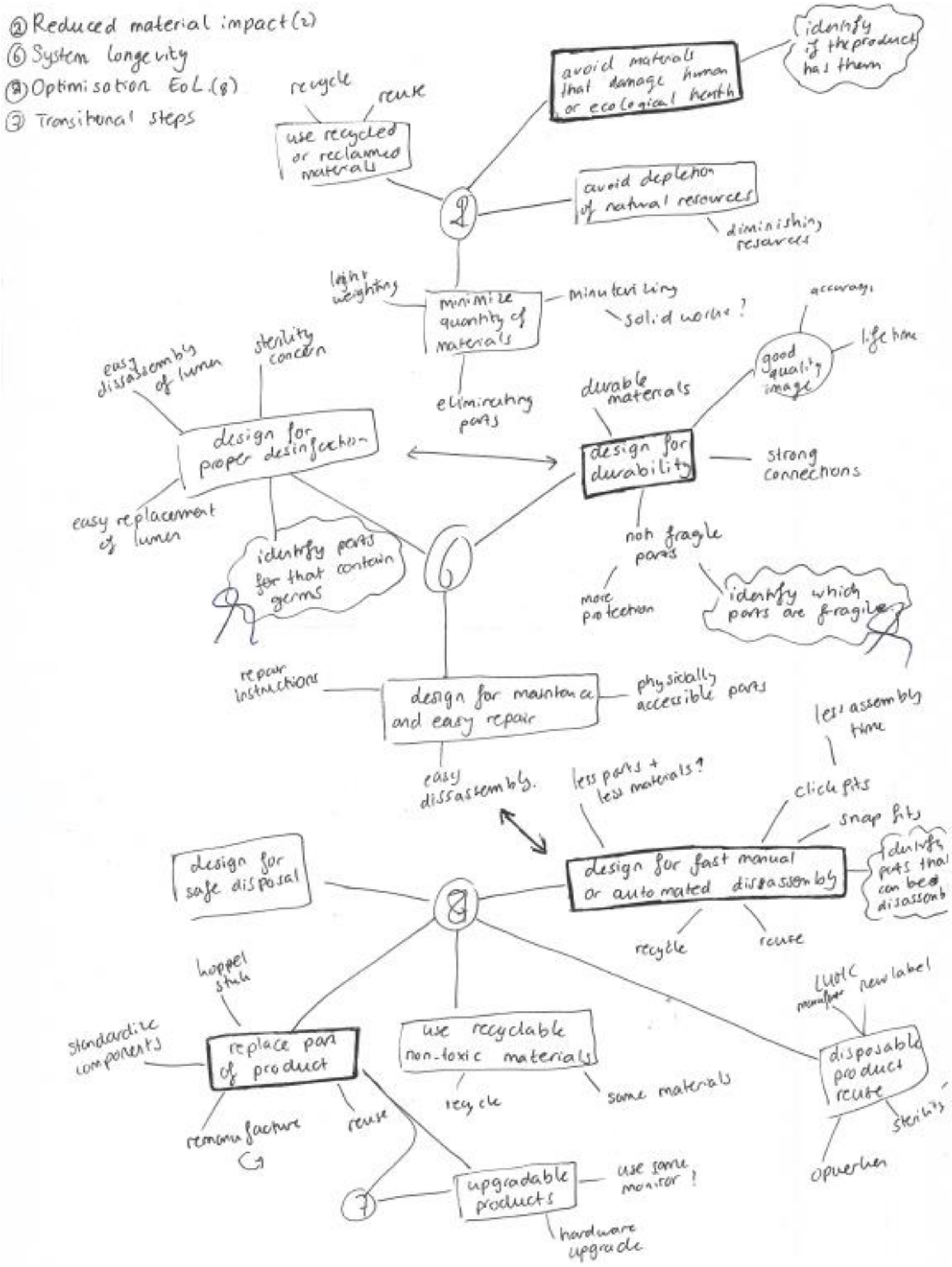

Figure 28: Mind map with solutions for the EcoDesign strategies for the sustainable flexible intubation scope

Appendix H: Cost analysis

A cost analysis was made to estimate the total costs per procedure of the disposable flexible video endoscope (AMBU, aScope 4 Regular) and the reusable fiberoptic bronchoscope (Storz, Broncho 1130 BNX). The costs for transport and capital equipment acquisition were excluded from the analysis due to lack of data.

The costs for the disposable FVS were presented in Table 55. The purchase price of the aScope 4 regular was obtained through the procurement overview (2019-2021) of the disposable flexible endoscopes of the LUMC. The disposable FVS must be ordered in sets of 5 devices. The costs of waste treatment was calculated by the weight of the device (0,15 kg) and the price of non-specific hospital waste (15,2/ton) at PreZero. The purchase price of the monitor was obtained through AMBU. The TCO of 450 disposable FVS is € 84.259,-, so the price per unit is €187,25.

Table 55: Cost overview of AMBU aScope 4 Regular

AMBU aScope 4 Regular	**Costs**	**Number**	**Price**
Purchase device	€ 185,00	450	€ 83.250,00
Waste treatment (0,152/kg)	€ 0,02	450	€ 9,00
Purchase monitor (aView)	€ 1.000,00	1	€ 1.000,00
Total			*€ 84.259,00*

The costs of the reusable FOB are displayed in Table 56. The costs for procurement of the device, repair, maintenance and price of the monitor were obtained through the LUMC. The fiberoptic bronchoscope was maintained twice a year and the device had to be repaired 1-2 times a year on average. The estimated lifetime of the reusable FOB was considered 6 years. The costs for one disinfection process were based on calculations for the price of one sterilization cycle of the LUMC; the price for one sterilization cycle ranged from 6-23 euro, so the highest limit of the range was considered. The costs for waste incineration were calculated by the weight of the device (0,34) and the price of non-specific hospital waste (15,2/ton) at PreZero. The TCO of 450 reusable FOB was €65.650,05, so the price per unit is 145,80.

Table 56: Cost overview of Storz, Bronco 1130 BNX

Fiberscope Storz Broncho 11301 BNXK	**Costs**	**Number**	**Price**
Purchase device	€ 12.000,00	1	€ 12.000,00
Repair	€ 4.500,00	8	€ 36.000,00
Maintenance	€ 150,00	12	€ 1.800,00
Disinfection	€ 23,00	450	€ 10.350,00
Waste treatment (0,152/kg)	€ 0,05	1	€ 0,05
Purchase monitor (C-MAC 8430 ZX)	€ 5.500,00	1	€ 5.500,00
Total			*€ 65.650,05*

The break-even point between the TCO of the disposable and reusable flexible intubation scope is at 209 intubated patients, which was determined through calculations in Matlab R2020a.

Appendix I: Concept evaluation

The CMLCA model of the reusable FOB was adjusted to predict the environmental impact of the final concept. The alterations of the input data of the LCA model for the final concept are displayed in Table 57.

Table 57: Alterations of input data of LCA model of D-FVS to final concept

Input D-FVS				**Input final concept**			
Amount	Unit	Activity	Number	Amount	Unit	Activity	Number
0,001	kg	Market for Glass fibers	G6812	0,004	kg	Market for polymethyl methacrylate [PMMA]	G3946
0,0052	kg	Market for Glass	G14716				
0,001	kg	Glass fibre production	G9930	0,004	kg	Spinning fibre	G9702
0,0227	kg	Market for polyurethane	G9680	0,0247	kg	Market for polyurethane	G9680

Appendix J: Selection of low-impact materials

In order to select an alternative material for brass, the environmental impact of other materials were analyzed. These alternative materials were required to have similar properties to brass, so the selected materials were aluminium-lithium, copper, aluminium-magnesium and bronze, see Table 58. The production of aluminium alloys showed to have lower environmental impact compared to brass, however Table 59 reports that the environmental impact of aluminium casting is much higher than manufacturing technique of brass casting. Therefore, there is not an optimal alternative for brass when you want to select a low-impact material for the device.

Table 58: Category indicator results of 1 kg of brass, lithium aluminium (AlLi), copper and magnesium aluminium (AlMg3) to compare the environmental impact between the materials

Impact category	Brass	AlLi	Copper	AlMg3	Bronze
Acidification	0.274	0.0701	0,107	0,0359	0,377
Climate change	4.46	9.34	14,3	6,9	5,13
Eutrophication	0.192	0.0399	0,0612	0,0102	0,255
Freshwater aquatic ecotoxicity	48.9	12.5	19,1	28,1	64,9
Human toxicity	189	55	84,3	13,6	252
Photochemical oxidation	0.0106	0.00424	0,00651	0,00213	0,0145
Stratospheric ozone depletion	2.17E-7	5.82E-7	8,92E-07	2,04E-07	2,99E-07
Terrestrial ecotoxicity	0.554	0.0581	0,0891	0,0222	0,689
ADP minerals	0.0504	0.0323	0,0496	0,00406	0,0349
ADP fossils	56.9	117	180	88,4	66,1

Table 59: Category indicator results of 1 kg of brass casting and casting aluminium to compare the environmental impact between the primary production processes

Impact category	Brass casting	Aluminium casting
Acidification	0,000346	0,431
Climate change	0,0675	104
Eutrophication	7,48E-05	0,185
Freshwater aquatic ecotoxicity	0,0195	40
Human toxicity	0,0569	66,6
Photochemical oxidation	1,64E-05	0,161
Stratospheric ozone depletion	3,14E-09	6,14E-06
Terrestrial ecotoxicity	0,00376	0,274
ADP minerals	6,55E-07	0,00151
ADP fossils	0,919	1,52E+03