Life Cycle Assessment on the collection and disposal of intra-operative collected fluids

Using conventional cannisters vs. the Neptune 3 system

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De Meern, The Netherlands
15th May 2023

Project information	
Title	Life Cycle Assessment on the collection and disposal of intra-operative collected fluids using conventional cannisters vs. the Neptune 3 system
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Version	1
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Associated files	Digital appendix 1: Material database Digital appendix 2: Inventory tables Digital appendix 3: Inventory results Digital appendix 4: Characterization results Digital appendix 5: Contribution analysis

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Executive summary

It is known that hospitals have a significant environmental footprint by producing different types of hazardous and non-hazardous waste. This study focuses on the fluid part of waste streams from the operating room (OR) and investigates the effects of a new method that can be used during surgical procedures in the processing of fluids: the Neptune 3. With this method, fluids from the surgical field are collected with the use of the Neptune 3 and are disposed via the sewage system. This is a novel approach in comparison with the conventional collection and storage of the fluids in bags for disposal via waste incineration, which is currently used in many hospitals around the world.

In the traditional waste treatment of harmless flushing fluids in surgical procedures, disposable collection materials are used, such as suction cannisters and WIVA containers. During an operation, dedicated healthcare staff is usually required in the OR for the management of fluid waste. The plastic suction cannisters with surgical fluids are disposed of and transported to be incinerated at high temperatures in a special incineration installation for hazardous waste.

The Neptune was developed as a medical device with an alternative approach to collecting and handling fluids in the OR. The Neptune 3 for the OR may be regarded as a medical “liquid suction system” providing collection and disposal of fluids released during surgical procedures through one closed system. This study investigates the difference in the environmental impact categories that are considered in the RECIPE characterization methods.

The environmental impact is evaluated by using the ISO 14040 and 14044 life cycle assessment (LCA) standards. The individual stages of the product's life cycle from raw material extraction to production, packaging, transport, use and reprocessing until final disposal of the Neptune 3 and suction canisters are evaluated in this study.

In this study the following references flows are used based on the functional unit:

- The collection and disposal of intra-operative collected fluids over 7 years of procedures in high-volume and low-volume scenarios with the use of the Neptune 3 system
- The collection and disposal of intra-operative collected fluids over 7 years of procedures in high-volume and low-volume scenarios with the use of cannisters.

This study focusses on the comparison of the use of conventional cannisters and the Neptune 3 system in terms of global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human health & terrestrial ecosystems), fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity and water consumption. From the conducted Life Cycle Assessment it can be concluded that the Neptune system is more beneficial when global warming, ozone formation terrestrial ecosystems, and fossil resource scarcity and water consumption are considered. The Neptune also has a lower impact in stratospheric ozone depletion, fine particulate matter formation, terrestrial acidification, and water consumption for the large volume scenarios (5 liter and more). In the case of Ionizing radiation, freshwater eutrophication, and human carcinogenic toxicity the Neptune only scores better in the very large volume procedure (10 liter and more). The Neptune has a larger score in the impact category of Marine eutrophication, Terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human non-carcinogenic toxicity, land use and mineral scarcity, with an increasing difference for the small volume categories. An overview of these trends are shown in the table below.

Benefit in each scenario	• Global warming • Ozone formation terrestrial ecosystem • Ozone formation human health • Fossil resource scarcity • Water consumption
Benefit in scenarios with 5 liters and more	• Stratospheric ozone depletion • Fine particulate matter formation • Terrestrial acidification
Benefit in scenario with 10 liters and more	• Ionizing radiation • Freshwater eutrophication • Human carcinogenic toxicity
Not beneficial compared to cannisters	• Marine eutrophication • Terrestrial ecotoxicity • Freshwater ecotoxicity • Marine ecotoxicity • Human non-carcinogenic toxicity • Land use • Mineral scarcity

By aggregating the mid-point results to end-point results it is observed that the Neptune systems is beneficial for resources in each scenario. In case of human health and ecosystems, the Neptune is beneficial for procedures with larger volumes.

The processing of liquids via the Neptune 3 system fits in well with the current ambitions of hospitals and governments to treat their waste in an environmentally friendly way. This is especially the case when large volumes are considered. Moreover, material input and waste are reduced by using the Neptune system as this system requires only a single-use manifold for each procedure instead of cannisters and WIVA containers, which require more material.

This life cycle analysis has been conducted in accordance with the protocol set out by Rijkswaterstaat, a Directorate-General of the Ministry of Infrastructure and Water Management of the Netherlands. During this study, Rijkswaterstaat was consulted several times to ensure alignment on the design, methodology, and results interpretation of the LCA. This life cycle analysis differs from the protocol on some aspects, all of which have been agreed upon by Rijkswaterstaat. The most notable deviation in this study from the protocol is the fact that this is a single cycle LCA, and not a multi cycle LCA. The reasoning behind this deviation is that with the Neptune, operative fluids directly become part of the water cycle. Next to the life cycle analysis on Neptune, the Dutch National Institute for Public Health and Environment (RIVM) conducted a study to assess the environmental and public health safety risks of disposing fluid through the sewage in hospital operating rooms (ORs). This study concluded that it is safe to dispose fluid in ORs through the sewage as there is no risk involved from a microbiological perspective. Only fluid used in patients with acute infections must be collected in containers and disposed as infectious material.

Glossary

Economic flow
A flow of goods, materials, services, energy or waste from one unit process to another; with either a positive (e.g. steel, transportation) or zero/negative (e.g. waste) economic value.

Elementary flow
Matter or energy entering or leaving the product system under study that has been extracted from the environment without previous human transformation (e.g. timber, water, iron ore, coal) or is emitted or discarded into the environment without subsequent human transformation (e.g. CO_2 or noise emissions, wastes discarded in nature).

Environmental impact
A consequence of an elementary flow in the environment system.

Functional unit
The quantified function provided by the product system(s) under study, for use as a reference basis in an LCA, e.g. 1000 hours of light (adapted from ISO).

(Life cycle) impact assessment. The third phase of an LCA, concerned with understanding and evaluating the magnitude and significance of the potential environmental impacts of the product system(s) under study.

(Life cycle) interpretation. The fourth phase of an LCA, in which the results of the Inventory analysis and/or Impact assessment are interpreted in the light of the Goal and scope definition (e.g. by means of contribution, perturbation and uncertainty analysis, comparison with other studies) in order to draw up conclusions and recommendations.

(Life cycle) inventory analysis. The second phase of an LCA, in which the relevant inputs and outputs of the product system(s) under study throughout the life cycle are, as far as possible, compiled, and quantified.

(Life cycle) inventory (analysis) result. The result of the Inventory analysis phase: a table showing all the elementary flows associated with a product system, supplemented by any other relevant information (adapted from ISO).

Life cycle assessment (LCA). Compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle; the term may refer to either a procedural method or a specific study.

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

System boundary. The interface between a product system and the environment system or other product systems.

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

Content

1. Introduction

Hospitals have a significant environmental footprint by producing different types of hazardous and non-hazardous waste [1]. Waste management in the operating room includes the disposal waste types varying from stainless steel waste to plastic waste as well as fluids from surgical procedures. In The United States of America, hospitals produce 5.9 Mton of waste annually and they are responsible for 8% of the total CO_2 emissions in the US [2]. In the Netherlands, the total emissions from healthcare are approximately 11 Mton of CO_2, which was 7% of the total CO_2 footprint of the Netherlands in 2019 [3].

In recent years, an increasing focus on sustainable healthcare has been noticed in the Netherlands. Furthermore, more attention is created by means of the Green Deal programs on Sustainable Healthcare which aims to reduce waste and realizing a 49% reduction of CO_2 emissions within healthcare in 2030 when compared to emissions levels in 1990 [4]. Increased awareness has also intensified with regard to the safety of OR staff and patients when dealing with risks on infections caused by waste flows.

This study is focusing on the fluid part of waste streams from the operating room (OR) and investigates the effects of a new method that can be used during surgical procedures in the processing of fluids: the Neptune 3 (Stryker, Kalamazoo, Michigan USA). With this method, fluids at the operating room are collected with the use of the Neptune 3 and are disposed via the sewage system. This is a novel approach in comparison with the conventional collection and storage of the fluids in bags for disposal via waste incineration, which is currently used in many hospitals.

In the traditional waste treatment of harmless flushing fluids in surgical procedures, disposable collection materials are used, such as suction cannisters and WIVA containers. During an operation, dedicated healthcare staff is usually required fluid management. The plastic suction cannisters with surgical fluids are disposed of and transported to be incinerated at high temperatures in a special incineration installation for hazardous waste. An example of an organization that is specialized in incineration of surgical waste is Zavin in the Netherlands.

This form of waste processing is an energy intensive process due to fluids which need to be incinerated and may have a negative impact on the environment due to CO_2 emissions. In addition, it puts pressure on the logistical chain of hospitals, as collection material has to be stored, transported, and processed. The traditional methods also create situations that are unsafe or pose a health hazard as OR personnel have to lift heavy canisters and vessels.

The Neptune was developed as a medical device with an alternative approach to collecting and handling fluids in the OR. The Neptune 3 for the OR may be regarded as a medical “liquid suction system” providing collection and disposal of fluids released during surgical procedures through one system.

The Neptune 3 is a closed mobile waste management system that protects the OR staff from exposure to suctioned fluids. Suction is used to remove surgical fluids to allow surgeons to view and work on the area and also sucks up surgical fluids and smoke from the area being operated on. The system consists of two appliances: the rover and the docking station. Via the docking station, the fluids collected by the rover are automatically removed from the rover and the collection container is cleaned. The docking station can be used by multiple rovers that are present in the OR. Moreover, for each procedure, a disposable manifold is used to connect the rover with the drain that is connected to the surgical site [5]. The collected fluids are disposed via the hospital’s drainage system to the sewerage system via the closed Neptune system.

2. Methods

For this study, the following research question was formulated:

- What is the environmental impact of local disposal of surgical fluids versus decentralized incineration?

The environmental impact is evaluated by using life cycle assessment (LCA) ISO standards. These standards regard the ISO 14040 and 14044 standards [7,8]. The individual stages of the product's life cycle from raw material extraction to production, packaging, transport, use and reprocessing until final disposal of the Neptune 3 and suction canisters are evaluated in this study. In this study SimaPro is used, which is a software that supports the modelling, calculations, and the methodological decisions of the LCA. The Life cycle impact analysis data was retrieved from the Ecoinvent database (Ecoinvent version 3.6, Zürich, Switzerland) [11]. Similar approaches were reported in literature where the environmental impact of medical related products, such as face masks, were evaluated by means of the LCA method [16].

This life cycle analysis has been conducted in accordance with the protocol set out by Rijkswaterstaat, a Directorate-General of the Ministry of Infrastructure and Water Management of the Netherlands. During this study, Rijkswaterstaat was consulted several times to ensure alignment on the design, methodology, and results interpretation of the LCA. This life cycle analysis differs from the protocol on some aspects, all of which have been agreed upon by Rijkswaterstaat. The most notable deviation in this study from the protocol is the fact that this is a single cycle LCA, and not a multi cycle LCA. The reasoning behind this deviation is that with the Neptune, operative fluids directly become part of the water cycle. Next to the life cycle analysis on Neptune, the Dutch National Institute for Public Health and Environment (RIVM) conducted a study to assess the environmental and public health safety risks of disposing fluid through the sewage in hospital operating rooms (ORs). This study concluded that it is safe to dispose fluid in ORs through the sewage as there is no risk involved from a microbiological perspective. Only fluid used in patients with acute infections must be collected in containers and disposed as infectious material.

3. Goal and scope definition

3.1 Goal definition

As mentioned in chapter 1, the Neptune 3 is proposed as an environmentally sustainable alternative to conventional suction cannisters. The goal of this study is to investigate whether the local disposal of surgical fluids from the OR using a device such as the Neptune 3 is indeed more environmentally friendly than decentralized incineration.

This is performed by means of conducting a Life Cycle Assessment to compare the process of draining and disposing of intra-operative collected fluids. This comparative study is made between Stryker's Neptune and conventional canisters.

To study this goal, an attributional LCA (ALCA) is applied. Thomassen, Dalgaard, Heijungs and de Boer [13] describe an ALCA as "the description of the pollution and resource flows within a chosen system attributed to the delivery of a specified amount of the functional unit" (p. 339). In this study, the delivered functional unit is the collection and disposal of intra-operative fluids. This functional unit is further elaborated on in section 2.3.

3.2 Scope definition

The scope of this study consists of temporal, geographical and technological scopes. Both technologies are currently applied. Therefore, the temporal scope of this study is set in the present. To increase the representativeness of the study, the use of recent data is of importance. Data that is obtained from literature is preferably from sources published the year 2016 to 2021 for both alternatives.

This study focuses on the situation in the Netherlands and thus, the geographical coverage is the Netherlands. Subsequently, all data that is used to model the foreground processes is based on the Netherlands. When data is lacking, the geographical scope is extended to geographical areas with similar characteristics of the Netherlands to increase the data availability. Moreover, the background data for the technologies is based on the country where it is produced.

Furthermore, this study focuses on the comparison between the use of the Neptune in the OR for high- and low-volume procedures, as defined in table 3, and the use of conventional canisters.

Finally, the technological coverage for the Neptune 3 consists of the rover, docking station and manifold. The technological coverage of the conventional suction canisters consists of the WIVA containers, the suction canisters, the bag, and lid. The drain used to connect the manifold and the patient is disregarded for both alternatives as this will be used in both alternatives.

3.3 Function, functional unit, alternatives, reference flows

The estimated lifespan of the Neptune 3 is seven years. The Neptune can be used during different procedures. In this study, it is assumed that a Neptune is used in the OR for high- and low volumes of intra-operative collected fluids. Table 1 gives an overview of all scenarios including number of procedures and collected volumes of intra-operative collected fluids per procedures. The scenarios are based on experiences from experts from the field that are familiar with the situation in hospitals in the Netherlands. The use of the Neptune 3 is compared to the use of the conventional cannisters for each scenario. Therefore, the included alternatives in this study are the Neptune 3 system and cannisters.

Table 1: included scenarios

	Number of procedures per year	intra-operative collected fluids included (L)
High-volume scenarios	400	24 liters
	400	20 liters
	400	10 liters
	400	7 liters
	800	5 liters
	800	2 liters
Low-volume scenarios	550	0.5 liter
	550	0.4 liter
	550	0.3 liter
	550	0.2 liter
	550	0.1 liter

The function provided with the use of both alternatives is the collection and disposal of intra-operative collected fluids. The resulting functional unit is the collection and disposal of intra-operative collected fluids over 7 years of procedures in high-volume and low-volume scenarios

Combining the two alternatives and the functional unit results in the following reference flows:

- The collection and disposal of intra-operative collected fluids over 7 years of procedures in high-volume and low-volume scenarios with the use of the Neptune 3 system
- The collection and disposal of intra-operative collected fluids over 7 years of procedures in high-volume and low-volume scenarios with the use of cannisters.

4. Inventory Analysis

4.1 System boundaries

The study focusses on the collection and disposal of intra-operative collected fluids resulting from high- and low-volume procedures in the operating room. This encompasses all processes related to the production of the required equipment and appliances, the transport, the electricity, and water used related to the collection in the OR and the final disposal and treatment of the collected fluids as shown in the flowchart as depicted in figure 1 for the Neptune 3 and figure 2 for the suction cannisters. In these flowcharts, the blue boxes represent background processes, whereas white boxes represent foreground processes. Background processes are input directly obtained from Ecoinvent, whereas the foreground processes are directly related to the Neptune 3.

The flowchart of the Neptune 3 starts with the production of the rover, docking station and manifolds. For each appliance, the main material and weight of the components is used to include the environmental impact caused the production of the required impact. Moreover, the transport from the location of the production of the components, final assembly and distribution route are included. Hereafter, the use of the Neptune is included in the system boundary. This encompasses electricity use, and water and detergent use for cleaning after use. Finally, the disposal and wastewater treatment are included.

The system boundaries for the second alternative, suction canisters are similar to the system boundaries of the Neptune 3. Here, the flowcharts start with the material and transport related to the production of the required equipment. Hereafter, the collected fluids and used equipment is in its entirety transported and incinerated.

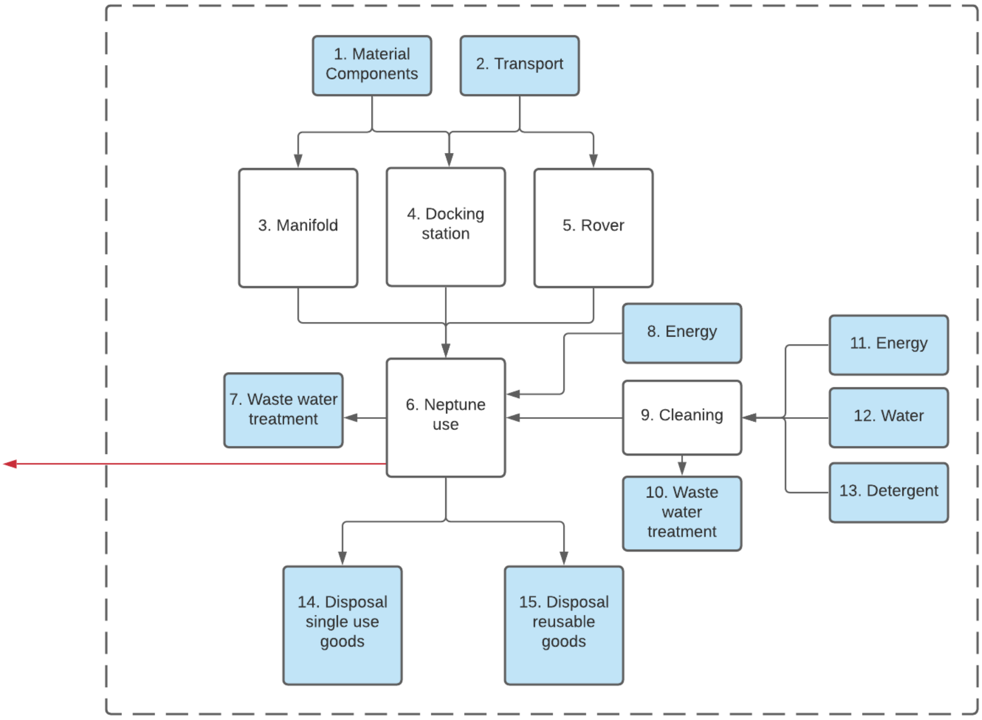

Figure 1: system boundaries Neptune 3 system

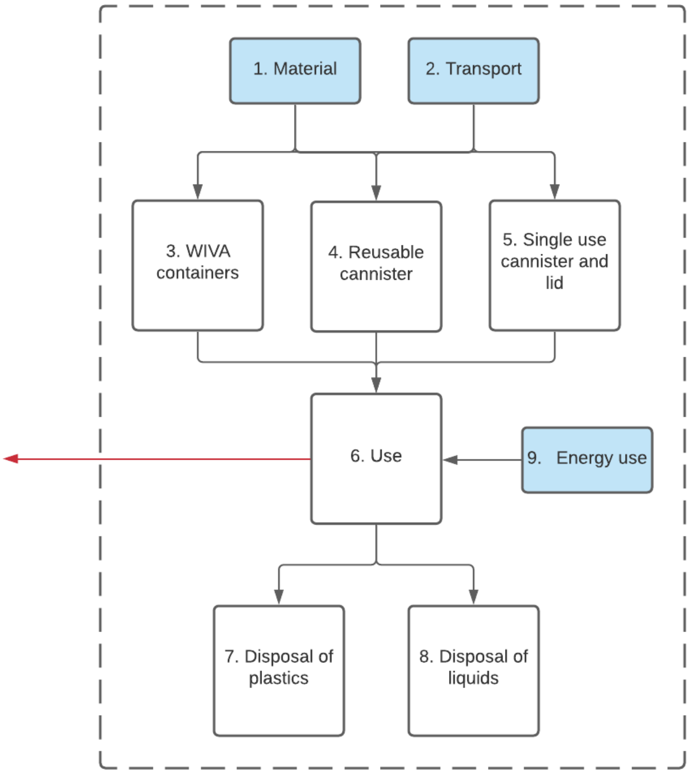

Figure 2: System boundaries conventional cannisters

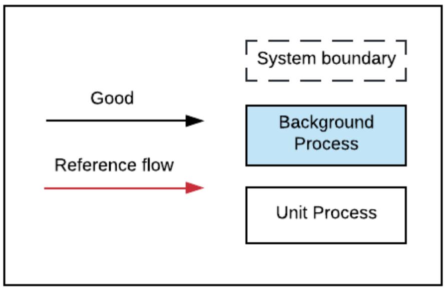

Figure 3: legend figure 1 & 2

4.1.1 Economy-environment system boundary

In the case of both alternatives, the subtraction of raw/virgin materials results in the inclusion of different environmental flows in the background processes. Eventually, these extracted elements will leave the economic system again as environmental flows when the material is incinerated after use.

4.1.2 Cut-off

The energy, buildings, machinery, and personnel related to the production, distribution and use of the appliances and equipment are disregarded from this study as this was not feasible with the current data availability on these processes. Moreover, the stand in which the cannisters are placed are cut-off due to the long lifespan of the product. Finally, the vacuum system (e.g. material) used for the cannisters is disregarded as this its main purpose is related to the air conditioning within the OR. Nevertheless, the energy use related to the creation of vacuum to use the cannisters is included.

4.2 Data collection

Data gathering has been done via desk research and field study. The material input and required transport for the suction cannister are based on information provided by the supplier of the cannisters in NL and desk research. All applicable data, assumptions and collection method can be found in digital appendix 2 – inventory analysis. Moreover, the main material, weight, and location of production of each of the components used for the Neptune 3 are provided by the producer's suppliers (digital appendix 1.1 – material database rover & digital appendix 1.1 – material database docking).

The inventory data related to distribution and waste treatments are mainly based on background information obtained from Ecoinvent 3.6. Nonetheless, the waste treatment flows in Ecoinvent are considered to be insufficient for the incineration of suction canister due to the large share of fluids that require additional energy input for the gasification process. Therefore, a new process was created specifically focused on incinerating fluids using the following in- flows and outflows:

- Economic input of municipal waste incineration facility: 2.5E-10 unit
  Based on incineration processes in Ecoinvent
- Economic input of heat, natural gas

  $$Q = m \cdot c \cdot \Delta T$$

  m = mass = 1kg
  c = specific heat = 4186 J/kg· °C
  ΔT = difference in temperature = 100 – 15 = 85 °C
  Q = heat energy = 0.36 MJ
- Economic input of transport, lorry: 0.0911 TKM
  Based on distance between OLVG Oost and Zavin = 91.1 KM and transport of 0.001-ton liquid waste
- Environmental outflow of heat equal to the input: 0.36MJ
- Environmental outflow of water equal to the input: 1 kg

Finally, based on the location of the production of the components and the location of the final assembly and the distribution route the total amount of transport is calculated from the producer of the components to the producer of the Neptune 3 and suction cannisters, to the distribution centers and final users.

The energy usage is determined by measurement during the use of the Neptune in the environment where it will be used during large scale usage. An overview of the measurement can be found in appendix C. A linear regression model was created based on 34 measurements over procedures in which a wide range of surgical liquids were collected (0.3 to 40 liters). The resulting model in the form $E[y_i] = \beta_0 + \beta_1 x_i$ with a confidence level of 99% was as following: $E[y_i] = 0.33 + 0.025x_i$. In this case x_i is the number of collected liters during a procedure and $E[y_i]$ the expected value at x_i.

This equation is illustrated using the 24 liter scenario as an example, which resulted in:

$$(0.33 + 0.025 \cdot 24) \cdot 400 = 372\,kWh$$

This resulted in the following values:

liters	Energy use per procedure (kWh)	number of procedures	Total kWh
24	0.93	400	372
20	0.83	400	332
10	0.58	400	232
7	0.505	400	202
5	0.455	800	364
2	0.38	800	304
0.5	0.3425	550	188.38
0.4	0.34	550	187
0.3	0.3375	550	185.63
0.2	0.335	550	184.25
0.1	0.3325	550	182.875

4.3 Multi-functionality and allocation

This study does not include multifunctionality problems in the foreground processes. In the background processes it was chosen to deal with multifunctionality by applying the cut-off approach, which means that additional goods that are produced in background processes are not including any impact. Hence, the impact caused by the background process is fully included in the product-system of both alternatives.

4.4 Results of inventory analysis

The unit-processes related to each product-system are scaled to deliver the quantity of the product or service required for the reference flow. This results in the inventory table in which the inputs from and outputs to the environment related to the functional unit are listed. The inventory tables, which can be found in digital appendix 3: Inventory results show the different emissions from the complete product-systems.

The inventory tables express the environmental impact of all product-systems in nearly two-thousand diverse environmental flows. Therefore, it is impractical to draw conclusions from solely the results of the inventory tables. To interpret the data, it is required to relate the results to relevant environmental impact categories. This will be discussed in the following section.

5. Impact assessment

As explained above, the inventory tables are too diverse and extensive to draw conclusions or to use for the decision-making process. In this phase, the wide variety of environmental flows are assigned and classified in a focused set of environmental impact categories. In this study, the mid-point indicators approach of ReCiPe [9] is used, since this a more comprehensive and established method in comparison to the end-point approach. The mid-point indicators are aggregated to fewer damage categories in the end-point approach. However, considering the principle of parsimony, the midpoint approach is preferred due to the inclusion of fewer assumptions.

5.1 Impact categories and characterization model

The results of the inventory table are translated into contributions to relevant environmental impact categories to compare the alternatives and to evaluate the product-systems. This study initially considers the impact categories defined in the RECIPE model, which are: global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human health & terrestrial ecosystems), fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity and water consumption. The results of the impact categories are determined by applying the ReCiPe midpoint characterization model. The midpoint results were converted into the endpoint categories of human health, ecosystems, and resources using the ReCiPe endpoint characterization model.

5.2 Classification

In this step, the environmental indicators from the inventory tables are assigned to the above-defined impact categories. The characterization factors from the ReCiPe characterization model are coupled to the environmental flows with the SimaPro software, through which the results are acquired.

5.3 Characterization results and discussion

The classification, as explained above, placed environmental interventions into impact categories. In the characterization step, the interventions are quantified in terms of a common unit [12]. The interventions are aggregated into a single score, the category indicator result. The midpoint results and relative difference for each considered impact category are shown in table 2 for all scenarios. The endpoint results are given in digital appendix 4 and are illustrated in figure 4,5,6 for ecosystems, human health, and resources, respectively.

5.3.1 results on the midpoint categories

This section elaborates in the differences in the results for all 18 midpoint impact categories. All results are shown in table 2. The differences were the Neptune are the better performing alternative are marked in green, the red numbers indicate a worse performance for the Neptune, and yellow indicates differences that are not significant.

Table 2: midpoint results and relative difference for all impact categories

Impact category	Global warming	Stratospheric ozone depletion	Ionizing radiation	Ozone formation, Human health	Fine particulate matter formation	Ozone formation, Terrestrial ecosystems	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication
0.1 Liter, Cannisters	621.14	0.00	14.72	1.53	0.53	1.62	1.46	0.16	0.01
0.1 Liter, Neptune	526.33	0.00	41.35	1.17	0.96	1.23	2.14	0.47	0.12
% difference	-15%	97%	181%	-24%	80%	-24%	47%	192%	1102%
0.2 Liter, Cannisters	622.98	0.00	14.74	1.53	0.53	1.63	1.47	0.16	0.01
0.2 Liter, Neptune	527.03	0.00	41.43	1.17	0.96	1.23	2.14	0.47	0.12
% difference	-15%	96%	181%	-24%	80%	-24%	46%	192%	1100%
0.3 Liter, Cannisters	624.82	0.00	14.75	1.54	0.53	1.64	1.47	0.16	0.01
0.3 Liter, Neptune	527.73	0.00	41.50	1.17	0.96	1.23	2.15	0.47	0.12
% difference	-16%	96%	181%	-24%	79%	-25%	46%	192%	1097%
0.4 Liter, Cannisters	626.66	0.00	14.77	1.55	0.54	1.64	1.47	0.16	0.01
0.4 Liter, Neptune	528.43	0.00	41.58	1.17	0.96	1.23	2.15	0.47	0.12
% difference	-16%	95%	182%	-25%	79%	-25%	46%	192%	1095%
0.5 Liter, Cannisters	628.50	0.00	14.78	1.56	0.54	1.65	1.48	0.16	0.01
0.5 Liter, Neptune	529.14	0.00	41.65	1.17	0.96	1.24	2.15	0.47	0.12
% difference	-16%	95%	182%	-25%	78%	-25%	45%	192%	1093%
2 Liter, Cannisters	960.31	0.00	21.92	2.46	0.83	2.60	2.26	0.24	0.01
2 Liter, Neptune	627.60	0.00	48.61	1.32	1.05	1.40	2.32	0.56	0.14
% difference	-35%	39%	122%	-46%	26%	-46%	3%	136%	823%
5 Liter, Cannisters	2316.30	0.00	47.30	5.98	2.02	6.34	5.48	0.57	0.04
5 Liter, Neptune	608.60	0.00	46.46	1.30	1.04	1.37	2.30	0.57	0.14
% difference	-74%	-42%	-2%	-78%	-48%	-78%	-58%	1%	309%
7 Liter, Cannisters	1756.66	0.00	35.26	4.56	1.53	4.83	4.17	0.43	0.03
7 Liter, Neptune	512.20	0.00	42.04	1.13	0.93	1.19	2.11	0.45	0.11
% difference	-71%	-30%	19%	-75%	-39%	-75%	-50%	4%	319%
10 Liter, Cannisters	2300.18	0.00	45.18	5.97	2.02	6.33	5.47	0.56	0.03
10 Liter, Neptune	527.48	0.00	43.69	1.15	0.94	1.21	2.13	0.46	0.11
% difference	-77%	-45%	-3%	-81%	-54%	-81%	-61%	-18%	227%
20 Liter, Cannisters	4578.66	0.00	87.98	11.92	4.02	12.63	10.91	1.11	0.07
20 Liter, Neptune	578.42	0.00	49.20	1.22	0.96	1.28	2.21	0.50	0.12
% difference	-87%	-70%	-44%	-90%	-76%	-90%	-80%	-55%	80%
24 Liter, Cannisters	5651.52	0.00	107.60	14.44	4.89	15.30	13.24	1.38	0.09
24 Liter, Neptune	598.80	0.00	51.40	1.24	0.98	1.31	2.24	0.52	0.13
% difference	-89%	-75%	-52%	-91%	-80%	-91%	-83%	-62%	49%
Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq

Impact category	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Land use	Mineral resource scarcity	Fossil resource scarcity	Water consumption
0.1 Liter, Cannisters	1039.32	10.48	14.04	36.58	223.24	5.52	0.64	276.01	7.55
0.1 Liter, Neptune	10377.07	126.54	165.79	115.21	2140.93	25.99	13.28	177.80	4.20
% difference	898%	1107%	1081%	215%	859%	371%	1990%	-36%	-44%
0.2 Liter, Cannisters	1055.49	10.52	14.10	36.75	224.24	5.56	0.64	276.57	7.55
0.2 Liter, Neptune	10379.98	126.60	165.86	115.24	2141.80	26.01	13.28	178.00	4.16
% difference	883%	1103%	1076%	214%	855%	368%	1964%	-36%	-45%
0.3 Liter, Cannisters	1071.65	10.56	14.16	36.92	225.25	5.61	0.65	277.13	7.56
0.3 Liter, Neptune	10382.92	126.66	165.94	115.27	2142.67	26.03	13.28	178.20	4.11
% difference	869%	1100%	1072%	212%	851%	364%	1938%	-36%	-46%
0.4 Liter, Cannisters	1087.81	10.59	14.22	37.09	226.25	5.66	0.66	277.69	7.56
0.4 Liter, Neptune	10385.83	126.72	166.02	115.30	2143.54	26.05	13.28	178.41	4.07
% difference	855%	1096%	1068%	211%	847%	361%	1912%	-36%	-46%
0.5 Liter, Cannisters	1103.98	10.63	14.27	37.26	227.25	5.70	0.67	278.25	7.52
0.5 Liter, Neptune	10388.77	126.78	166.10	115.32	2144.42	26.06	13.29	178.61	4.02
% difference	841%	1093%	1064%	210%	844%	357%	1888%	-36%	-46%
2 Liter, Cannisters	1974.97	16.37	22.18	58.01	355.00	9.37	1.16	421.66	11.10
2 Liter, Neptune	10744.12	134.39	175.91	118.85	2277.36	27.86	13.50	218.50	4.07
% difference	444%	721%	693%	105%	542%	197%	1060%	-48%	-63%
5 Liter, Cannisters	4610.31	34.92	47.83	142.00	806.82	21.53	2.70	1021.70	23.23
5 Liter, Neptune	10664.82	132.80	173.92	118.27	2262.55	27.36	13.46	212.92	1.05
% difference	131%	280%	264%	-17%	180%	27%	399%	-79%	-95%
7 Liter, Cannisters	3388.63	25.29	34.71	106.78	594.58	16.04	1.97	781.96	21.49
7 Liter, Neptune	10351.56	125.89	164.83	114.88	2116.25	26.08	13.27	166.80	1.75
% difference	205%	398%	375%	8%	256%	63%	573%	-79%	-92%
10 Liter, Cannisters	4542.11	33.26	45.76	141.47	787.36	21.05	2.66	1017.76	27.13
10 Liter, Neptune	10415.39	127.22	166.51	115.49	2135.29	26.48	13.32	171.19	0.78
% difference	129%	282%	264%	-18%	171%	26%	401%	-83%	-97%
20 Liter, Cannisters	8993.66	64.66	89.17	282.14	1550.93	41.53	5.25	2029.24	54.10
20 Liter, Neptune	10628.15	131.66	172.12	117.52	2198.73	27.80	13.46	185.84	-2.44
% difference	18%	104%	93%	-58%	42%	-33%	156%	-91%	-105%
24 Liter, Cannisters	10956.37	79.98	110.32	355.84	1921.77	50.60	6.43	2452.17	65.41
24 Liter, Neptune	10713.26	133.44	174.36	118.34	2224.11	28.33	13.51	191.69	-3.73
% difference	-2%	67%	58%	-67%	16%	-44%	110%	-92%	-106%
Unit	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3

The results show that the Neptune 3 can be considered to have a lower environmental impact in the larger volume procedures for **global warming** (15 – 89 % reduction)**, ozone formation terrestrial ecosystems & human health** (24 – 91 % reduction)**, fossil resource scarcity** (36 – 92 % reduction) **and water consumption** (44 – 106 % reduction)**.** The Neptune also has a lower impact in **stratospheric ozone depletion, fine particulate matter formation, terrestrial acidification** for the large volume scenarios (5 liter and more). In the case of **Ionizing radiation, freshwater eutrophication, and human carcinogenic toxicity** the Neptune only scores better in the very large volume procedure (10 liter and more). The Neptune has a larger score in the impact category of **Marine eutrophication, Terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human non-carcinogenic toxicity, land use and mineral scarcity,** with an increasing difference for the small volume categories.

5.3.2 results on the endpoint categories

The 18 midpoint results are converted to three final impact categories, which are ecosystem, human health, and resources. This aggregation helps to compare the relative effects of each impact category. It should be noted that although there is a scientific consensus on the midpoint-categories, there is less consensus on the translation to the endpoint categories (LAP3, 2021). It is of importance to be mindful of this when interpreting the results. The results are shown in figures 4, 5 and 6 .

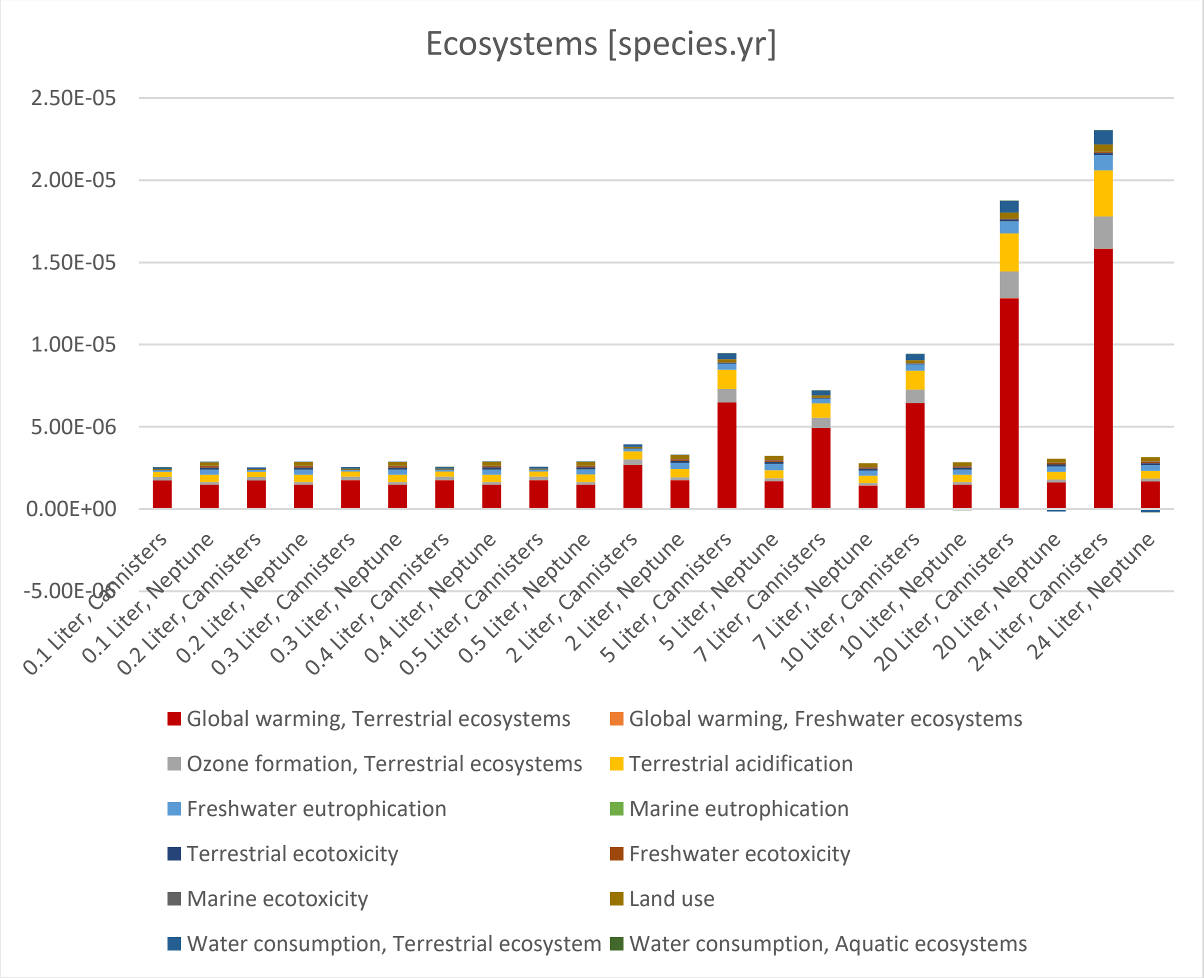

Figure 4: Endpoint results ecosystem

The relative results of the ecosystem endpoint category show that the Neptune category is the better performing alternative for scenarios from 2 liter and upwards. This is largely attributed to the resulting waste from using cannisters. The lower volume categories have a slightly higher impact for the Neptune. When looking at the contribution of the impact categories, it is evident that global warming has the largest effect on ecosystems followed by terrestrial acidification and ozone formation for both alternatives. It should be noted that the Neptune is the better performing alternative for each scenario when global warming is considered (table 2).

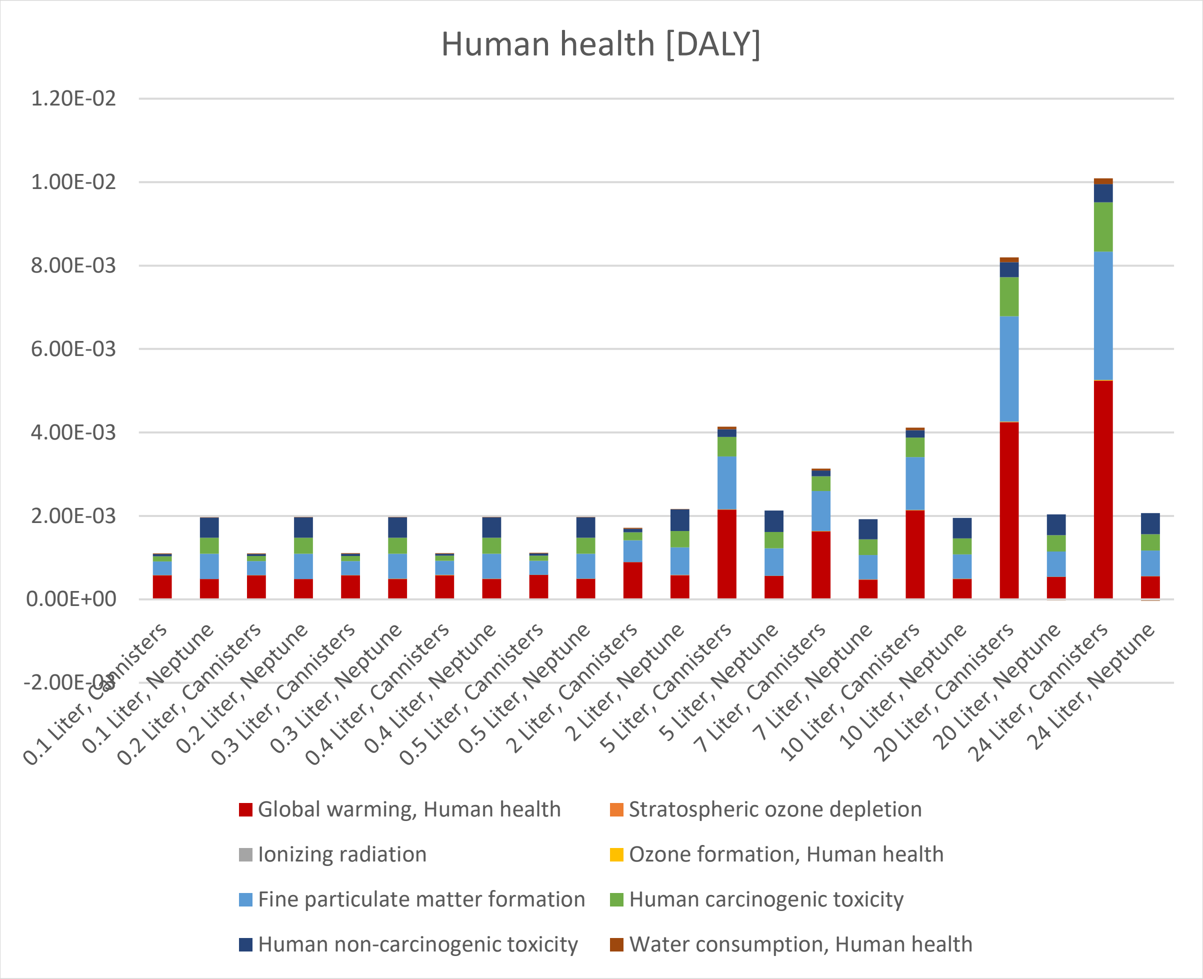

Figure 5: Endpoint results Human Health

The relative results for human health show a remarkable difference between the alternatives for the larger volume scenarios (5 to 24 liter). Furthermore, it may be observed that the canisters alternative performs better for the small volume procedures (0.1 to 0.5 liter). Similar to the ecosystem endpoint category, the contribution shows that, global warming has the largest effect. This is followed by fine particulate matter formation and human carcinogenic toxicity. In this case, the difference is also largely attributed to the resulting waste from using cannisters. Moreover, the use of single use plastic in the liner and material used to produce the rover is causing an increase in fine particulate matter formation. Finally, the rover is also causing the impact in human carcinogenic toxicity, where in the case of canisters this is caused by the waste treatment process.

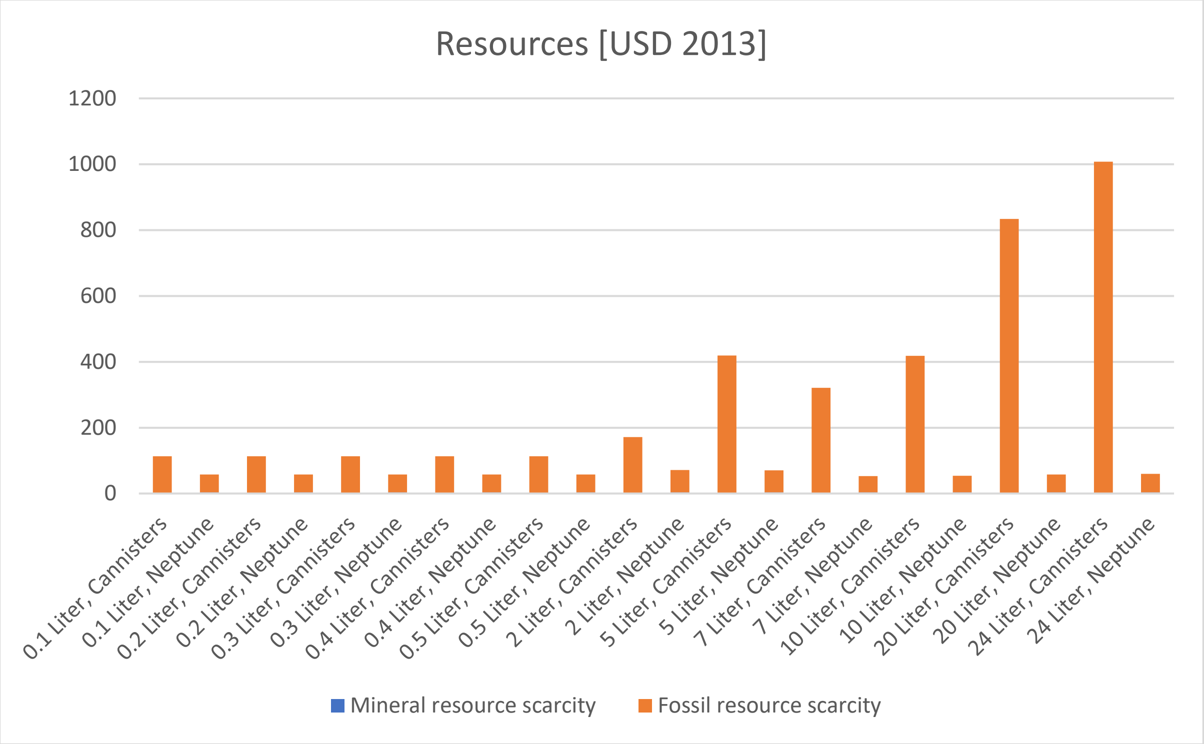

Figure 6: Endpoint results Resources

The results for resources show a remarkable difference between the alternatives, especially in the larger volume scenarios. Furthermore, it may be observed that the difference between both alternative is smaller the low volume procedures (0.1 to 0.8 liter). The main contributor to this endpoint category is fossil resource scarcity.

To further illustrate the differences between using the Neptune compared to conventional cannisters, the reduction in global warming and fossil resources were translation to number of flights from Amsterdam to Barcelona and barrels of oil, respectively. These calculations have been made based on an amount of 195 kg CO_2 per flight between Amsterdam and Barcelona and 136 kg per barrel of oil. This resulted in the following values:

Scenario	**Flights**	**Barrels of oil**
0.1 Liter	0.5	0.7
0.2 Liter	0.5	0.7
0.3 Liter	0.5	0.7
0.4 Liter	0.5	0.7
0.5 Liter	0.5	0.7
2 Liter	2.1	1.8
5 Liter	8.8	6.0
7 Liter	6.4	4.5
10 Liter	9.1	6.2
20 Liter	20.5	13.6
24 Liter	25.9	16.6

5.4 Interventions for which characterization factors are lacking.

In the results shown in the previous sections, only the environmental extensions with characterization factors are included. In some cases, characterization factors are lacking. This is mainly because research still must be executed to indicate characterization factors for all interventions. In this study, 1051 and 1052 interventions were lacking characterization factors for the Neptune 3 and Cannister alternatives, respectively. It is important to note that these interventions are not included in the category indicator results. This is to be considered one of the pitfalls of LCA. An overview of all flows and the flows for which characterization factors are lacking is given in digital appendix 3– inventory results.

6. Interpretation

6.1 Consistency check

In a LCA study, it is necessary to make several assumptions. It is therefore important to recognize that inconsistencies may occur between the Neptune 3 and cannister models. The consistency check is applied to determine whether assumptions, modelling choices and data are consistent with the goal and scope of the study, as defined in chapter 2.

One of the main assumptions made in this study are the emissions caused by the different means of waste treatment, which were wastewater treatment and incineration for the Neptune and Cannister alternatives, respectively. Here, the main point was the inclusion of the emissions in the respective Ecoinvent background processes. In Ecoinvent, the emissions are included to a similar extend. These are, however, not directly applicable to the two alternatives. Subsequently, two options were considered to ensure representativeness and consistency between both alternatives with regards to the waste treatment processes. The first option was to directly adapt the Ecoinvent background processes for waste treatment. The second option was to change the emissions of the Ecoinvent process for the treatment of wastewater to the emissions related to intra-operative collected fluids as already has been done to the incineration of liquids process. The main component of this substance is salt solution (0.9%), which was chosen as the composition of the resulting emissions for the incineration of liquids and wastewater treatment process. The two options are compared in the sensitivity analysis (section 5.5).

6.2 Completeness check

The completeness check is applied to determine if all relevant information with regards to the LCA-model is available and complete. Throughout the study, a variety of experts in the medical field were consulted to ensure that all factors are included and representative.

6.3 Contribution analyses

Contribution analyses have been performed to indicate the contribution of each stage of the life cycle of each alternative to the overall environmental profile. This analysis is used to determine hotspots and to compare the importance of different life cycle stages to the result. Digital appendix 5 show the figures that distinguishes the contribution for each sub-process of the Neptune 3 and cannisters for all scenarios and impact categories.

From the contribution analysis, it can be noted that in case of the Neptune system the rover is contributing largely to all impact categories. Further analysing the data shows that this is mainly due to the input of the printed circuit board assemblies and copper-rich material. Furthermore, the cleaning cycle contributes notably to all impact categories, but especially in marine eutrophication and land use. Finally, single use manifolds and electricity use that is related to each use contribute notably to the impact of most impact categories.

In the case of the cannister alternative it is observed that the treatment of waste plays an important role in all scenarios and impact categories. Furthermore, the use of WIVA containers contributes Here also applies that the use of WIVA containers is largely depending on the volume. Hence, the contribution of the WIVA containers is proportional to the collected volume of fluids. Another mentionable detail is the use of the single use suction bags. It is assumed that the only reusable suction bag that is used has a volume of 2 litres. Hence the suction bag has a bigger contribution in the procedures with small or uneven volumes as the suction bag is not fully filled.

6.4 Sensitivity analysis

One of the uncertainties of this model was the inventory data of the wastewater treatment process. Therefore, a sensitivity analysis is performed over the inventory data related to the wastewater treatment of the collected fluids (appendix B). It was found that the impact between the baseline and the adapted wastewater treatment process for each category didn't result in a notable difference.

A second uncertain factor was the energy mix as this might change in the future. The Netherlands has the ambition to have 100% renewable energy by 2050 (Ministerie van Algemene Zaken, 2022). It was therefore chosen to replace the original Dutch electricity mix with an all-renewable resource energy mix from Ecoinvent. The results are shown in appendix D.1 and compared to the original results in appendix D.2. The relative differences are shown below for the impact categories were identified to be contributing the most to the endpoint results. A negative value in these figures indicate that the Neptune is the better performing alternative. When we look at global warming, we see that the difference becomes more negative. This means that the Neptune is increasingly positive in terms of global warming compared to the cannisters. When we look at fine particulate matter formation, we see a positive number for the small volume scenarios. In this case, the cannisters are the better performing alternative. We see that the positive values reduce after introducing the new energy mix. This means that the difference between the cannisters and Neptune decreases. In case of the 2-liter scenario, we observe that the Neptune becomes the better performing alternative. The tables in de appendices show that changing the energy mix is positive for the Neptune for global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human health), fine particulate matter formation, ozone formation (terrestrial ecosystems), freshwater eutrophication and fossil resource scarcity. There was no change on the scenarios with less than 7 liter and a larger benefit for the Neptune system on the scenarios with larger volumes for terrestrial acidification, marine eutrophication, terrestrial ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use and mineral resource scarcity.

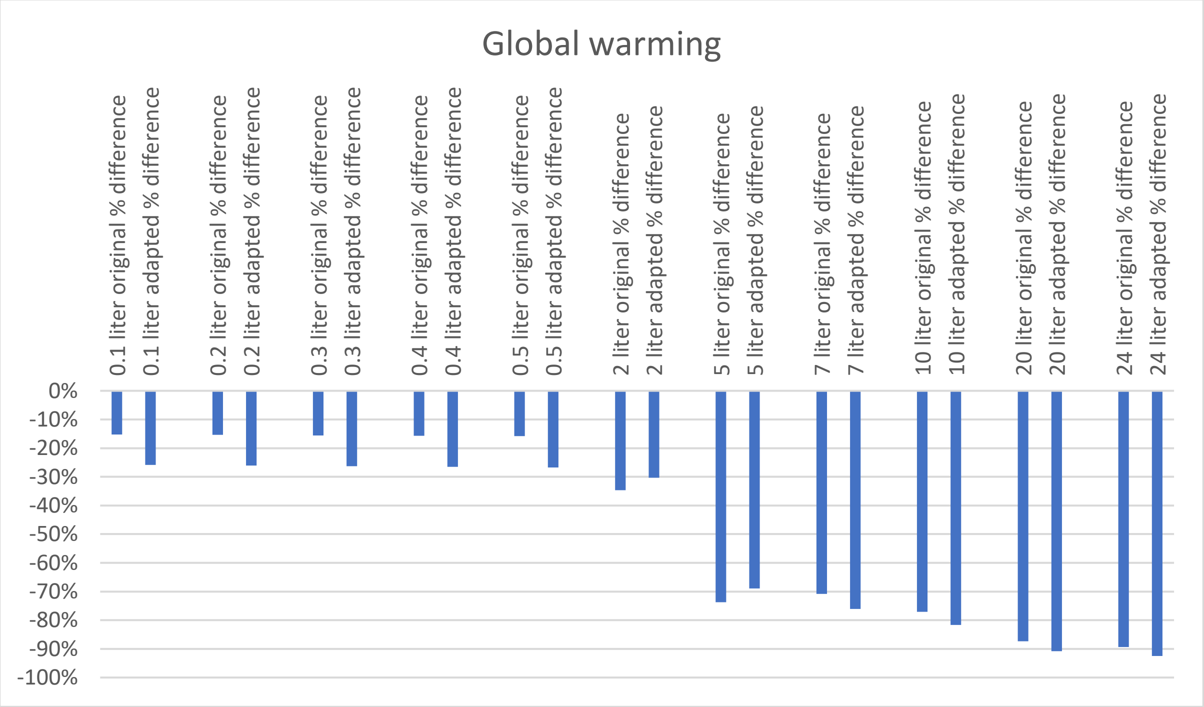

Figure 7: Relative differences global warming

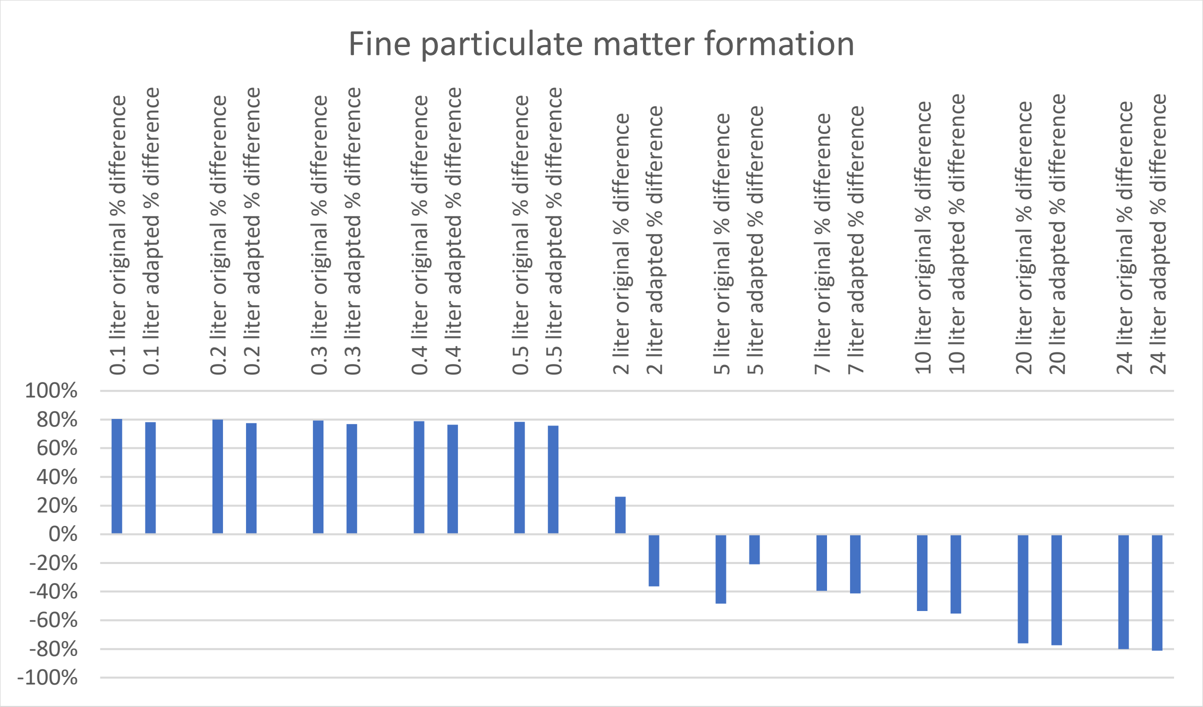

Figure 8: Relative differences fine particulate matter formation

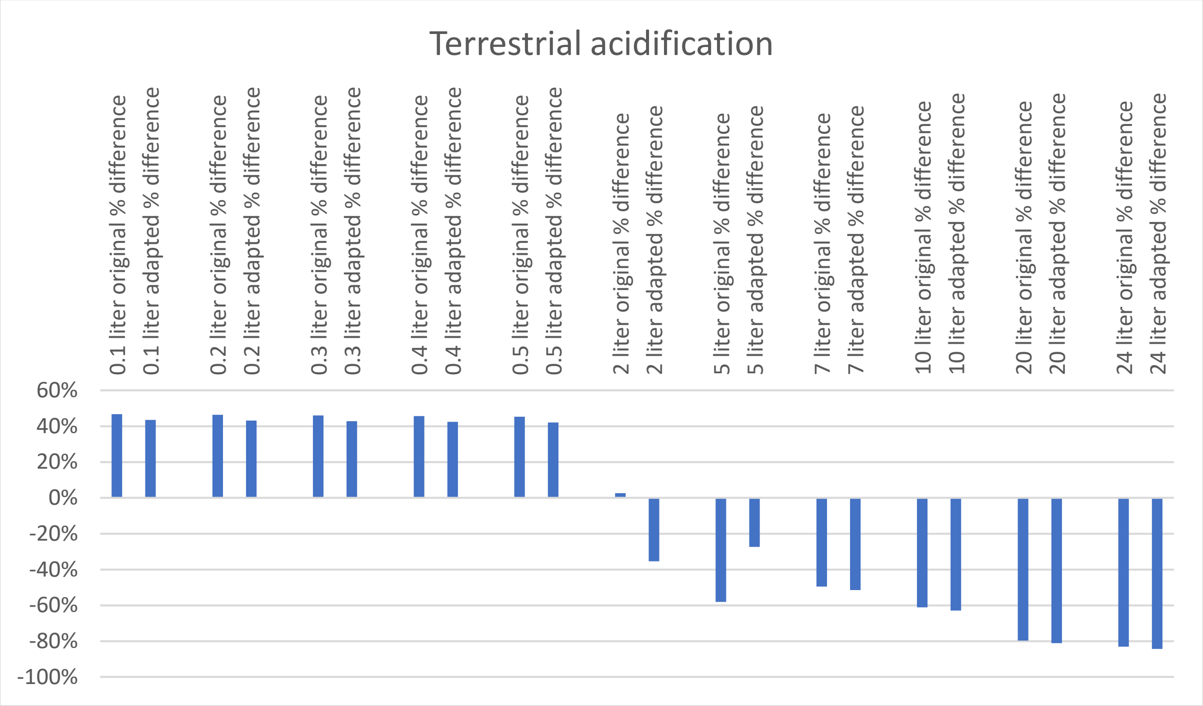

Figure 9: Terrestrial acidification

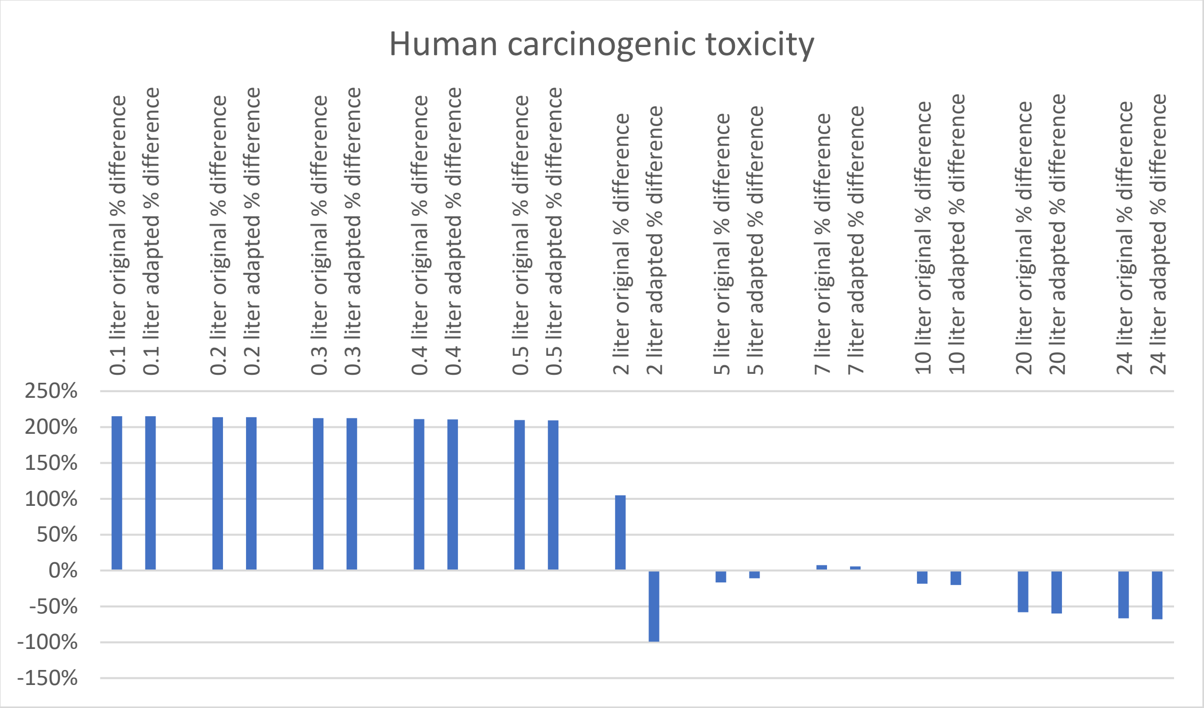

Figure 10: Relative differences human carcinogenic toxicity

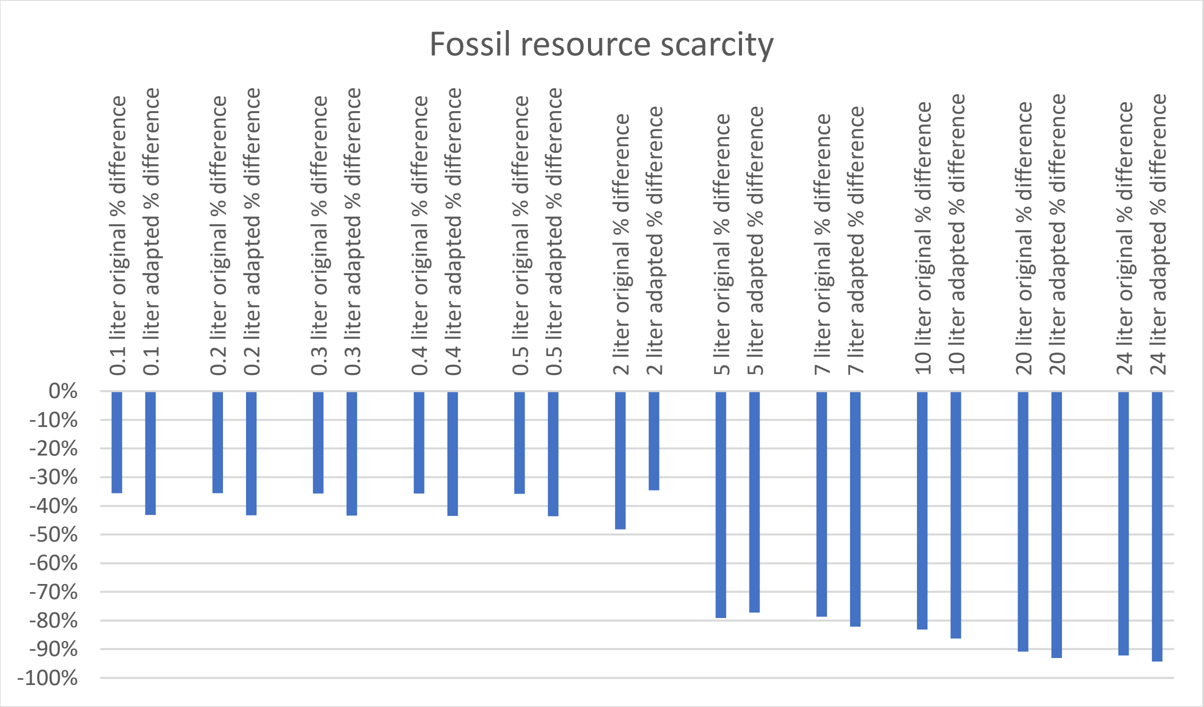

Figure 11: Relative differences fossil resource scarcity

7. Discussion and Conclusion

To our knowledge, this is the first study that compares an alternative system for the collection and disposal of surgical fluid with the conventional cannisters. This study focusses on the comparison of the use of conventional cannisters and the Neptune 3 system in terms of global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human health & terrestrial ecosystems), fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity and water consumption. From the conducted Life Cycle Assessment it can be concluded that the Neptune system is more beneficial when global warming, ozone formation terrestrial ecosystems, and fossil resource scarcity and water consumption are considered. The Neptune also has a lower impact in stratospheric ozone depletion, fine particulate matter formation, terrestrial acidification, and water consumption for the large volume scenarios (5 liter and more). In the case of Ionizing radiation, freshwater eutrophication, and human carcinogenic toxicity the Neptune only scores better in the very large volume procedure (10 liter and more). The Neptune has a larger score in the impact category of Marine eutrophication, Terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human non-carcinogenic toxicity, land use and mineral scarcity, with an increasing difference for the small volume categories.

By aggregating the mid-point results to end-point results it is observed that the Neptune systems is beneficial for resources in each scenario. In case of human health and ecosystems, the Neptune is beneficial for procedures with larger volumes.

The performed sensitivity analysis showed that the relative outcomes does not change after the introduction of an adapted wastewater treatment process. After changing these input data, the Neptune remained the alternative with a lower score in all scenarios for global warming and the high-volume scenarios for fossil resource scarcity. The second sensitivity analysis that was performed over the energy mix shows that the impact of the Neptune is positively impacted at a higher rate than the Canisters for global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human health), fine particulate matter formation, ozone formation (terrestrial ecosystems), freshwater eutrophication and fossil resource scarcity. There was no change on the scenarios with less than 7 liter and a larger benefit for the Neptune system on the scenarios with larger volumes for terrestrial acidification, marine eutrophication, terrestrial ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use and mineral resource scarcity.

With the use of the closed system Neptune 3, the surgical flushing fluids can be discharged to the sewer via the docking station, so that they no longer have to be processed in incinerators outside the hospital. Compared to canisters, the Neptune 3 system uses less material resulting in reduced global warming impact and fossil depletion. This may also result in consequential economic benefits, which would need to be confirmed by future assessment. The Neptune 3 system realizes CO_2 reduction because no transport and combustion are required. Incineration of 1 tonne of clinical waste generates no less than 3 tonnes of CO_2 [15]. The processing of liquids via the Neptune 3 system fits in well with the current ambitions of hospitals to treat their waste in an environmentally friendly way. This is especially the case when large volumes are considered. Moreover, material input and waste are reduced by using the Neptune system as this system requires only a single-use manifold for each procedure instead of cannisters and WIVA containers.

The developed Neptune 3 for the OR may be regarded as a medical “liquid suction system” providing collection and disposal of liquids released during surgical procedures through one system. This has several advantages. (1) The OR staff no longer must deal with lugging collection materials or collecting fluids and can pay attention to the patient and the cooperation / training of colleagues. (2) Less collection materials are needed and costs for purchase, storage, transport, and disposal are lower[1]. (3) Not having to lift heavy canisters reduces the risk of back pain and other injuries. (4) OR staff need to spend less time cleaning the OR or using canisters. Because the Neptune 3 does not require any drainage holes in the OR floor, the work floors are drier, which reduces the risk of slipping and is also more hygienic because no open connection to the sewer in the OR is required.

This life cycle analysis has been conducted in accordance with the protocol set out by Rijkswaterstaat, a Directorate-General of the Ministry of Infrastructure and Water Management of the Netherlands. During this study, Rijkswaterstaat was consulted several times to ensure alignment on the design, methodology, and results interpretation of the LCA. This life cycle analysis differs from the protocol on some aspects, all of which have been agreed upon by Rijkswaterstaat. The most notable deviation in this study from the protocol is the fact that this is a single cycle LCA, and not a multi cycle LCA. The reasoning behind this deviation is that with the Neptune, operative fluids directly become part of the water cycle. Next to the life cycle analysis on Neptune, the Dutch National Institute for Public Health and Environment (RIVM) conducted a study to assess the environmental and public health safety risks of disposing fluid through the sewage in hospital operating rooms (ORs). This study concluded that it is safe to dispose fluid in ORs through the sewage as there is no risk involved from a microbiological perspective. Only fluid used in patients with acute infections must be collected in containers and disposed as infectious material.

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[1] In addition, the hospital saves an average of approximately 3.6 minutes by using the new technology (Patel, 2004). Assuming a lower limit of 40 euros per operating theatre minute [14], the indirect financial saving are therefore at least 132 euros per procedure.

8. References

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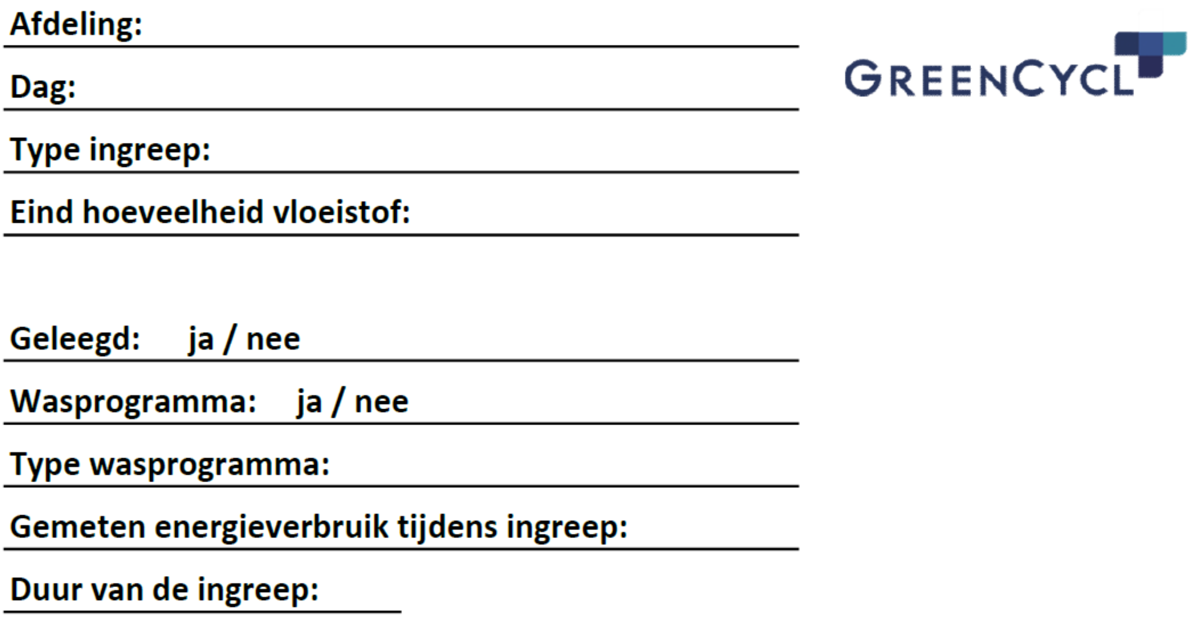
9. Appendices / Supporting information

Appendix A: Data collection sheet

Dit onderzoek dient ter bepaling van milieu impact van het afzuigen van vloeistoffen tijdens een operatie. Voor de berekening van milieu impact wordt onder meer gekeken naar CO_2 uitstoot, energie- en waterverbruik van afzuiging via conventionele potten ten opzichte van het geautomatiseerde, Neptune 3 systeem. In het onderzoek worden de gehele productlevenscyclus waaronder de winning van de materialen, productie, energie en waterverbruik tijdens de ingreep en afvalfase in de berekening meegenomen. De gegevens, ingevuld op dit formulier, zijn van grote waarde voor het onderzoek.

Vragenlijst Neptune:



Afdeling:

Dag:

Type ingreep:

Eind hoeveelheid vloeistof:

Geleegd: ja / nee

Wasprogramma: ja / nee

Type wasprogramma:

Gemeten energieverbruik tijdens ingreep:

Duur van de ingreep:

Gelieve dit formulier te mailen naar info@greencycl.nl. Hartelijk dank voor uw medewerking en de input.

Mochten er vragen ontstaan o.b.v. dit formulier of het onderzoek kunt u contact opnemen met het bovenstaande emailadres.

DISCLAIMER: Dit formulier valt buiten de algemene verordening gegevensbescherming. Gelieve geen persoonsgegevens invullen

This study serves to determine the environmental impact of collection surgical liquids during a procedure. To calculate the environmental impact, CO_2 emissions, and energy- and water usage of the use of the Neptune 3 are considered and compared to the use of conventional cannisters. In this study, the entire product life cycle, which entails material, production, energy and water usage and disposal is considered. The data filled in on this form is a great contribution to this research.

Department:

Day:

Type of procedure:

Final volume collected liquids

Emptied: yes / no

Washing program: yes / no

Type washing program:

Measured energy usage during procedure:

Duration of procedure:

Please email this form to info@greencycl.nl. Thank you for your contribution and input.

Should there be any questions regarding this form or this study, please contact the email above.

DISCLAIMER: This form is outside the scope of the General Data Protection Regulation. Please do not enter any personal details

Appendix B: adapted wastewater treatment process

The inventory data related to the wastewater treatment of the collected fluids is based on the inventory table adapted from Ecoinvent. Here, all processes and extensions that are not related to the treatment of intra-operative fluids are excluded. Moreover, the extensions are based on a salt solution of 0.9% as this is the main component of the intra operative collected fluids. Knowing that Sodium has a molair mass of 22.99 gram and Chloride has a molair mass of 35.45 gram, it is calculated that sodium and chloride contribute for 39.34% and 60.66% to the weight of NaCL, respectively. A 0.09% salt solution in 1 litre of wastewater results therefore in the emissions of 0.0035 kg sodium and 0.0055 kg chloride in water. This results in the following inventory table:

Process = [P8569] treatment of wastewater, average, capacity 1E9l/year[Europe without Switzerland]			
Economic inflows			
Name	Value	Unit	Uncertainty
process-specific burdens, residual material landfill_market for process-specific burdens, residual material landfill[Europe without Switzerland]	0.00173	kilogram	-
process-specific burdens, slag landfill_market for process-specific burdens, slag landfill[Europe without Switzerland]	0.011	kilogram	-
heat, district or industrial, other than natural gas_market for heat, district or industrial, other than natural gas[Europe without Switzerland]	0.0507	megajoule	-
process-specific burdens, municipal waste incineration_market for process-specific burdens, municipal waste incineration[Europe without Switzerland]	0.0605	kilogram	-
sewer grid, 1E9l/year, 30 km_market for sewer grid, 1E9l/year, 30 km[GLO]	2.82E-07	kilometer	-
heat, district or industrial, natural gas_market for heat, district or industrial, natural gas[Europe without Switzerland]	0.00295	megajoule	-
municipal waste incineration facility_market for municipal waste incineration facility[RoW]	1.51E-11	unit	-
liquid manure spreading, by vacuum tanker_market for liquid manure spreading, by vacuum tanker[GLO]	0.000604	cubic meter	-
electricity, low voltage_market group for electricity, low voltage[Europe without Switzerland]	0.206	kilowatt hour	-

wastewater, average_treatment of wastewater, average, capacity 1E9l/year[Europe without Switzerland]	1	cubic meter	-
cement, unspecified_market for cement, unspecified[Europe without Switzerland]	0.000691	kilogram	-
wastewater treatment facility, capacity 1E9l/year_market for wastewater treatment facility, capacity 1E9l/year[GLO]	2.66E-08	unit	-
electricity, high voltage_market group for electricity, high voltage[Europe without Switzerland]	0.00869	kilowatt hour	-
aluminium sulfate, powder_market for aluminium sulfate, powder[GLO]	0.00315	kilogram	-
Economic outflows			
Name	Value	Unit	Uncertainty
Environmental resources			
Name	Value	Unit	Uncertainty
Environmental emissions			
Name	Value	Unit	Uncertainty
Sodium, ion[('water',)]	0.0035	kilogram	-
Water[('air',)]	0.1	cubic meter	-
Water[('water',)]	0.9	cubic meter	-
Chloride, ion[('water',)]	0.00546	kilogram	-

Appendix C: overview of measurements

afdeling	dag	type ingreep	liters	geleegd	wasprogramma	energieverbruik	duur
OK	1-Sep	TUR-T	4.15	N	-	0.4	30
OK	1-Sep	TUR-P	34	J	5	1.3	120
OK	1-Sep	TUR-P	9.6	J	5	0.4	30
OK	1-Sep	TUR-P	3.9	J	5	0.5	50
OK	6-Sep	TUR-T	10	N	-	0.4	30
OK	6-Sep	TUR-P	17	J	5	0.5	60
OK	6-Sep	TUR-P	25	J	5	1.2	90
OK	12-Sep	DUBBEL J - WISSEL	0.4	N	-	0.3	20
OK	12-Sep	URS	1.6	N	-	0.4	45
OK	12-Sep	PNL	4.8	N	-	1.2	150
OK	13-Sep	TUR-T	11.75	N	-	0.7	42
OK	13-Sep	TUR-T	18.32	J	2	0.9	18
OK	14-Sep	TUR-P	40	J	5	1.4	190
OK	19-Sep	TUR-P	9	N	-	0.4	30
OK	19-Sep	TUR-P	14.7	J	5	0.5	60
OK	19-Sep	TUR-P	12.7	J	5	0.4	45
OK	26-Sep	Blaasteen	2.2	N	-	0.1	15
OK	26-Sep	URS	2.1	N	-	0.8	80
OK	26-Sep	URS	2.3	N	-	0.7	120
OK	26-Sep	URS	5	N	-	1	150
OK	26-Sep	DUBBEL J - WISSEL	3.3	N	-	0.8	30
OK	3-Oct	TUR-P	33	J	-	1.4	120
OK	3-Oct	TUR-T	14	N	-	0.5	60
OK	3-Oct	Dubbel J	0.85	N	-	0.1	15
OK	3-Oct	Dubbel J	0.45	N	-	0.1	10
OK	3-Oct	URS	2	J	5	0.3	45
OK	4-Oct	TUR-T	2.85	N	-	0.2	15
OK	4-Oct	TUR-T	4.85	N	-	0.2	15
OK	4-Oct	TUR-T	15.73	J	5	0.6	56
OK	5-Oct	URS	0.3	N	-	0.6	10
OK	5-Oct	TUR-T	10.2	N	-	0.6	50
OK	44847	TUR-P	20	J	2	0.8	75
OK	44847	TUR-T	5	N	-	0.2	20
OK	44847	TUR-T	23	J	5	0.7	75

Appendix D.1: results sensitivity analysis

Impact category	Global warming	Stratospheric ozone depletion	Ionizing radiation	Ozone formation, Human health	Fine particulate matter formation	Ozone formation, Terrestrial ecosystems	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication
0.1 Liter, Cannisters	592.64	0.00	11.52	1.49	0.52	1.59	1.43	0.15	0.01
0.1 Liter, Neptune	439.31	0.00	31.56	1.06	0.93	1.13	2.06	0.44	0.11
% difference	-26%	90%	174%	-29%	78%	-29%	44%	191%	1173%
0.2 Liter, Cannisters	594.48	0.00	11.53	1.50	0.52	1.59	1.44	0.15	0.01
0.2 Liter, Neptune	439.35	0.00	31.56	1.06	0.93	1.13	2.06	0.44	0.11
% difference	-26%	90%	174%	-29%	77%	-29%	43%	191%	1170%
0.3 Liter, Cannisters	596.32	0.00	11.55	1.51	0.52	1.60	1.44	0.15	0.01
0.3 Liter, Neptune	439.40	0.00	31.56	1.06	0.93	1.13	2.06	0.44	0.11
% difference	-26%	89%	173%	-29%	77%	-30%	43%	191%	1167%
0.4 Liter, Cannisters	598.16	0.00	11.56	1.52	0.53	1.61	1.45	0.15	0.01
0.4 Liter, Neptune	439.44	0.00	31.56	1.06	0.93	1.13	2.06	0.44	0.11
% difference	-27%	88%	173%	-30%	76%	-30%	42%	191%	1165%
0.5 Liter, Cannisters	600.00	0.00	11.58	1.52	0.53	1.62	1.45	0.15	0.01
0.5 Liter, Neptune	439.48	0.00	31.56	1.06	0.93	1.13	2.06	0.44	0.11
% difference	-27%	88%	173%	-30%	76%	-30%	42%	191%	1161%
2 Liter, Cannisters	850.00	0.00	39.70	2.41	0.82	2.55	2.22	0.22	0.01
2 Liter, Neptune	592.64	0.00	11.52	1.49	0.52	1.59	1.43	0.15	0.01
% difference	-30%	-54%	-71%	-38%	-36%	-38%	-35%	-33%	-34%
5 Liter, Cannisters	2274.84	0.00	42.64	5.94	2.00	6.29	5.44	0.55	0.03
5 Liter, Neptune	706.02	0.00	35.04	1.97	1.58	2.04	3.95	0.64	0.15
% difference	-69%	-36%	-18%	-67%	-21%	-68%	-27%	17%	333%
7 Liter, Cannisters	1735.93	0.00	32.93	4.53	1.53	4.81	4.15	0.42	0.03
7 Liter, Neptune	416.07	0.00	31.22	1.02	0.89	1.08	2.01	0.41	0.11
% difference	-76%	-36%	-5%	-78%	-41%	-78%	-52%	-2%	318%
10 Liter, Cannisters	2279.45	0.00	42.84	5.95	2.01	6.31	5.45	0.55	0.03
10 Liter, Neptune	417.08	0.00	31.27	1.02	0.90	1.08	2.02	0.42	0.11
% difference	-82%	-50%	-27%	-83%	-55%	-83%	-63%	-24%	224%
20 Liter, Cannisters	4557.93	0.00	85.64	11.89	4.01	12.61	10.89	1.10	0.07
20 Liter, Neptune	420.43	0.00	31.42	1.03	0.91	1.09	2.05	0.45	0.12
% difference	-91%	-74%	-63%	-91%	-77%	-91%	-81%	-59%	75%
24 Liter, Cannisters	5630.80	0.00	105.26	14.41	4.88	15.28	13.22	1.37	0.09
24 Liter, Neptune	421.77	0.00	31.48	1.04	0.91	1.10	2.06	0.46	0.12
% difference	-93%	-79%	-70%	-93%	-81%	-93%	-84%	-66%	45%
Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq

Impact category	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Land use	Mineral resource scarcity	Fossil resource scarcity	Water consumption
0.1 Liter, Cannisters	1022.03	10.02	13.42	35.82	208.47	4.86	0.62	267.60	8.24
0.1 Liter, Neptune	10324.28	125.13	163.90	112.87	2095.84	23.98	13.23	152.14	6.29
% difference	910%	1148%	1121%	215%	905%	394%	2037%	-43%	-24%
0.2 Liter, Cannisters	1038.20	10.06	13.48	35.99	209.48	4.90	0.63	268.16	8.24
0.2 Liter, Neptune	10326.80	125.18	163.96	112.88	2096.37	23.98	13.23	152.15	6.26
% difference	895%	1144%	1116%	214%	901%	389%	2009%	-43%	-24%
0.3 Liter, Cannisters	1054.36	10.10	13.54	36.15	210.48	4.95	0.64	268.72	8.24
0.3 Liter, Neptune	10329.33	125.23	164.02	112.89	2096.91	23.98	13.23	152.16	6.24
% difference	880%	1140%	1111%	212%	896%	385%	1982%	-43%	-24%
0.4 Liter, Cannisters	1070.52	10.13	13.60	36.32	211.48	5.00	0.64	269.28	8.25
0.4 Liter, Neptune	10331.85	125.28	164.09	112.90	2097.44	23.99	13.23	152.17	6.21
% difference	865%	1136%	1107%	211%	892%	380%	1955%	-43%	-25%
0.5 Liter, Cannisters	1086.68	10.17	13.65	36.49	212.48	5.04	0.65	269.85	8.20
0.5 Liter, Neptune	10334.33	125.33	164.15	112.91	2097.87	23.99	13.24	152.18	6.22
% difference	851%	1132%	1102%	209%	887%	376%	1929%	-44%	-24%
2 Liter, Cannisters	2100.00	16.00	97700.00	4110.00	78800.00	8.41	1.14	409.00	12.10
2 Liter, Neptune	1022.03	10.02	13.42	35.82	208.47	4.86	0.62	267.60	8.24
% difference	-51%	-37%	-100%	-99%	-100%	-42%	-46%	-35%	-32%
5 Liter, Cannisters	4585.16	34.25	46.93	140.88	785.34	20.57	2.67	1009.48	24.22
5 Liter, Neptune	10729.37	134.55	176.49	125.55	2376.66	26.48	13.42	229.60	0.58
% difference	134%	293%	276%	-11%	203%	29%	402%	-77%	-98%
7 Liter, Cannisters	3376.06	24.95	34.26	106.22	583.85	15.56	1.96	775.85	21.99
7 Liter, Neptune	10293.25	124.33	162.75	112.29	2066.45	23.86	13.22	138.46	4.06
% difference	205%	398%	375%	6%	254%	53%	574%	-82%	-82%
10 Liter, Cannisters	4529.54	32.93	45.31	140.91	776.63	20.57	2.64	1011.65	27.63
10 Liter, Neptune	10348.42	125.43	164.12	112.51	2078.09	23.92	13.25	138.64	3.44
% difference	128%	281%	262%	-20%	168%	16%	401%	-86%	-88%
20 Liter, Cannisters	8981.08	64.33	88.72	281.58	1540.19	41.05	5.24	2023.13	54.60
20 Liter, Neptune	10532.31	129.11	168.69	113.27	2116.88	24.14	13.37	139.26	1.36
% difference	17%	101%	90%	-60%	37%	-41%	155%	-93%	-98%
24 Liter, Cannisters	10943.80	79.64	109.87	355.28	1911.03	50.12	6.42	2446.06	65.91
24 Liter, Neptune	10605.87	130.57	170.51	113.57	2132.40	24.23	13.41	139.51	0.53
% difference	-3%	64%	55%	-68%	12%	-52%	109%	-94%	-99%
Unit	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3

Appendix D.2: relative differences sensitivity analysis

Impact category	Global warming	Stratospheric ozone depletion	Ionizing radiation	Ozone formation, Human health	Fine particulate matter formation	Ozone formation, Terrestrial ecosystems	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication
0.1 liter original % difference	-15%	97%	181%	-24%	80%	-24%	47%	192%	1102%
0.1 liter adapted % difference	-26%	90%	174%	-29%	78%	-29%	44%	191%	1173%
0.2 liter original % difference	-15%	96%	181%	-24%	80%	-24%	46%	192%	1100%
0.2 liter adapted % difference	-26%	90%	174%	-29%	77%	-29%	43%	191%	1170%
0.3 liter original % difference	-16%	96%	181%	-24%	79%	-25%	46%	192%	1097%
0.3 liter adapted % difference	-26%	89%	173%	-29%	77%	-30%	43%	191%	1167%
0.4 liter original % difference	-16%	95%	182%	-25%	79%	-25%	46%	192%	1095%
0.4 liter adapted % difference	-27%	88%	173%	-30%	76%	-30%	42%	191%	1165%
0.5 liter original % difference	-16%	95%	182%	-25%	78%	-25%	45%	192%	1093%
0.5 liter adapted % difference	-27%	88%	173%	-30%	76%	-30%	42%	191%	1161%
2 liter original % difference	-35%	39%	122%	-46%	26%	-46%	3%	136%	823%
2 liter adapted % difference	-30%	-54%	-71%	-38%	-36%	-38%	-35%	-33%	-34%
5 liter original % difference	-74%	-42%	-2%	-78%	-48%	-78%	-58%	1%	309%
5 liter adapted % difference	-69%	-36%	-18%	-67%	-21%	-68%	-27%	17%	333%
7 liter original % difference	-71%	-30%	19%	-75%	-39%	-75%	-50%	4%	319%
7 liter adapted % difference	-76%	-36%	-5%	-78%	-41%	-78%	-52%	-2%	318%
10 liter original % difference	-77%	-45%	-3%	-81%	-54%	-81%	-61%	-18%	227%
10 liter adapted % difference	-82%	-50%	-27%	-83%	-55%	-83%	-63%	-24%	224%
20 liter original % difference	-87%	-70%	-44%	-90%	-76%	-90%	-80%	-55%	80%
20 liter adapted % difference	-91%	-74%	-63%	-91%	-77%	-91%	-81%	-59%	75%
24 liter original % difference	-89%	-75%	-52%	-91%	-80%	-91%	-83%	-62%	49%
24 liter adapted % difference	-93%	-79%	-70%	-93%	-81%	-93%	-84%	-66%	45%
Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq

Impact category	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Land use	Mineral resource scarcity	Fossil resource scarcity	Water consumption
0.1 liter original % difference	898%	1107%	1081%	215%	859%	371%	1990%	-36%	-44%
0.1 liter adapted % difference	910%	1148%	1121%	215%	905%	394%	2037%	-43%	-24%
0.2 liter original % difference	883%	1103%	1076%	214%	855%	368%	1964%	-36%	-45%
0.2 liter adapted % difference	895%	1144%	1116%	214%	901%	389%	2009%	-43%	-24%
0.3 liter original % difference	869%	1100%	1072%	212%	851%	364%	1938%	-36%	-46%
0.3 liter adapted % difference	880%	1140%	1111%	212%	896%	385%	1982%	-43%	-24%
0.4 liter original % difference	855%	1096%	1068%	211%	847%	361%	1912%	-36%	-46%
0.4 liter adapted % difference	865%	1136%	1107%	211%	892%	380%	1955%	-43%	-25%
0.5 liter original % difference	841%	1093%	1064%	210%	844%	357%	1888%	-36%	-46%
0.5 liter adapted % difference	851%	1132%	1102%	209%	887%	376%	1929%	-44%	-24%
2 liter original % difference	444%	721%	693%	105%	542%	197%	1060%	-48%	-63%
2 liter adapted % difference	-51%	-37%	-100%	-99%	-100%	-42%	-46%	-35%	-32%
5 liter original % difference	131%	280%	264%	-17%	180%	27%	399%	-79%	-95%
5 liter adapted % difference	134%	293%	276%	-11%	203%	29%	402%	-77%	-98%
7 liter original % difference	205%	398%	375%	8%	256%	63%	573%	-79%	-92%
7 liter adapted % difference	205%	398%	375%	6%	254%	53%	574%	-82%	-82%
10 liter original % difference	129%	282%	264%	-18%	171%	26%	401%	-83%	-97%
10 liter adapted % difference	128%	281%	262%	-20%	168%	16%	401%	-86%	-88%
20 liter original % difference	18%	104%	93%	-58%	42%	-33%	156%	-91%	-105%
20 liter adapted % difference	17%	101%	90%	-60%	37%	-41%	155%	-93%	-98%
24 liter original % difference	-2%	67%	58%	-67%	16%	-44%	110%	-92%	-106%
24 liter adapted % difference	-3%	64%	55%	-68%	12%	-52%	109%	-94%	-99%
Unit	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3