Developing a Carbon Emissions Tool for Dutch Operating Rooms Using a Hybrid Modelling Approach

A MSc thesis for Industrial Ecology

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Abstract

Climate change is a large and global concern. The healthcare sector contributes between 6% and 10% to national carbon emissions in developed countries. Within the healthcare sector, operation rooms are very resource-intensive. A lot of energy, medical products, equipment and pharmaceuticals are required to perform surgery on a daily basis. This report explores methods to calculate the carbon footprint of Dutch operation rooms. Based on these, a tool is developed to calculate total carbon footprint and identify contributing processes. A data collection trial is completed during this development, identifying difficulties in the data collection and calculation process as well as generating some emission results. A tool is designed from the results of this trial. It is based on life cycle analysis, while also including emission factors calculated from sector carbon disclosures. Differences from either one of these carbon emission calculation methods are evaluated and if possible, compared. A final selection of calculation methods for each process is selected and used in the tool. The tool is capable of both internally monitoring carbon emissions over different time periods and comparing emission results with other hospitals. Both these functions can be used to identify emission hotspots, inspire improvements and monitor changes in emissions. Sensitivity of the model to different characterization methods and scope definitions is tested. Ultimately, this tool is aimed to aid in reducing CO2-eq emissions within operation rooms. Recommendations are made to further improve this tool and its data collection procedure.

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Contents

List of abbreviations

AMC – Amsterdam Medical Centre

DEFRA – Department of Environment, Food & Rural Affairs

EEIO – Environmentally Extended Input-Output (Analysis)

GHG – Greenhouse Gas

GWP – Global Warming Potential

HVAC – Heat, Ventilation and Air Conditioning

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LUMC – Leiden University Medical Centre

OR – Operation Room

UMCU – University Medical Centre Utrecht

Glossary of terms

Alternative – Alternative one of a set of product systems studied in a particular LCA, e.g. for comparison. In the case of this study, this is dynamic and defined by the tool user. It can be Hospital A in years 2018, 2019 and 2020 or it can be Hospitals A, B, C and D, or a combination of hospitals and years.

Category indicator - A quantifiable representation of an impact category, e.g. infrared radiative forcing for climate change.

(Category) Indicator result - The numerical result of the characterization step for a particular impact category. As this study deals only with the impact category of climate change, this will be for example: 12 kg CO2-equivalents for climate change.

Characterization - A step of impact assessment, in which the elementary flows assigned qualitatively to a particular impact category (in classification) are quantified in terms of a common unit for that category, allowing aggregation into a single score: the indicator result.

Characterization factor - A factor derived from a characterization model for expressing a particular elementary flow in terms of the common unit of the category indicator. As this study deals only with climate change, this is the Global Warming Potential (GWP).

Characterization model - A mathematical model of the impact of elementary flows with respect to a particular category indicator.

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.

Economic process - See unit process.

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. CO2 or noise emissions, wastes discarded in nature).

Emission factor – A factor derived from the characterization model for expressing the total emissions of a unit process in terms of the common unit of the category indicator. This is a sum of all the life cycle (as defined by goal and scope) emissions of that unit process. Multiplying the input of the unit process by the emission factor should yield the same indicator result as multiplying all elementary flows of that unit process and its upstream and downstream processes with their respective characterization factors, for the same indicator category. As this study deals only with climate change, the emission factor is expressed in Global Warming Potential per unit (of the unit process; e.g. kgCO2eq/kWh).

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

Function - A service provided by a product system or unit process

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).

Goal and scope definition - The first phase of an LCA, establishing the aim of the intended study, the functional unit, the reference flow, the product system(s) under study and the breadth and depth of the study in relation to this aim.

(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.

Impact category - A class representing environmental issues of concern to which elementary flows are assigned, e.g. climate change, loss of biodiversity.

Input - A product (goods, materials, energy, services), waste for treatment or elementary flow (including resource extraction, land use, etc.) modeled as 'entering' a unit process (adapted from ISO).

(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 - 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; the term may refer to either a procedural method or a specific study.

Normalization - A step of Impact assessment in which the indicator results are expressed relative to reference information, e.g. relative to the indicator results for global elementary flows in 1995.

Normalization result - The result of the normalization step: a table showing the normalized indicator results for all the selected impact categories, supplemented by any other relevant information.

Normalized indicator result- The numerical result of normalization for a particular impact category, e.g. 0.02 year for climate change.

Reference flow - 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.

(Product) System - A set of unit processes interlinked by material, energy, product, waste or service flows and performing one or more defined functions.

Scope 1 – All direct emissions. In this study, emissions due to inhalation anesthetics.

Scope 2 – All indirect emissions due to electricity consumption. As in other literature this has included space heating. Space heating is classified as scope 2 throughout this report, even though in Dutch hospitals this is done with natural gas.

Scope 3 – Other indirect emissions. In this study, this includes emissions due to sterilization and the consumption of products.

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.

Sources for glossary terms: ISO (2006a); Guinée et al. (2002)

1 Introduction

Climate change is of large and increasing global concern. It poses the greatest risk to public health in the 21st century (Costello et al., 2009; Watts et al., 2015). To avoid the most damaging effects, the target of keeping global temperature rise well below 2 °C has been set in the Paris agreement (UNFCCC, 2015). In order to reach this target, environmental improvements are required in all economic sectors, including healthcare.

While the healthcare sector has a huge body of academic research to its name, very little of it is concerned with its environmental effects. There are several publications that estimate carbon footprints of national healthcare systems between 6 and 10% of total national emissions (Chung & Meltzer, 2009; Gupta Strategists, 2019; NHS Sustainable Development Unit, 2018). These all rely on approximating emissions from economic data. While this method is suitable for national accounts, it does not allow for a high degree of detail. This becomes a problem when zooming in on smaller sectors within the healthcare sector, something that is required to find tailored improvements.

Within the healthcare sector, the Operation Rooms (OR) department is especially resource-intensive, as surgery requires specialized tools, a sterile environment, use of consumables and energy intensive machinery. The OR-department is therefore an important place to improve environmental performance in the hospital. The only study specifically examining the carbon footprint of operating rooms found emissions of about 3-5 million kg CO2-equivalent for the use of 21-24 operating rooms for one year (MacNeill et al., 2017). These hospitals were located in Vancouver, Canada; Minneapolis, US; and Oxford, UK. Extrapolation of these results to the number of operating theatres within these three countries would yield a total carbon footprint of 9.7 million tonnes CO2eq/year, or about 0.15% of the total sum of these countries' national emissions (MacNeill et al., 2017). However, this study calculates most product emissions by multiplying waste weights with emission factors related to materials. Such material emission factors are rough estimates, as they aggregate material emissions over a wide range of uses, while each might have very different CO2-footprints. It can be logically expected that plastic use in an OR is associated with different emissions than it is when used in, for example, packaging. Plastics used in the OR are required to be sterile, and are produced in lower quantities for more specialized purposes.

Life Cycle Assessment (LCA) can offer an improvement over such product emission factors, as it aims to assess the life cycle impact by assessing each process in a product's life cycle and its associated emissions. It can only do so if you have cradle to gate LCA data specified particularly to the use that is studied. However, LCA data is not available for all products used in the surgical suite. In a previous, non-published report, a hybrid approach using LCA data as well as product emission factors were used to make a more precise estimate of the carbon footprint of the OR-department of the Leiden University Medical Centre's 20 ORs (Hendriks et al., 2020). The emissions were calculated to be around 4.55 million kg CO2-equivalent annually. This equates to about 7-8% of total hospital emissions.

The previously mentioned study offered insight into those processes most contributing to the total emissions, but is limited to one hospital. It offers little comparative value, both in time and location. It is also difficult and labour-intensive to be repeated by employees. To increase its comparative value, this study will develop and test a practical method to evaluate greenhouse gas emissions of OR departments of Dutch hospitals. It will also assess in more depth the different types of emission calculation possibilities by doing a sensitivity analysis. Using this method, potential environmental improvements can be identified. The following question can then be answered:

How can the greenhouse gas emissions of Dutch OR-departments accurately and repeatably be calculated, and how can this help decrease their emissions?

By developing this method, hospitals are enabled to accurately track and compare their OR's emissions. In this research question, 'repeatably' should be interpreted both as repeatable by scientists, but also by environmental coordinators employed by a hospital. This research develops a tool to analyse these emissions easily. This tool can be used by the hospitals to annually monitor their improvements, and signalize potentials for improvements through comparison with other hospitals and comparison over time. Furthermore, it is able to convey results on environmental performance, will normalize results per procedure and per OR, and perform hot spot analysis.

1.1 Literature Review

Several studies on the environmental performance of the healthcare system are published. They are done on a national scale using economic data, based on environmentally extended input-output (EEIO) modelling. In the US, the healthcare sector is estimated to contribute between 8 and 10 percent of the national carbon footprint (Chung & Meltzer, 2009). In the UK, the health and social care sector is estimated to represent 6.3% of the national carbon footprint (NHS Sustainable Development Unit, 2018). The Canadian estimate is 4.6% of the national total and the Australian about 7% (M. J. Eckelman et al., 2018; Malik et al., 2018). In the Netherlands, this is estimated to be around 7% (Gupta Strategists, 2019). Paradoxically, these emissions made to improve health locally are adversely impacting public health globally through climate change effects (M. J. Eckelman & Sherman, 2016, 2018).

Environmental effects other than climate change have also been estimated in the case of the US. It was found that the healthcare sector contributed to 12% of total national acidification, 1.5% of ecotoxicity and 9% of respiratory disease from particulate matter (M. J. Eckelman & Sherman, 2016). Additionally, the US healthcare system is responsible for 7% of the total commercial and institutional US water use. All these environmental effects combined were estimated to equal between 123 000 – 381 000 disability-adjusted life years (M. J. Eckelman et al., 2018). While these other environmental effects are beyond the scope of this study, it is important to note that carbon emissions are not the only adverse effect caused by the healthcare sector.

Hospitals are an important and relatively intensive part of the healthcare sector. There are multiple estimates of carbon footprints of Dutch hospitals. These are generally made using a CO2 footprint calculation tool based on emission factors and direct emissions to air (Oudmaijer, 2019). Hospitals such as the AMC, UMCU and LUMC have performed such a hospital-scale CO2 footprint estimation. For the AMC, the use of fuel for buildings was by far the largest emitter, with waste treatment, travel, and upstream activities taking up the bulk of the remainder (Oudmaijer, 2019). For the LUMC the electricity use was the largest contributor to CO2 footprint, with travel habits, waste treatment and fuel for buildings also having sizeable impacts (LUMC, 2017). Using a different methodology, based on annual spending on product groups, the UMCU estimated its largest contributors to CO2 footprint to be pharmaceuticals and energy use (de Graaff & Broeren, 2018). Implants, travel habits and disposable products were the next three largest (de Graaff & Broeren, 2018).

The methodology used by de Graaff & Broeren uses a hybrid approach (de Graaff & Broeren, 2018). In this, some emissions of processes at the hospital are estimated through life cycle assessment data, while others are estimated through economic estimation methods. The latter works by dividing disclosed carbon emissions of relevant companies over their disclosed revenues, calculating an emission per euro spent in the product category which that company produces. This is limited to the companies that disclose their carbon emissions. It is also limited in detail, as the emission per euro is calculated for all of the revenue this company creates, not just the revenue from the product you wish to study. However, in some cases it is the best way to calculate emissions of product groups that otherwise have no greenhouse gas emission data published. Using this method, de Graaff & Broeren (2018) are the only ones that have been able to calculate emissions specific to product groups within the medical or pharmaceutical industry, while including scope 1, 2 and 3 emissions.

Another study did also calculate pharmaceutical industry emissions using a similar method (Belkhir & Elmeligi, 2019). By including companies both from the ET carbon dataset as well as the Carbon Disclosure Project and using more recent data entries, more companies could be included (Belkhir & Elmeligi, 2019). A calculation could be made using 25 major pharmaceutical companies as opposed to the 7 used by de Graaff & Broeren (2018). However, this study is not specific to the Netherlands. More importantly, it does not include scope 3 emissions. Scope 3 emissions in this industry are generally between 80-90% of the total (CDP, 2020). Important to keep in mind though, is that these companies sell to each other as well. Therefore, this 80-90% cannot simply be added to the first two scopes, as emissions would be counted double. This issue is the reason that scope 3 was not included in the Belkhir and Elmigili study. Because of this, it is likely an underestimation of the real lifecycle emissions of medical products by a significant amount. To estimate this amount, a proportion of scope 3 to scope 1 and 2 emissions is required for the pharmaceutical industry. This data is not available. However, for the general manufacturing industry, this is about 80% (Hertwich & Wood, 2018). A general trend is observed as well: for more complex industry, this number increases. The difference between the emission factors calculated by de Graaff & Broeren (2018) and Belkhir & Elmeligi (2019) is 80% for pharmaceuticals, and 84% for an average of medical products. Based on the current literature, these seem reasonable numbers, and the emission factors from de Graaff & Broeren (2018) are used in this report to include scope 3 emissions.

Double counting can be avoided by using EEIO methodology. Such national-sized CO_2 estimations are based on large economic models, built for national level data. It can be used for smaller scopes, but it can be limiting in the level of detail when examining cases that are more specific. Such models work by evaluating the linkages between economic consumption activities and environmental impacts (Kitzes, 2013). It effectively does so by assigning an emission factor to an economic sector. Most importantly to this discussion: it assumes homogeneous production within its defined sectors (Kitzes, 2013). Thus, all products produced by one sector are assumed to have the same environmental impact per dollar. This by itself is not wrong, but if the defined sectors are not separating the different products examined in the research system, it cannot differentiate. EEIO is limited to the detail of its defined sectors, and is therefore most suited for large-scale analyses. The EEIO method cannot supply more level of detail than that of its corresponding economic sector data. Due to this lack of detail, EEIO data could not be used in this study.

When examining cases as detailed as the use of an operation room, it is better to use LCA data. This, when available, works the other way around: process data and its corresponding environmental extensions are described in a database, and a collection of these processes is used to describe a product or system to be analyzed (Guinée & Lindeijer, 2002). Due to this, LCA is most suitable for small, well-defined product systems. However, LCA data is not available for all processes required to do a full LCA on the operation room use. For the processes for which LCA data is unavailable, this study uses emission factors calculated through carbon disclosures of sectors. There is currently no information on these factors that indicate whether they will be an over- or underestimation

In the context of operation rooms LCA's are only done on a procedure level, i.e. a specific surgery. These are helpful, as they can be used to improve procedures and gain insight in the carbon intensive processes within these. For example, a procedural study on delivering infants find that disposable use, electricity use and heat and ventilation systems are the major contributors to the total carbon footprint (Campion et al., 2012). This matches the findings of both the hospital- and national-wide estimations, strengthening their explanatory power. The same contributors are found for a hysterectomy procedure, while this study also names the use of anesthetic gases as a major carbon intensive addition (Thiel et al., 2015).

To analyze emissions associated with the use of such specific products in the surgical suite, several LCA studies have also been done. Such studies have concluded that the use of reusable Laryngeal Mask Airways are less impactful than the use of the disposable type of this product (M. Eckelman et al., 2012). LCA's on pharmaceuticals are scarce, as production data is often not available. For products such as morphine, for which the production method is more well-known, an LCA has been done (McAlister et al., 2016). For the production of this specific pharmaceutical, it is concluded that most of the carbon footprint is embedded in the final stage of production: the packaging, sterilization, mixing and filling of the product together account for almost 90% of the total carbon emission. However, this does not mean other pharmaceuticals have similar emissions. A study comparing the life cycle emissions of twenty anesthetic drugs found a high range of values: from 11 to 3000 kg CO2-eq emissions per kg drug (Parvatker et al., 2019). In comparison to bulk chemicals, which range from 2-15 kg CO2-eq, emissions are very high. The number of synthesis steps required to produce pharmaceuticals seems correlated with the total emissions (Parvatker et al., 2019).

It can be concluded that LCA methodology is especially suitable for such small product systems, but data availability becomes an issue when considering an OR-wide scale. Conversely, current EEIO data lacks the level of detail to describe the ORs use accurately. MacNeill et al. (2017) successfully used a hybrid method of both LCA based emission factors and manually calculated emission factors to calculate carbon footprints of three ORs. They calculated emissions for anesthetic gases based on a study by Sulbaek Andersen et al., which defines GWP100 CO2-equivalent emissions for isoflurane, desflurane and sevoflurane (Sulbaek Andersen et al., 2010). Many use Sulbaek Andersen et al. (2010) as a source for the radiative forcing coefficient and its corresponding GWP100 emission factor (Hodnebrog et al., 2013; Sherman et al., 2018; Thiel et al., 2015; Vollmer et al., 2015). This is because Sulbaek Anderson et al. measured the IR spectra of these anesthetics and hence calculated their radiative forcing. Other publications also calculate these emission factors, but they are often based on these same measurements, changing only the calculation method or examined time horizon. Heat, ventilation and air conditioning (HVAC) energy requirements were calculated based on airflow rates and temperature records. Lighting audits were done to estimate electricity use for lighting. These two were combined with the carbon intensity of the local electricity grid to calculate CO2-equivalent emissions for the buildings. Lastly, waste audits were done to find out what materials were used in the OR. Carbon footprints were calculated from these audits by using the British Department of Environment, Food & Rural Affairs (DEFRA) greenhouse gas life-cycle emissions, which take into account upstream as well as downstream emissions (Hill et al., 2011). These DEFRA greenhouse gas emissions are not specific to the medical industry; they include industry production and waste of products groups such as “plastics”, “aluminum” or “wood”. They are likely an underestimation, as the medical industry has a more difficult production process than an average plastic or metal product. They need to keep a sterile environment, have much larger overhead, and invest much more resources into research and development.

In Hendriks et al., LCA data is used in a hybrid approach with both LCA and emission factors from sector disclosures are used, though the scope is much reduced to one hospital, and data is gathered over a much shorter period (Hendriks et al., 2020). Additionally, transport of both employees and patients is not considered in this study. In MacNeill et al. a hybrid approach is taken as well, but they do not include parts of the system, and especially the emissions for medical product groups are likely to be underestimations due to their methodology (MacNeill et al., 2017). Though both studies use hybrid approaches, there is no comparison of LCA-methods versus economic estimation models. Hendriks et al. use LCA data to estimate the greenhouse gas emissions of ventilation, sterilization, lighting, equipment use, waste, product transport, washing and cleaning and economic estimation methods based on the study by de Graaff & Broeren are used to estimate cradle-to-gate emissions of medical equipment, diagnostics, disposables, reusables, implants, and pharmaceuticals (de Graaff & Broeren, 2018; Hendriks et al., 2020). Lastly, emissions during the use of inhalation anesthetics are manually calculated based on studies by Oudmaijer and Sulbaek Andersen et al. (Oudmaijer, 2019; Sulbaek Andersen et al., 2010). These processes and methods are summed up in Table 1

Calculated process in (Hendriks et al., 2020)	**Emission factor calculations are based on**
Inhalation anesthetics direct emissions (scope 1)	Global warming potentials of sevoflurane, isoflurane and desflurane (Oudmaijer, 2019; Sulbaek Andersen et al., 2010)
Ventilation, sterilization, lighting, equipment use, waste treatment, product transport, washing of linen, cleaning of OR (scope 2 & 3)	LCA data from ecoinvent 3.6 (Wernet et al., 2016)
Production of: medical equipment, diagnostic products, disposables, reusables, implants, pharmaceuticals (scope 3)	Emission data per euro (de Graaff & Broeren, 2018)

Table 1: processes analysed and emission factor sources in the LUMC study (Hendriks et al., 2020)

Both OR-specific hybrid LCA studies from MacNeill et al. and Hendriks et al. arrive at similar total carbon footprints for the similar sized operation suites: between 3 and 5 million kg CO2-equivalent (Hendriks et al., 2020; MacNeill et al., 2017). However, it can be seen that there are large differences in the emission contributions between hospitals. Anesthetic gas emissions generate 63% to less than 1% of the carbon footprint for different hospitals (Hendriks et al., 2020; MacNeill et al., 2017). Energy use ranges from 33%-88% of the non-anesthetic gas emissions, with the supply chain representing 12%-67% of the non-anesthetic gas emissions (Hendriks et al., 2020; MacNeill et al., 2017).

This study will use the analytical framework developed in Hendriks et al., (2020). As seen in Table 1, this makes use of manually calculated emission data, the Ecoinvent 3.6 database for LCA data, as well as emission factors calculated by CE delft for the UMC calculation (de Graaff & Broeren, 2018; Wernet et al., 2016). The use of different source material for different process calculation is required. Not a single publication offers all emission factors satisfactorily. However, the scope of these emission factors differs to some extent. Ecoinvent 3.6 emission data includes life cycle data, meaning cradle to gate emissions. Similarly, de Graaff & Broeren include scope 1, 2, and 3 emissions through the GHG protocol. They do not employ LCA methodology and databases, but do include cradle to gate emissions throughout their methodology. In this respect, their calculated emission factors are very similar in nature to the ecoinvent data. Lastly, the direct emissions from inhalation anesthetics emissions only include scope 1 emissions, namely the emissions during the use phase of the products. However, the scope 2 and 3 emissions are taken into account in the production of pharmaceuticals through the emission factor by de Graaff & Broeren (2018).

In all GHG emission calculations, a characterization needs to be made. Regardless of the methodology used being LCA or EEIO or a different methodology, a time horizon for GHG emissions can make a large difference in the results. Since the Kyoto protocol, Global Warming Potential 100 (GWP100) is the standard metric used for greenhouse gas emissions (IPCC, 2014; Qin et al., 2013). GWP100 assesses the global warming potential of an emission over a period of 100 years. For policymaking, it is very useful as this causes GHG emissions to be calculated in the same way. However, especially for emissions of anesthetic gases, there are arguments to use other time horizons when discussing the global warming potential. Whether GWP20, GWP100 or any other time horizon is used, GWP is always relative to CO2. As anesthetic volatiles have much shorter atmospheric lifespans than CO2, they are relatively less impactful over a longer time horizon (Özelsel, Sondekoppam, & Buro, 2019). As volatile anesthetic gases are short atmospheric life span gases, their effect is underplayed when using a GWP100 method. Therefore, Özelsel et al. (2019) recommend to use shorter horizon GWP’s when comparing anesthetic gases. When comparing a basket of gases for emission goals of countries, GWP100 is still recommended (Özelsel, Sondekoppam, & Buro, 2019; Qin et al., 2013). The line of reasoning for this is reversed: the global warming potential caused by gas emissions should not be assessed on a short time horizon basis, as their effects will also affect generations to come. Especially gases that have a long atmospheric lifetime will have their effects underestimated if a shorter time horizon is used. This report is somewhere in the middle. Many different types of emissions are included, but anesthetic gases are a much larger part of the total than it would be in a national economy. Therefore, GWP100 is used but a sensitivity analysis is performed with GWP20.

It is also recognized that most GHG emission studies give a static image of the greenhouse gas emissions over a one-year period. It is difficult to repeat these studies, especially if hospitals are expected to do this without the help of the researchers originally involved in it. However, repeating such studies can actually be a very powerful tool in identifying and monitoring emission improvements. There is currently no method available to environmental coordinators or policymakers in hospitals to calculate emissions of the OR department. A user-friendly method to calculate these can be used for internal monitoring of emissions, and changes thereof induced by policy change. Additionally, repeatability in other hospitals can enable external comparisons. This can incite improvements not thought of during internal monitoring. This is an important goal of this study, which in part develops a tool that is intended to be user friendly, minimizes mistakes and optimally enables hospitals to both monitor internally and compare externally their surgery related CO2-equivalent emissions. Ideally, these two functions (internal monitoring and external comparison) would be identical. However, due to practical reasons the two are treated as separate systems in the calculation tool that is developed. Large parts of these systems overlap, but not all.

The studies named in this literature review only use environmental endpoints to describe the performance of ORs. However, decision-making in hospitals is often highly dependent on doctors, who think from a medical perspective. To increase comparability between hospitals, the number of operation rooms, number of procedures and an indication of annual costs will all be used as normalizing factors. In this way, the environmental burden of processes can be expressed on a per-operation room, per-procedure or per-euro basis.

An overview of the literature presented can be found Table 2 (below).

Topic	**Author(s) and year**	**Title**	**Scope**
General literature on data and methodology	(Kitzes, 2013)	An Introduction to Environmentally-Extended Input-Output Analysis	EEIO
	(Guinée & Lindeijer, 2002)	Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards	LCA
	(Wernet et al., 2016)	The ecoinvent database version 3 (part I): overview and methodology	Ecoinvent 3
	(Hill et al., 2011)	Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting	DEFRA/DECC
	(Qin et al., 2013)	Climate Change 2013: The Physical Science Basis. Technical Summary	Global, kyoto protocol
	(IPCC, 2014)	AR5 Fifth Assessment Report: Climate Change	Global, IPCC
	(Belkhir & Elmeligi, 2019)	Carbon footprint of the global pharmaceutical industry and relative impact of its major players	Global, pharmaceutical industry
Carbon footprint of national healthcare	(Chung & Meltzer, 2009)	Estimate of the carbon footprint of the US health care sector	US
	(NHS Sustainable Development Unit, 2018)	Reducing the use of natural resources in health and social care	UK
	(Gupta Strategists, 2019)	Een stuur voor de transitie naar duurzame gezondheidszorg	NL
	(M. J. Eckelman & Sherman, 2016)	Environmental Impacts of the U.S. Health Care System and Effects on Public Health	US
	(M. J. Eckelman et al., 2018)	Life cycle environmental emissions and health damages from the Canadian healthcare system: An economic-environmental-epidemiological analysis	CA
	(Malik et al., 2018)	The carbon footprint of Australian health care	AU
Carbon footprint of hospital	(Oudmaijer, 2019)	Hoe bereken je de CO2-footprint van een OK?	AMC (NL)
	(de Graaff & Broeren, 2018)	Impact analyse MVI UMC Utrecht	UMC (NL)
	(LUMC, 2017)	LUMC 2017 Scanner	LUMC (NL)

LCA of medical procedures	(Campion et al., 2012)	Life cycle assessment perspectives on delivering an infant in the US	Infant delivery (US)
	(Thiel et al., 2015)	Environmental Impacts of Surgical Procedures: Life Cycle Assessment of Hysterectomy in the United States	Hysterectomy (US)
Carbon footprint of medical product use	(M. Eckelman et al., 2012)	Comparative Life Cycle Assessment of Disposable and Reusable Laryngeal Mask Airways	Laryngeal Mask Airways
	(McAlister et al., 2016)	The Environmental footprint of morphine: A life cycle assessment from opium poppy farming to the packaged drug	Morphine
	(Sulbaek Andersen et al., 2010)	Inhalation anaesthetics and climate change	Inhalation anesthetics
	(Hodnebrog et al., 2013)	Global warming potentials and radiative efficiencies of halocarbons and related compounds: A comprehensive review	Inhalation anesthetics, among others
	(Özelsel, Sondekoppam, & Buro, 2019)	The future is now—it's time to rethink the application of the Global Warming Potential to anesthesia	Inhalation anesthetics
	(Vollmer et al., 2015)	Modern inhalation anesthetics: Potent greenhouse gases in the global atmosphere	Inhalation anesthetics
	(Wernet et al., 2010)	Life cycle assessment of fine chemical production: a case study of pharmaceutical synthesis	Pharmaceuticals
	(Parvatker et al., 2019)	Cradle-to-Gate Greenhouse Gas Emissions for Twenty Anesthetic Active Pharmaceutical Ingredients Based on Process Scale-Up and Process Design Calculations	Anesthetic pharmaceuticals
Operation Rooms	(MacNeill et al., 2017)	The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems	UMMC (US), JRH (UK), VGH (CA)
	(Hendriks et al., 2020)	Sustainable Operating Room: Project Report	LUMC (NL)
	(Oudmaijer, 2019)	Hoe bereken je de CO2-footprint van een OK?	AMC (NL)

Table 2: Overview of the literature presented.

1.2 Problem statement

1.2.1 The academic knowledge gaps

Based on the introduction and literature review, the following knowledge gaps have been identified:

1) There is no practical OR-specific carbon footprint internal monitoring method
2) There is no practical OR-specific carbon footprint external comparison method

3) There is no comparison of different emission calculation methods: both different emission factors and different consumption data collection can yield different results
4) There is no OR-specific environmental improvement pathway for Dutch hospitals

From these, both the research question and research methodology are derived.

1.2.2 The research question

How can the greenhouse gas emissions of Dutch OR-departments accurately and repeatably be calculated, and how can this help decrease their emissions?

1.2.3 Sub-questions

To answer the main research question, a collection of sub-questions will need to be answered:

1) *How can greenhouse gas emissions of Dutch OR departments be accurately calculated? → Goal and scope, system boundaries, functional unit, assumptions and calculation equation*
2) *What are the CO2 footprints of services and goods yearly consumed by ORs → emission factors based on LCA databases, economic estimations, and literature sources.*
3) *What are the consumed goods and services and how can data on the use of these within Dutch OR departments be repeatably collected? → Data collection of consumed goods, proxy data calculation procedures, questionnaire feedback*
4) *How can the results of the calculations be reported transparently and effectively to hospitals? → presentation of results, interpretation of results, normalization of results, tool design*
5) *What differences do different calculation methods for greenhouse gas emissions of Dutch OR departments make? → Sensitivity of results to assumptions/data (distinguished between sensitivity related to: 1. System definition (RQ1), emission factors (RQ2) and consumption data collection (RQ3)*
6) *How can these greenhouse gas emission calculations be used to decrease greenhouse gas emissions of Dutch OR departments? → Improvement pathway (distinguished between 1. Improvement of the performance of hospitals and 2. The future improvement of the calculation tool)*

2 Methods

2.1 How can greenhouse gas emissions of Dutch OR departments be accurately calculated?

To answer this question, a clear goal, scope and system needs to be identified and described. This is builds upon the work of the LUMC study (Hendriks et al., 2020). For the sake of clarity and completeness, the entire goal and scope definition of the handbook of life cycle assessment (LCA) is included in this report (Guinée & Lindeijer, 2002). As this work is catered towards a user-friendly tool, some changes have been made compared to the LUMC study. Therefore, all these points will be mentioned.

2.2 Goal definition

The primary goal of this report is to develop and test a method to:

1) Monitor the carbon footprint of an OR department over multiple years
2) Determine and compare the carbon footprint of different OR departments
3) Compare different emission factors that can be used to calculate this carbon footprint
4) Compare different data collection methods of consumed goods and services
5) Develop an improvement pathway for Dutch OR departments
6) Develop an improvement pathway for this calculation tool

This is done to be able to get a more detailed and dynamic insight in the environmental performance of the operation room and the contributing processes to its carbon footprint. The calculation of this is done from an LCA perspective. This calculates total greenhouse gas emissions caused by the functional unit, which is the function provided by the system you are analyzing within a set scope. Ideally, a cradle to grave approach is used, but in many cases, parts of the life cycle are omitted to allow for practical data collection. This is discussed in more detail in the data collection chapter. Through this method, improvements regarding the mitigation of GHG emissions can be identified, proposed and monitored. These can stem from the internal monitoring of operation room department emissions, as well as be inspired by results from other hospitals. The results of this study and the tool that is developed are communicated with Dr. Hans Friedericy, anesthesiologist at the LUMC, Prof Dr. Frank Willem Jansen, gynecologist at the LUMC, as well as around 10 environmental coordinators of different Dutch hospitals.

2.3 Scope definition

Following the ISO14040 guidelines for Life Cycle Assessment studies, a short description will be given of the geographical and temporal scope of the study, together with the technological coverage (EeBGuide, 2012). Additionally, this study will only examine carbon equivalent emissions, and thus climate change as an impact category. Though it would be better to include more impact categories, there is little other indicator data on processes specific to the medical industry. This tool is also intended for communication purposes, and climate change is better known, and thus easier communicable than other environmental endpoints.

2.3.1 Geographical scope

The foreground processes are located inside the respective hospitals that use this tool. The background processes, such as the production of medical disposables or pharmaceuticals, may be located anywhere in the world. They are often based on processes found in ecoinvent, in which case the most likely location or region was chosen if possible (Wernet et al., 2016). In some cases, the tool allows for manual choices that have different geographical scope. For example, for electricity consumption, the Dutch electricity mix can be chosen, but a different emission factor that is specific to the electricity provider can also be filled in. These must be carefully selected however, and match the cradle to gate emissions that are analyzed throughout this report.

2.3.2 Temporal scope

The tool and its emission factors are based on a life cycle assessment study done with data from 2018 (Hendriks et al., 2020). However, many of the emission factors are based on older studies or on the Ecoinvent 3.6 LCI database, and can therefore be older (de Graaff & Broeren, 2018; MacNeill et al., 2017; Wernet et al., 2016). Especially the data from Ecoinvent can in some cases be much older than the citation date implies, though still the most recent known value.

2.3.3 Technological scope

The technological scope includes all the equipment used to run the operation room department. This includes medical equipment, ventilation systems et cetera. However, as will be discussed in the data collection section, some of these have been omitted from the analysis tool to improve the data collection practicality and reliability.

2.4 Definition of function, functional unit, alternatives, reference flows

In this study, the function is using an operation room complex. The functional unit is using the operation room complex for the period of one year. The alternatives are dynamic; they can be any hospital or any year of use. The reference flows are thus also dynamic, they can be using the OR complex of any hospital for any year, or an average of these.

Function	Functional unit	Alternative	Reference flow
Using operation room complex	Using operation room complex for one year	Hospital X in year Y	Using operation room complex of hospital X in year Y

Table 3: description of function, functional unit, alternatives and reference flows.

2.5 System boundaries definition

The system boundaries are based on the system boundaries defined in the LUMC study (Hendriks et al., 2020). These are drawn around an average aggregate of processes at the OR complex of the LUMC during one year. This includes all processes, spaces and technology that enable the OR to operate during one year. It includes all of the operating rooms, washing rooms, recovery room, canteens, offices and storage spaces. Furthermore, it includes the HVAC system and sterilization department as well as all of the products and equipment that are used within a year. It does not include transport of patients and employees.

This system has been simplified to allow for easier data collection and a clearer focus on the relevant processes. All foreground processes that, including their linked background processes, contributed less than 5% of the total carbon footprint at the LUMC have been omitted from the system boundary in this study. These can be found in Figure 1, in the box at the top outside the system boundary. The only exception to this rule is the use of inhalation anesthetics, which has been proven in literature to be a major contributor to emissions in some hospital's OR's (MacNeill et al., 2017). This has been done to improve the practicality of data collection, while retaining most of the explanatory power of the original system. It is recognized that this is less complete, and might miss processes that are small at the LUMC but could be large contributors in other hospitals. The current literature does not suggest there are any processes overlooked beyond those mentioned (Hendriks et al., 2020; MacNeill et al., 2017). However, the literature specific to operation rooms is limited. Based on the current state of information, this is a tradeoff deemed favorable. The system boundaries and cutoffs can be found in the flowchart below.

2.6 Multifunctionality and allocation

There are no true multifunctional processes in the model. However, the sterilization activity creates a sterilization service for both the OR department and other departments in the hospital. This is dealt with through a proportion modifier. One proportion of the sterilization service goes to the OR department, and another goes to the rest of the hospital. The emissions of the sterilization are distributed proportionally.

2.7 Flowcharts of defined systems

Two flowcharts are created: one for the internal monitoring system and one for the external comparison system. This distinction is required, as some of the data collection could not be completed with enough quality to guarantee fair comparison between hospitals, while still useful for internal monitoring. These considerations are discussed in more detail in the scope 1-3 emission factors and scope 1-3 consumed goods and services chapters. The external comparison system has a few more unit processes cut-off outside the system boundary. These are discussed shortly in chapter 2.8 – Cut-offs, and in more detail for each process in chapters 2.16-2.18 (data collection).

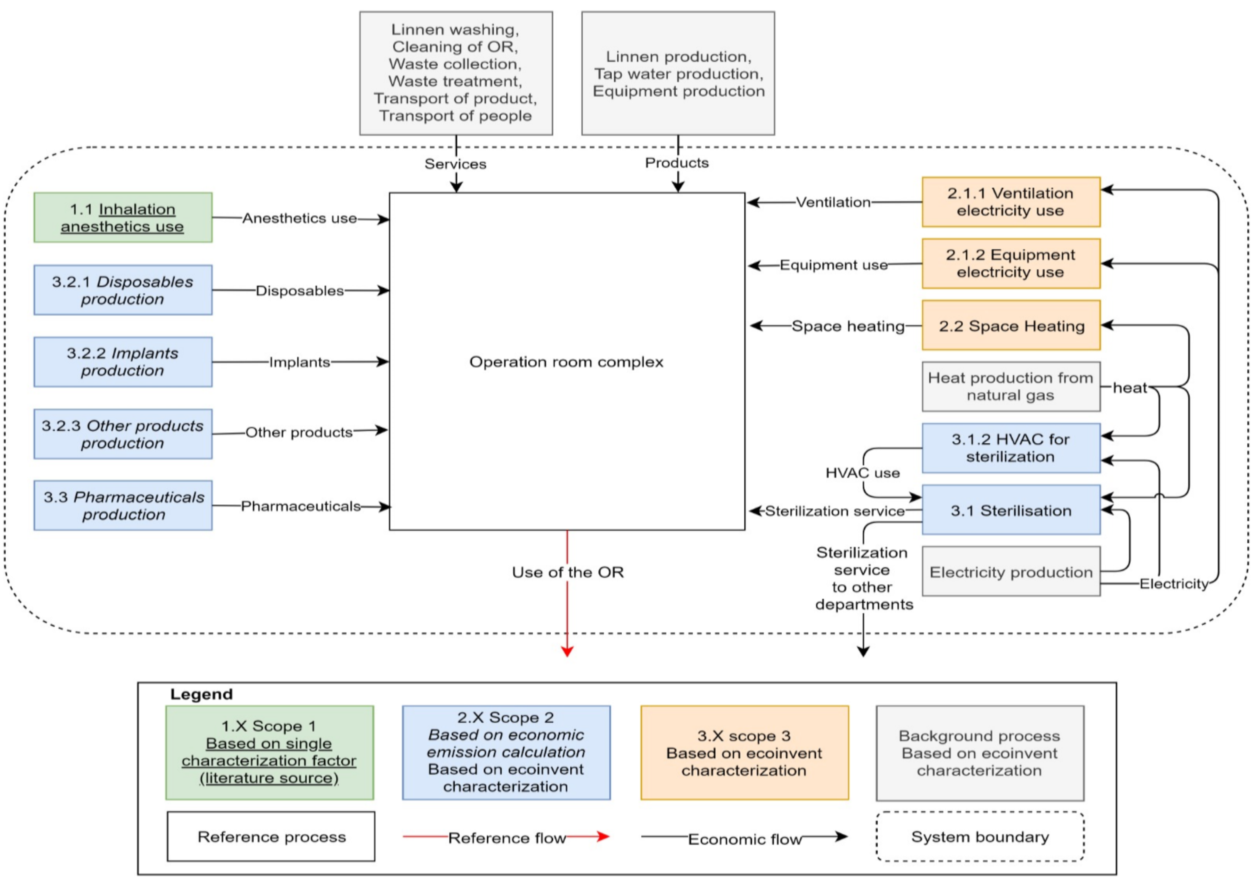


Figure 1: Flowchart of the processes modelled and omitted in the analysis tool, when using the internal monitoring system.

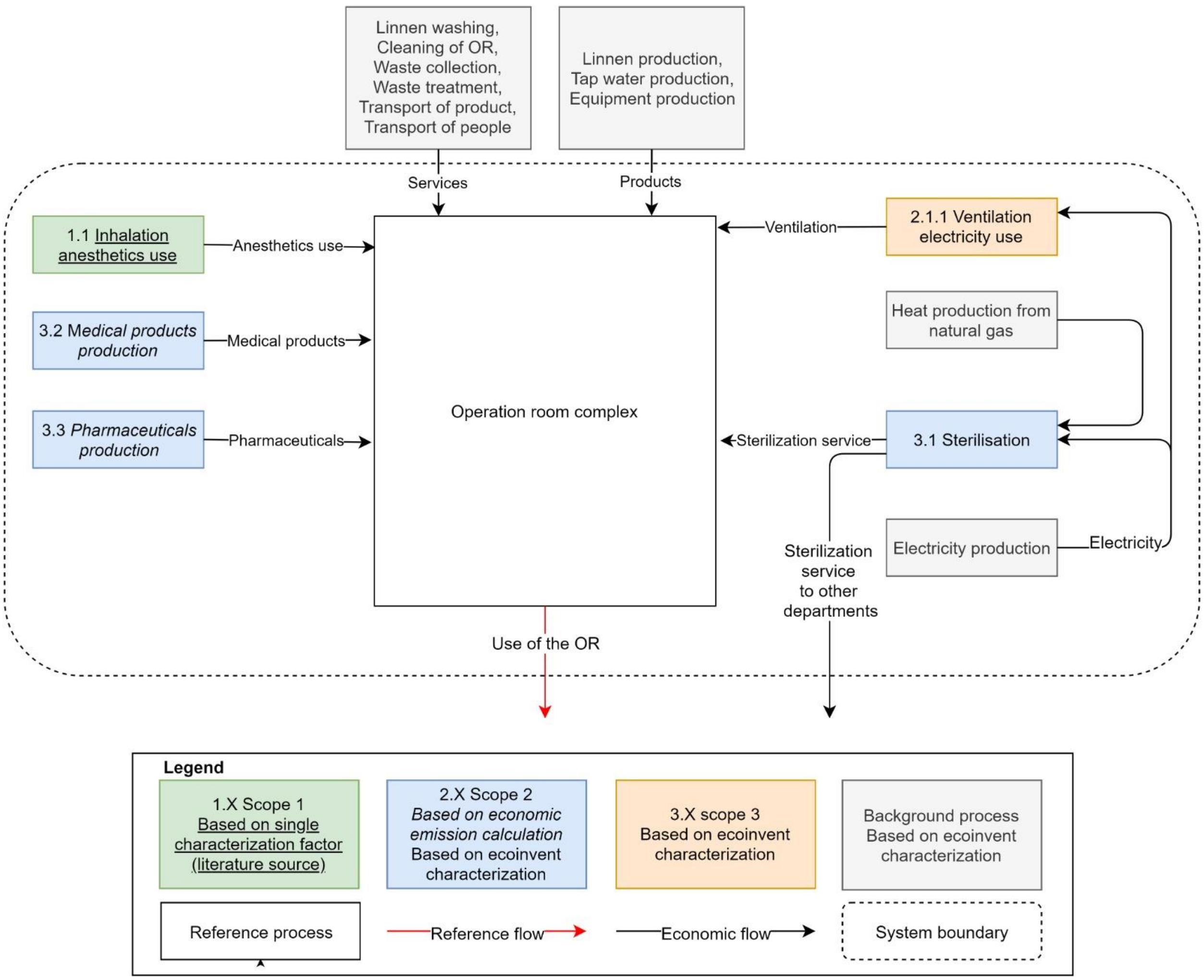


Figure 2: Flowchart and system boundaries of the system used to calculate external comparison carbon footprint.

2.8 Cut-offs

The processes outside of the system boundary are identified but cut-off. For the internal monitoring system the cut-off processes were:

- Equipment use (excluding ventilation)*
- Linen washing*
- Cleaning of OR*
- Waste collection*
- Waste treatment*
- Transport of product*
- Transport of people**
- Tap water production*
- Equipment production*

All processes marked with one * are not included due to them contributing less than 5% in the LUMC study. Transport of people, marked with two ** is not included as it is beyond the scope of this study. Though the use of the OR could be defined to include this, it has been chosen not to do this. In the literature published so far, this choice has been made in the same way (Hendriks et al., 2020; MacNeill et al., 2017). For the external comparison system, data collection reliability issues added the following cut-off processes to this list:

- Space heating gas use (if not measured)
- Space heating & ventilation for sterilization

2.9 Characterization

Due to the nature of the tool, characterization is dealt with differently than is common in LCA studies. As there is only one impact category studied, and unit processes are defined beforehand, it is possible to calculate emission factors based on characterized scores for these unit processes. Effectively, these emission factors are impact category scores on the level of a process. These allow for the calculation of the total kgCO2-eq emissions per unit process, by only entering its input. These emission factors are calculated by calculating the climate change indicator result for each identified unit process per singular unit. For example, the total indicator result of using 1kg of steam for sterilization was calculated to be 0.28 kgCO2-eq. This number can then be used as an emission factor: the number of kg steam used multiplied by 0.28 is the indicator result for the unit process (the total emission in kgCO2-eq associated with the use of that process). In this case, 0.28 kgCO2-eq is called the *emission factor* for the unit process of steam use.

The calculation of these emission factors was performed in three ways:

1. Characterization factors from literature were used. For scope 1 processes, only 1 elementary flow was identified per unit process. In this case, the characterization factor can be used as an emission factor. This characterization factor is then based on literature, using GWP100 characterization.
2. For processes for which LCA data was used, emission factors were calculated using Ecoinvent 3.6 process data, and the CML2001 GWP100a characterization model (Guinée & Lindeijer, 2002; Wernet et al., 2016).
3. For procurement processes, emission factors found in de Graaff & Broeren (2018) were used directly. These are characterized using the IPCC 2013 GWP100a characterization model.

By calculating the emission for each unit process in this way, it becomes feasible to calculate contributions to the total, as each unit process has an input, an emission factor and an indicator result associated with it. Additionally, unit processes that do not have life cycle inventory data available, but do have such emission factors can be easily included in the model.

2.10 Formula for calculation model

The model used in this report calculates the yearly emission of the OR using the following formula:

$$Annual\ CO2eq\ emission\ of\ OR\ Department\ =$$

$$\sum_{good\ or\ service}^{last\ good\ or\ service} emission\ factor\ of\ good\ or\ service * annual\ consumption\ of\ good\ or\ service$$

Equation 1: Formula for the calculation of the total annual CO2eq emission of an OR department used in the model. Annual CO2eq emissions of OR Department is expressed in kgCO2-eq. Emission factor of good or service is expressed in kgCO2-eq/unit of consumption. Annual consumption of good or service is expressed in unit of consumption, this can be a number of things, such as kg, kWh, MJ or euro.

The summation part of this formula consists of the emissions calculated for each good or service used within the OR, multiplied by their respective emission factor. Each of these goods or services will be discussed in the following chapters. Each good and service is linked to scope 1, 2, or 3 emissions as per the GHG protocol (Ranganathan et al., 2004). This is also done by MacNeill et al. (2017), in which they report emissions as follows: scope 1, anesthetic gases; scope 2, electricity use, energy for space heating; and scope 3, surgical supply chain, waste disposal. Grouping energy for space heating in scope 2 is not always accurate to the GHG protocol, as it requires direct emissions within the organization to be grouped in scope 1. However, some buildings are heated using electricity (scope 2) and some using local burning of natural gas (scope 1). To maintain comparability, space heating is included in scope 2, regardless of heating method, similar to the method of MacNeill et al. (2017).

2.11 What are the CO2 footprints of services and goods yearly consumed by ORs?

This question addresses the first part of the input required in the formula described above. Using accurate emission factors is crucial in calculating an accurate annual CO2eq emission. Only the emission factors within the defined system boundary are included in this analysis. The method used in this report is based on the method used in the LUMC study, but has been adapted (Hendriks et al., 2020). It is grounded in Life Cycle thinking, meaning that the entire life cycle of products or processes are intended to be taken into account.

The basis of this method as discussed in the literature review has been adapted to the following order of preferred emission calculation:

1) Direct calculation based on physical data: elementary flows and characterization factors are known and can be directly multiplied to calculate the indicator results (total CO2eq emissions).
2) Using data from similar processes from LCA databases or studies: elementary flows are not known, but unit processes are similar to processes already quantified in LCA databases or studies. These can be used as a substitute.
3) Using data from economic estimation methods: elementary flows are not known, and there are no similar processes quantified in LCA databases or studies. However, there is data on the emissions of product groups or sectors, and dividing this over the revenue of this sector, an estimation of emissions per euro spent in this sector can be made.

This preferred order of emission calculation is theoretical in nature. It provides a guidance, but the best option is determined on a case-by-case basis. For example, if direct calculation omits a large part of the life cycle while LCA data does not, option two may be preferable. In the case of the second option, the emission data were extracted from ecoinvent v3.6 using CMLCA 6.1 software if data availability allowed (Heijungs, 2018; Wernet et al., 2016). Compared to the LUMC study, the third option has been adapted from just EEIO data to include a more broad definition of economic estimation methods, to allow for specific data for the medical sector (Hendriks et al., 2020). As seen in the literature review, the method of CE Delft allows for more specific inclusion and exclusion of companies and their respective emissions than using input-output models would (de Graaff & Broeren, 2018). However, other options are also explored.

2.12 Scope 1 emission factors

GHG protocol scope 1 emissions are direct emissions within the organizational boundary. Within the OR department, scope 1 emissions are reported as anesthetic gas emissions (Hendriks et al., 2020; MacNeill et al., 2017). Three volatile anesthetic gases are identified: sevoflurane, isoflurane and desflurane.

2.12.1 Direct emission due to the use of inhalation anesthetics

For inhalation anesthetics, a few gases have been identified in the literature as relevant to single out due to their large greenhouse gas potential. For these only the use of the actual gas is calculated separately in this section, and not the production life cycle. It is assumed that all gas that is used is emitted to the environment. The production lifecycle is part of scope 3, and is included in the pharmaceuticals section. Multiple sources have been identified in the literature review. The emission factors calculated by Sulbaek Andersen et al. (2010) are identified as the most reliable, though special attention must be paid to the time horizon over which these are calculated. GWP100 is used, but a shorter time horizon will likely increase the contribution of these emissions. This is further explored in the sensitivity analysis.

The emission factors of the anesthetic gases included in the tool can be seen in tool sheet 1.1 (Appendix 1.6) in the column “emission factor” after selecting a unit of data entry under “unit” (eenheid).

Activity	**Emission factor**	**Unit**	**Source**
Use of sevoflurane	130	kgCO2eq/kg	(Sulbaek Andersen et al., 2010)
Use of isoflurane	510	kgCO2eq/kg	(Sulbaek Andersen et al., 2010)
Use of desflurane	2540	kgCO2eq/kg	(Sulbaek Andersen et al., 2010)

Table 4: The emission factors used in the tool to calculate carbon footprint from direct emissions due to the use of inhalation anaesthetics.

2.13 Scope 2 emission factors

Scope 2 emissions include emissions due to electricity use and space heating (MacNeill et al., 2017; Ranganathan et al., 2004). Within the system boundaries chosen for this model, this includes the electricity use of the HVAC system and the energy requirement of the space heating.

2.13.1 HVAC electricity use

The HVAC system is often the largest consumer of electricity within an OR-department. It runs at least for the majority of the day, often for 24 hours a day. It also has a much higher circulation rate than an average ventilation system, to maintain air quality within the OR. To calculate emission due to electricity use, the most accurate way is to use LCA data. Direct calculation is inaccurate, as it would require calculations down a large number of downstream processes. LCA data includes the entire life cycle, and is relatively well documented for electricity production. The Dutch electricity mix is included, as well as a selectable option of Dutch energy from wind (1-3 MW onshore turbine) as a proxy for green energy. A few selectable options have been included in the tool; these are displayed in Table 5. They include the Dutch energy mix, electricity produced from mainly non-renewable sources. The Dutch wind energy is another option, this is electricity produced solely from wind turbines as a proxy for green energy. Differences between these options will be addressed in the sensitivity analysis. The water use and the life cycle of the HVAC system itself are not included in the scope of this study.

These emission factors can be seen in tool sheet 2.1 in the column "emission factor" after selecting a unit of data entry under "unit" (eenheid).

Activity	**Emission factor**	**Unit**	**Source**
Use of electricity – Dutch mix (ecoinvent 3.6, original data from 2017 – extrapolated by ecoinvent to 2019, characterized by CML2001)	0.646	kgCO2eq/kWh	(Wernet et al., 2016)
Use of electricity –Dutch wind (ecoinvent 3.6, original data from 2017 – extrapolated by ecoinvent to 2019, characterized by CML2001)	0.0149	kgCO2eq/kWh	(Wernet et al., 2010, 2016)

Table 5: The emission factors used in the tool to calculate carbon footprint from electricity use for the HVAC system.

2.13.2 Gas (Space heating)

Space heating is often combined with the HVAC system, as the HVAC system will often distribute the heated air to heat the building. In the Netherlands, the heating is usually provided using natural gas. While it would be possible to use direct emissions of burning natural gas, this would not take into account the entire life cycle of the burning of gas. Therefore, LCA data that takes into account both the life cycle and the burning of the gas is used (Wernet et al., 2016). Table 5 displays the emission factors used to calculate emissions associated to using heat energy. Two different possible units are displayed for the use of heat energy. Both of these are based on the same emission factor, only the denominator is changed. Both can be used as a possible input, they calculate the same result. The life cycle of HVAC system itself is excluded from the scope of this study, as it contributes to less than 5% to the total emissions.

These emission factors can be seen in tool sheet 2.2 in the column "emission factor" after selecting a unit of data entry under "unit" (eenheid).

Activity	**Emission factor**	**Unit**	**Source**
Use of heat energy (from natural gas)	0.0648	kgCO2eq/MJ	(Wernet et al., 2016)
	2.5817	kgCO2eq/m3 gas	(Wernet et al., 2016)

Table 6: The emission factors used in the tool to calculate carbon footprint from heat energy use for the HVAC system.

2.14 Scope 3 emission factors

Scope 3 emissions include all other indirect emissions as a consequence of the analyzed activity (MacNeill et al., 2017; Ranganathan et al., 2004). These include embedded emissions in products used in the OR, such as disposables and pharmaceuticals. It also includes emissions associated with services provided to the OR department, such as the sterilization of materials.

2.14.1 Sterilization

The sterilization of tools and products used in the OR department is a very energy intensive process. In the Netherlands, it is usually done by burning natural gas to create steam, and running that steam into a specialized machine that sterilizes the product.

These emission factors can be seen in tool sheet 3.1 in the column “emission factor” after selecting a unit of data entry under “unit” (eenheid).

<u>Option 1: sterilization via life cycle assessment data on energy use (measured energy use)</u>

Sterilization machines use large amounts of steam to sterilize products. On top of this, electricity is used to run these machines. Additionally, a similar HVAC system as discussed in the previous topic is usually run to clean the air in the sterilization department. For gas and electricity, the emission factors used are the same as they were for the HVAC system. It is possible to calculate the emission related to the steam production via the use of natural gas or to calculate it directly from the amount of steam used. Both are alternative inputs to the same calculation of emissions from the use of steam, efficiency losses are taken into account. The water use and the life cycle of the sterilization system itself are not included in the scope of this study. Measured energy use values can be directly multiplied with the emission factors of Table 7 to calculate the CO2-equivalent emissions associated with that unit process.

<u>Option 2: sterilization via life cycle assessment data on energy use (calculated energy use)</u>

Alternatively, energy use can be calculated. Detailed information on this is given in 2.14.1 Sterilization. For this option, the same emission factors found in Table 7 can be used.

Activity	**Emission factor**	**Unit**	**Source**
Steam consumed	0.28	kgCO2eq/kg steam	(Wernet et al., 2016)
Natural gas use for steam production	0.0648	kgCO2eq/MJ	(Wernet et al., 2016)
	2.5817	kgCO2eq/m3 gas	(Wernet et al., 2016)
Use of electricity – Dutch mix (ecoinvent 3.6, original data from 2017 – extrapolated by ecoinvent to 2019, characterized by CML2001)	0.6461515	kgCO2eq/kWh	(Wernet et al., 2016)

Use of electricity –Dutch wind (ecoinvent 3.6, original data from 2017 – extrapolated by ecoinvent to 2019, characterized by CML2001)	0.014938	kgCO2eq/kWh	(Wernet et al., 2010, 2016)

Table 7: The emission factors used in the tool to calculate carbon footprint from heat energy use and electricity use for sterilization.

<u>Option 3: sterilization via life cycle assessment data on sterilized product</u>

If steam, heat and electricity use for sterilization data is not available, this can also be estimated based on the amount of product that is sterilized. There are studies that estimate the energy use of steam sterilization (McGain et al., 2016, 2017). However, these assume steam is produced with electricity, and only estimate electricity and water use of the steam sterilization itself, not the life cycle beyond that. Therefore, this method is likely an underestimation. These studies calculate an electricity use of 1.9 kWh per kg product sterilized. This is used directly as an input for this study, so that it adapts when the carbon intensity of the electricity use is changed.

Activity	**Electricity use**	**Unit**	**Source**
Use of steam sterilization	1.9	kWh/kg product	(McGain et al., 2017)

Table 8: The emission factor used in the tool to calculate carbon footprint of steam sterilization through mass of sterilized product.

2.14.2 Medical products

The emissions due to the use of medical products are different in nature to those discussed so far. In contrast to the emissions so far, which have stemmed from energy use or direct emissions, these emissions arise during the production process of the products themselves. It is difficult to track down all the emissions of all the processes that make up this production chain. Therefore, emission factors have to be based on industry average emissions, either per euro spent or per kg product produced within that industry. In the literature review, three methods to do this have been identified. The method based on de Graaff & Broeren (2018) is preferred, as it is both specific to the pharmaceutical industry and it includes scope 3 emissions for this industry. Both other methods are either not specific to the pharmaceutical industry (MacNeill et al., 2017) or do not include scope 3 emissions (Belkhir & Elmeligi, 2019).

These emission factors can be seen in tool sheet 3.2 in the column “emission factor” after selecting a unit of data entry under “unit” (eenheid).

<u>Option 1: calculation through economic estimation method including scope 1, 2 and 3 emissions (de Graaff & Broeren, 2018)</u>

De Graaff & Broeren (2018) calculated emission factors for multiple categories: implants, disposables, diagnostics, medical equipment, reusables and pharmaceuticals. Pharmaceuticals will be treated separately. Based on the LUMC study, disposables and implants had significant impacts. Spends on other categories can optionally be entered in the tool under “other medical products”. The emission factor for this is calculated as a weighted average of the non-included categories. The calculation procedure for this is described in Appendix 1.1.

De Graaff & Broeren (2018) have used an average of two companies that produce medical disposables and have disclosed their carbon emissions to calculate a carbon emission factor per euro spent on medical disposables. The advantage of this is that it is more specific to medical disposables. However, it is based only on the disclosure of carbon emissions of two companies, and does not include the use phase emissions nor the downstream (waste collection and treatment) phases. However, as discussed before, the use phase is generally negligible for medical disposables. Waste collection and treatment can be separately calculated, though this is not in the scope of this study.

Using the same method, but with only one company disclosing carbon emission data for this product type, de Graaff & Broeren (2018) calculated an emission factor per euro spent on implants. Again, this does include the production phase, but not the use phase and waste disposal and treatment emissions. While there are likely environmental emissions during the use phase of implants, very few of these will be greenhouse gas emissions. The waste disposal and treatment emissions could be calculated, however these are excluded from the scope of this study as they do not reach the 5% threshold.

As will be discussed in the upcoming chapter on the collection of data on the amount of consumed goods and services, the differentiation between these categories proved difficult and labor-intensive for most hospitals. The separation of consumed product is now optional in the data entry tool. To accommodate this, a weighted average has been calculated based on the provided data, to create a single emission factor for all medical products grouped together. This offers less insight in what products cause emissions, but is a much more feasible in data-entry. Option 1 is recommended for external comparison.

Activity	**Emission factor**	**Unit**	**Source**
Production of all medical products (weighted average)	0.369	kgCO2eq/euro	Adapted from de Graaff & Broeren (2018)

Table 9: The emission factor used in the tool to calculate carbon footprint of the production of average medical products through the expenditure on such products.

<u>Option 2: calculation through economic estimation method including scope 1, 2 and 3 emissions, split up into categories (de Graaff & Broeren, 2018)</u>

To create a more detailed insight in which products cause emissions, consumed goods and services can still be separated into categories. In this case, disposables are defined as any product intended for one time use such as catheters, intravenous drippers, disposable clothing and suture materials. Implants are defined as products that are inserted into the body for a longer period, such as orthopedic implants, stents, ICD's, pacemakers and heart valves. Diagnostic products include all products that are used in the lab, such as lab chemicals, reagents, lab materials and equipment. Reusables are products intended for use of more than one time, such as endoscopic instruments and drills. Often, these products need to be sterilized before use. Medical equipment includes diagnostic, therapeutic and mobile equipment. As these last three categories have shown to be minor in the case of the OR complex, both by spends and by emission, they are grouped into one category "other" to simplify data collection. The emission factor for this is calculated as a weighted average (Appendix 1.1). Option 2 is recommended for internal monitoring.

Activity	**Emission factor**	**Unit**	**Source**
Production of disposables	0.34	kgCO2eq/euro	(de Graaff & Broeren, 2018)
Production of implants	0.45	kgCO2eq/euro	(de Graaff & Broeren, 2018)
Production of diagnostic products	0.225	kgCO2eq/euro	(de Graaff & Broeren, 2018)
Production of reusables	0.14	kgCO2eq/euro	(de Graaff & Broeren, 2018)
Production of medical equipment	0.14	kgCO2eq/euro	(de Graaff & Broeren, 2018)
Production of other medical products (weighted average of Diagnostics, medical equipment and reusables)	0.145	kgCO2eq/euro	Adapted from de Graaff & Broeren (2018)
Production of all medical products (weighted average)	0.369	kgCO2eq/euro	Adapted from de Graaff & Broeren (2018)

Table 10: The emission factors used in the tool to calculate carbon footprint of the production of disposables, implants and other medical products through the expenditure on such products.

<u>Option 3: calculation through waste weights and life cycle inventory data</u>

Alternatively, emissions of disposables can be calculated through waste weights and life cycle inventory data, as was discussed in the literature review (MacNeill et al., 2017). While waste weights are used in this method, the waste treatment emissions are not included. The total weight of waste is used to estimate what products this waste used to be. By doing so, the emissions during the production phase of these products can be calculated through the waste weights. This does assume that the life cycle environmental impacts of the waste generated in the OR department matches that of ordinary products. There is no life cycle inventory data on specific medical product groups, so generic product groups have to be used. This is likely an underestimation as opposed to generic products; medical supplies are often produced in sterile environments using less efficient production methods. They also require a lot more research and development than generic product groups, which is not taken into account in this type of calculation.

This method requires the measurement of waste volumes of several types: municipal solid waste, domestic waste, hazardous waste, fluid waste, sharps, cytotoxic waste, black box waste (material that is both acutely toxic and infectious), recycling, and reusable textiles. These then all have an associated production and disposal emission factors, which combined create a lifecycle emission factor. The use phase is not included in this calculation, though for disposables this is usually zero. For example, there are no emissions in the use phase of bandaging, only in the production or waste disposal. The emissions related to wastes are based on the emission factors calculated by MacNeill et al., who calculate them from DEFRA greenhouse gas life-cycle emissions. They can be seen in Table 11. More categories are included in this calculation than just disposables, as all products that end up in the waste stream are included in this method. However, the emission factors are based on economy-wide uses, and not specific to the medical industry. In general industry, emissions per kg product are often lower than in the medical industry. For example, a needle produced for the medical industry needs to be produced in a sterile environment and needs to be packaged in an (often individual) sterile packaging, as opposed to a needle produced in general industry that is used for sewing; this does not need to be sterile and can be packed with hundreds in a single box. As they are based on emissions per kilogram product, this assumption of equality between sectors likely results in an underestimation of emissions. Therefore, using option 3 emission factors is not recommended, and options 1 and 2 are preferred.

Waste type	**Emission factor**	**Unit**	**Source**
Municipal solid waste	3.938	kgCO2-eq/kg	(MacNeill et al., 2017)
Hazardous waste	2.874	kgCO2-eq/kg	(MacNeill et al., 2017)
Reusable textiles	0.2993	kgCO2-eq/kg	(MacNeill et al., 2017)
Fluid waste	0.0125	kgCO2-eq/kg	(MacNeill et al., 2017)
Sharps	2.740	kgCO2-eq/kg	(MacNeill et al., 2017)
Cytotoxic waste	4.561	kgCO2-eq/kg	(MacNeill et al., 2017)
Recycling (paper and plastic)	2.751	kgCO2-eq/kg	(MacNeill et al., 2017)

Table 11: Life cycle emission factors of the production phase of different waste types, based on *(MacNeill et al., 2017)*

<u>Alternative calculation (not included in tool): calculation through economic estimation method including only scope 1 and 2 emissions (Belkhir & Elmeligi, 2019)</u>

Similar to option 1, an average carbon-equivalent emission per dollar of the pharmaceutical industry has been calculated by Belkhir & Elmeligi (2019). This number was 0.04855 kgCO2-eq/$, or 0.054376 kgCO2-eq/euro. Conversely, this number can be used to calculate emissions for medical products or pharmaceuticals through expenditure figures. The large majority of procurement expenditures for hospitals, and for OR's in particular, goes toward the pharmaceutical industry. Thus, it can be assumed that this emission factor is an accurate one for the average expenditure within the OR. However, this assumes the same emission factor for medical products as well as for pharmaceuticals. This is not realistic, but pharmaceutical suppliers do not separate their emissions over their departments. Thus, no differentiation is possible using this methodology at this moment. As stated in the literature review, this emission factor is much lower as it does not include scope 3 emissions for these companies. Therefore, this emission factor is not recommended nor included in the tool.

Activity	Emission factor	Unit	Source
Production of medical products	0.054376	kgCO2eq/euro	(Belkhir & Elmeligi, 2019)

Table 12: The emission factor used in the tool to calculate carbon footprint of the production of medical products through the expenditure on such products.

2.14.3 Pharmaceuticals

For pharmaceuticals, three different methods have been identified. Similar to those of medical products, emission factors per euro can be used from either of the two discussed studies (Belkhir & Elmeligi, 2019; de Graaff & Broeren, 2018). They have the same drawbacks as before, as Belkhir & Elmeligi do not include scope 3 emissions and are not specific to the Netherlands, and de Graaff & Broeren base their numbers on a limited amount of companies. Alternatively, an emission factor per kg pharmaceutical from LCA studies can be used, but there are no general LCA's on pharmaceuticals. There are only LCA's on individual pharmaceuticals or on a limited set of pharmaceuticals. Differences between these are large, so inferring information about the average from the individual studies is difficult.

These emission factors can be seen in tool sheet 3.3 in the column "emission factor" after selecting a unit of data entry under "unit" (eenheid).

<u>Option 1: pharmaceutical emissions through economic estimation models including scope 1, 2 and 3 emissions (de Graaff & Broeren, 2018)</u>

Using the same economic estimation method as for disposables and implants, an estimate can be made that is more representative for the wide array of pharmaceuticals used. This estimation is based on the carbon emission and revenue disclosure of four major pharmaceuticals producers (de Graaff & Broeren, 2018). Once again, this does include the production processes and upstream activities, but not the use and waste disposal activities of the life cycle. However, waste disposal can be separately calculated, though this is outside of the scope of this study.

Activity	Emission factor	Unit	Source
Production of pharmaceuticals	0.31	kgCO2eq/euro	(de Graaff & Broeren, 2018)

Table 13: The emission factor used in the tool to calculate carbon footprint of pharmaceutical production through the expenditure on such products.

<u>Alternative calculation (not included in the tool): pharmaceutical emissions through economic estimation models including scope 1 and 2 emissions (Belkhir & Elmeligi, 2019)</u>

Using the same economic estimation method as for medical products, an estimate can be made for the production of pharmaceuticals (Belkhir & Elmeligi, 2019). The same emission factor is used for this, but the two are separated as data collection usually is too. Therefore, it provides more detail into the emissions. Again, this is likely a sizeable underestimation as scope 3 emissions are not included for the companies that produce these pharmaceuticals. Therefore, the use of this emission factor is not recommended nor included in the tool.

Activity	Emission factor	Unit	Source
Production of pharmaceuticals	0.054376	kgCO2eq/euro	(Belkhir & Elmeligi, 2019)

Table 14: The emission factor used in the tool to calculate carbon footprint of pharmaceutical production through the expenditure on such products.

<u>Alternative calculation (not included in the tool): pharmaceutical emissions through carbon footprint of LCI data</u>

Calculating the carbon footprint of pharmaceuticals through LCA data is challenging, as pharmaceuticals have different associated emissions. For morphine, the CO2-eq/kg life cycle emission is 2040 McAlister et al. (2016). An LCA on undisclosed pharmaceutical “substance A” found a CO2-eq/kg life cycle emission of 67.6 (Wernet et al., 2010). Calculating the total emission of pharmaceuticals from either one of these will yield very different results, and there is no reason to assume any one of the two is more correct, or an average should be used. In a study using up-scaled lab-scale synthesis data, LCI data of 20 different anesthetic drugs were calculated (Parvatker et al., 2019). Different synthesis steps in medicine production have very different greenhouse gas emissions, though there is a positive correlation between the amount of synthesis steps and the GHG emissions (Parvatker et al., 2019).

If one were to calculate the emissions of pharmaceuticals in this way, data on the total weight of pharmaceuticals used in the OR department during one year is required. While this is an option to calculate emissions, the amount of LCA data is limited to the twenty anesthetic pharmaceuticals. This is not a perfect substitute for the average use of pharmaceuticals, and before more well defined LCA data on pharmaceutical production is published, this emission factor is not recommended nor included in the tool.

Activity	Emission factor	Unit	Source
Life cycle of pharmaceuticals – morphine substitute	2040	kgCO2/kg	(McAlister et al., 2016)
Life cycle of pharmaceuticals – substance A substitute	67.6	kgCO2/kg	(Wernet et al., 2010)
Life cycle of pharmaceuticals – average of 20	340	kgCO2/kg	(Parvatker et al., 2019)
Life cycle of pharmaceuticals – median of 20	79	kgCO2/kg	(Parvatker et al., 2019)

Table 15: The possible emission factors used to calculate carbon footprint of pharmaceuticals life cycle emissions through LCA data substitutes and total mass.

2.15 What are the consumed goods and services and how can data on the use of these within Dutch OR departments be collected in an accurate and repeatable way?

This question deals with the second part of the calculation formula: the annual consumption amount of good or services. A data collection trial was run with initially seven academic hospitals, followed by another eight peripheral hospitals two weeks later. A questionnaire was sent to these hospitals, which required data to be filled in on the consumption of goods and services that contributed more than 5% of the total emissions in the LUMC study as well as data on inhalation anesthetics (Appendix 1.2). The responses to the questionnaire were below expectation, due to coinciding with the peak of the COVID-19 outbreak, and hospitals and their employees were preoccupied. Direct data entries were collected during the trial and problems that arose during the data collection were identified. If possible, direct communication was employed to assist and overcome data collection issues.

The responses of the trial were used to assess the feasibility of the data collection on each of the consumed goods and services. Additionally, the trial was discussed in a feedback session. Based on this, the previously explored options for emission calculation factors were categorized in one of three categories:

1. Suitable for external comparison: data collection of consumption data for these products or services went well, and responses were of sufficient quality to allow comparison between hospitals. This means data returned by different hospitals was similar, used the same method and described the same number. For example, the use of anesthetic gases in number of bottles per year.
2. Suitable for internal monitoring: data collection of consumption data for these products or services went not as good, and responses were of insufficient quality to compare between hospitals. This means one of two things; either the large majority of hospitals could not provide the data in the required form as it required too much resources, or hospitals returned data that described different scopes than required. Often, data required to be adapted to the scope of the OR. Available data was either on more detailed department level or on hospital level. For example, many hospitals could easily provide a total spend on procurement, but could not split these spends up into categories. Alternatively, spends on the total hospital level were known, but not those for the OR department alone. However, while these data may not compare well between hospitals, they can be used for internal monitoring. If used for internal monitoring, the user must make sure that the data is collected in the same way each year.
3. Unsuitable for both external comparison and internal monitoring: data collection for this was insufficient. Most hospitals do not have the required infrastructure or measurements in place to make an accurate and repeatable estimation of this data. Therefore, it cannot be used at this moment, for both external comparison and internal monitoring.

For each consumed good and service, the responses are discussed and summarized. Part of the results of the trial are discussed within the methodology section, as further modelling choices are made based on these. Questionnaire results, in combination with the emission factors discussed previously, were used to develop a carbon footprint calculation tool. This tool is designed to be used independently by environmental coordinators of interested hospitals.

2.16 Scope 1 consumed goods and services

2.16.1 Inhalation anesthetics

The amount of inhalation anesthetics examined is limited, and only the administered amounts of these three anesthetics were sought after. Most hospitals in the trial were able to prepare this data easily and quickly. There is little room for error, as just the number of bottles used and the volume of those bottles is required. Hospitals got this data either from OR staff advisors, or from the pharmacy. This number is suitable for both internal monitoring as well as external comparison.

The consumed goods for this activity need to be entered in the tool in sheet 1.1 in the column "input" (invoer) after selecting a unit of data entry under "unit" (eenheid).

Activity	Input unit(s)	Suitable for internal monitoring	Suitable for external comparison
Use of sevoflurane	kg	Yes	Yes
Use of isoflurane	kg	Yes	Yes
Use of desflurane	kg	Yes	Yes

Table 16: Inhalation anesthetic activity inputs and their suitability for internal monitoring and external comparison.

2.17 Scope 2 consumed goods and services

2.17.1 HVAC electricity use

For the use of electricity for the HVAC system, two options of data collection exist. First, if there is direct measurement of electricity use, this can be entered directly into the tool. If the electricity use is already calculated, it can also be entered directly. Second, and most prevalent, is the case where there is no direct measurement of electricity use for the OR department. This proved to be a challenge for the collection of this data. In this case, electricity needs to be calculated based on the average power use and operating hours of the machines. The rated power of the machines can be used for this. This is a relatively stable, accurate and repeatable data point for the energy use of the HVAC system. This number is suitable for both internal monitoring as well as external comparison.

The consumed goods and services for this activity need to be entered in the tool in sheet 2.1 in the column "input" (invoer) after selecting a unit of data entry under "unit" (eenheid).

Activity	Input unit(s)	Suitable for internal monitoring	Suitable for external comparison
Use of electricity	kWh	Yes	Yes
Rated power	kW	Yes	Yes
Operating hours	hours	Yes	Yes

Table 17: HVAC electricity consumption input and its suitability for internal monitoring and external comparison.

2.17.2 Gas (space heating)

There are again two possible options to input this into the tool. First, the natural gas use can be directly measured. If this is the case, metered readings of gas use in either m3 or MJ can be put into the tool directly. Second, if there is no direct measurement in place, it can be calculated based on the capacity of the equipment and hours of use. The average natural gas use and operating hours of the machines are required for this. However, this might not be available and highly dependent on the temperature, so multiple estimates of the gas use throughout the year have to be made if there is not already some sort of metering or estimation available. The energy requirement for space heating can be used for internal monitoring purposes, but needs to be calculated in the same way each year. This is possible within hospitals, but becomes challenging when comparing different hospitals, as they often have different heating systems. These are often integrated systems, using natural gas boilers, heat exchangers and air treatment machinery. Highly varying numbers were returned in the collection trial. Therefore, this option has been flagged as unsuitable for external comparison at this moment. However, if the calculation is done for the same hospital in the same way each year, it can still be used for internal monitoring. If a more robust and feasible method for the calculation of energy use for space heating in the OR specific is developed, this can be included in external comparison. However, it is much easier and more precise to install a gas meter.

The consumed goods and services for this activity need to be entered in the tool in sheet 2.2 in the column “input” (invoer) after selecting a unit of data entry under “unit” (eenheid). Only measured use of natural gas is suitable for external comparison. There are too many variables to make an accurate calculation to compare different hospitals.

Activity	Input unit(s)	Suitable for internal monitoring	Suitable for external comparison
Use of heat energy (from natural gas) MEASURED	MJ	Yes	Yes
	m3 gas	Yes	Yes
Average use of natural gas	m3/h	Yes	No
Operating hours	Hours	Yes	No

Table 18: Space heating energy consumption inputs and their suitability for internal monitoring and external comparison.

2.18 Scope 3 consumed goods and services

2.18.1 Sterilization

The consumed goods and services for this activity need to be entered in the tool in sheet 3.1 in the column “input” (invoer) after selecting a unit of data entry under “unit” (eenheid).

<u>Option 1: sterilization via life cycle assessment data on energy use (measured energy use)</u>

For sterilization, the natural gas use is more constant, as it is used to create steam instead of heating a building. Therefore, it is less dependent on outside temperature. More hospitals were confident in providing this natural gas usage than that for space heating. Again, a measured value of natural gas use can be used or one can be calculated (option 2). For electricity, either a measured or a calculated value can be used as well.

For a complete calculation from a life cycle perspective, the HVAC system at the sterilization department should be taken into account as well. Therefore, if data is available, it is recommended to consider this for internal monitoring within hospitals over multiple years.

In the trial, some hospitals struggled to separate the HVAC energy requirements for the sterilization department. Therefore, this value is not used for external comparison. Instead, only the gas and electricity use of the sterilization machines themselves should be used for comparison between hospitals.

The input units and suitability for internal and external monitoring can be found in Table 19.

Activity	Input unit(s)	Suitable for internal monitoring	Suitable for external comparison
Use of heat energy (from natural gas, for steam production)	Kg steam	Yes	Yes
	m3 gas	Yes	Yes
Use of electricity (for steam production)	kWh	Yes	Yes
Use of heat energy (from natural gas, for HVAC)	MJ	Yes	No
	m3 gas	Yes	No
Use of electricity (for HVAC)	kWh	Yes	No
Total sterilized product (alternative)	kg product	Yes	No

Table 19: Sterilization service consumption inputs for option 1 and their suitability for internal monitoring and external comparison.

<u>Option 2: sterilization via life cycle assessment data on energy use (calculated energy use)</u>

Energy use of the sterilization department can be calculated. For this option, the average running hours of the sterilization machines are required, as well as the average electricity use and natural gas use for steam production. For these last two, natural gas is used to generate steam. If the steam consumption is entered, natural gas use is no longer required, and vice versa. The input units and suitability for internal and external monitoring can be found in Table 20.

Activity	Input unit(s)	Suitable for internal monitoring	Suitable for external comparison
Rated power sterilization machines	kW	Yes	Yes
Average gas use sterilization machines	M3/h	Yes	Yes
Average steam consumption sterilization machines	Kg/h	Yes	Yes
Running hours sterilization machines	h/yr	Yes	Yes
Rated power HVAC for sterilization	kW	Yes	No
Average gas use HVAC for sterilization	M3/h	Yes	No
Average running hours HVAC for sterilization	h/yr	Yes	No

Table 20: Sterilization service consumption inputs for option 2 and their suitability for internal monitoring and external comparison.

Option 3

The method of calculation through total sterilized material can also be used. This could be compared, but only with hospitals that use the same method of data collection, or for internal monitoring. It is not comparable with the other method of data collection, as it is based on an electric system and only models direct energy used for sterilization. If no energy use data is available however, this option can be very useful for internal monitoring.

Activity	Input unit(s)	Suitable for internal monitoring	Suitable for external comparison
Total sterilized product (alternative)	kg product	Yes	No

Table 21: Sterilization service consumption input for option 3 and its suitability for internal monitoring and external comparison.

2.18.2 Medical products

The consumed goods and services for this activity need to be entered in the tool in sheet 3.2 in the column “input” (invoer) after selecting a unit of data entry under “unit” (eenheid).

Option 1: calculation through economic estimation method including scope 1, 2 and 3 emissions (de Graaff & Broeren, 2018)

For disposables, there are three options to collect the data, one for each type of emission calculation. Option 1 and 2 are similar: they require data on the annual expenditure on medical products. These expenditures need to be calculated carefully, as all the products procured to be used inside the OR department are to be included, and all that are used elsewhere are to be excluded. Option 1 only uses the total spend on medical products, while option 2 differentiates between disposable medical products, implants and other medical products. The input for option 1 can be found in Table 22, alongside its suitability for internal monitoring and external comparison.

Activity	Input unit(s)	Suitable for internal monitoring	Suitable for external comparison
Production of medical products	Euro spent	Yes	Yes

Table 22: Medical products consumption input for option 1 and its suitability for internal monitoring and external comparison.

<u>Option 2: calculation through economic estimation method including scope 1, 2 and 3 emissions, split up into categories (de Graaff & Broeren, 2018)</u>

Splitting up expenditures into categories needs to happen carefully. Again, all the products procured to be used inside the OR department are to be included, and all that are used elsewhere are to be excluded. Then, expenditures need to be split up: disposables are defined as any one-time use products, excluding pharmaceuticals and implants. This includes among others: catheters, disposable clothing and suture materials. Similar to disposable spends, expenditures on medical implants used within the OR department are also calculated. They are defined as objects that are inserted into the body during operations, such as orthopedic implants, vascular prostheses and pacemakers. All other products that are procured (so option 1 – disposables – implants) are classified as “other products”.

This requires close cooperation with the procurement department and a medical expert to place each product group within these requirements. The differentiation between product groups proved difficult for some hospitals, as it required manual labor from the procurement department. Therefore, a weighted average of the emission factor for a general “medical products” category was created based on the data that was provided by trial hospitals (Appendix 1.1). This option is suitable for both internal monitoring as well as external comparison. The differentiation between product categories is still useful, but will only be used for internal monitoring. The input units and suitability for internal monitoring and external comparison can be found in Table 23.

To clarify: for external comparison, only the expenditure on the total medical products is used. For internal monitoring, if local data collection allows, more insight can be gained by splitting the expenditures into three groups: expenditures on disposables, implants, and other medical products.

Activity	Input unit(s)	Suitable for internal monitoring	Suitable for external comparison
Production of disposables	Euro spent	Yes	No
Production of implants	Euro spent	Yes	No
Production of other medical products	Euro spent	Yes	No

Table 23: Medical products consumption input for option 2 and its suitability for internal monitoring and external comparison.

Option 3: calculation through waste volume data, using non-medically specific industry emission factors from DEFRA (MacNeill et al., 2017)

Lastly, option 3 requires the collection of waste volume data. The method used to collect this is a one-week waste audit, weighing all types of waste for the period of one week. This data is extrapolated to a one year period, and matched with the waste categories from (MacNeill et al., 2017). While this is a reliable method, it is favorable to choose one option for external comparison. As data on annual expenditures is more easily available, and the emission factor associated with it is specific to the medical industry, option 1 is chosen in this study.

Activity	Input unit(s)	Suitable for internal monitoring	Suitable for external comparison
Hazardous waste life cycle	kg waste	Yes	No
Reusable textiles life cycle	kg waste	Yes	No
Fluid waste life cycle	kg waste	Yes	No
Sharps life cycle	kg waste	Yes	No
Cytotoxic waste life cycle	kg waste	Yes	No
Recycling (paper and plastic) life cycle	kg waste	Yes	No

Table 24: Medical products consumption inputs for option 3 and their suitability for internal monitoring and external comparison.

Alternative calculation (not included in tool)

If the alternative calculation were used, the same total spend on medical products used in option 1 would be used, but combined with the alternative emission factor.

2.18.3 Pharmaceuticals

The consumed goods and services for this activity need to be entered in the tool in sheet 3.3 in the column “input” (invoer) after selecting a unit of data entry under “unit” (eenheid).

Option 1: pharmaceutical emissions through economic estimation models including scope 1, 2 and 3 emissions (de Graaff & Broeren, 2018)

Three options to calculate emissions due to pharmaceutical use were identified in the chapter on emission factors. However, only one was deemed suitable for inclusion in the tool. The first requires the annual expenditure on pharmaceuticals used within the OR. This can be calculated in a similar way as the medical products though pharmaceutical procurement usually goes through a separate department, the pharmacy. Again, open communication with this department is required to make sure all pharmaceuticals that are ordered for use in the OR are included, and all pharmaceuticals that are used elsewhere are excluded. Only then can a total annual spend be calculated and used as an input for the emission calculation. If this is done, option 1 is suitable for both internal monitoring as well as external comparison.

Activity	Input unit(s)	Suitable for internal monitoring	Suitable for external comparison
Consumption of pharmaceuticals (production phase only)	Euro spent	Yes	Yes

Table 25: Pharmaceutical consumption input for option 1 and its suitability for internal monitoring and external comparison.

<u>Alternative calculation methods (not included in the tool)</u>

In the chapter on emission factors, two alternative calculation methods were identified. The first of these alternative methods does not include scope 3 emissions, and is therefore not included in the tool (Belkhir & Elmeligi, 2019). It requires the same total spend as option 1. The second alternative requires the total weight of the pharmaceuticals used in the OR (McAlister et al., 2016). This is can be calculated through the number of pharmaceuticals ordered and their respective weight, though this is highly impractical. Combined with the limited life cycle emission data on pharmaceuticals, it is not recommended to use this option. Option 1 is recommended for both internal monitoring as well as external comparison.

2.19 How can the results of the calculations be reported transparently and effectively to hospitals?

The presentation of the model calculations and results involves three stages:

1. Transparency in the use of model calculations: all formulas and supporting emission factors are clearly displayed in the calculation tool, and their sources can be found in the accompanying report.
2. Absolute values of carbon footprints can be found for each data entry and each group of data entries. At this point, the only calculation made is the data entry multiplied by the emission factor. In the case of groups of data entries, the respective data entries are summed up.
3. In order to allow for fair comparisons between hospitals or different periods, the results are normalized through strict procedures. These will be discussed in the coming chapter

2.20 Normalization

To be able to compare emission data, either for internal monitoring or for external comparison, it is necessary to normalize the results. For this, several options were explored in the trial:

- **Total annual procedures**
- Number of OR's in department
- Total surface area of these OR's
- Total CO2-footprint of hospital

Of these, total annual procedures is the most logical one for most processes, because most emissions are related to the action of performing a procedure. For example, disposables, pharmaceuticals, anesthetics, implants and sterilized products are all used during procedures. Only the HVAC is more distant from this, as it is more dependent on the number of OR's and their respective volume.

For both internal monitoring and external comparison, total annual procedures is recommended as the normalization number. The normalization is achieved by dividing emissions of each activity over the total number of procedures. For some activities, additional normalization by number of OR's or total CO2-footprint of the hospital is also calculated in this report, to infer other insights or to showcase this possibility. This normalization denominator can also be changed manually in the tool.

$$Normalized\ process\ emissions = \frac{Absolute\ process\ emissions}{Normalization\ denominator}$$

Equation 2: The normalization of process emissions. Absolute process emissions are emissions in kgCO2-eq per year. Generally, the normalization denominator will be the number of completed procedures per year. However, it can also be changed to number of OR's in the department, total surface area of these OR's, or total CO2-footprint of the entire hospital. The normalized process emissions are expressed in kgCO2-eq per procedure (or any other normalization denominator).

2.21 Data visualization in the carbon footprint tool – Internal monitoring

To showcase the capabilities of the carbon footprint tool without needing data from multiple years, an internal monitoring dataset was invented. The dataset was based on the LUMC 2018 values, and designed to showcase changes in the use of disposables (increasing) and a switch in electricity provider (greener energy).

2.22 Data visualization in the carbon footprint tool – external comparison

In the carbon footprint tool, a one-size fits all data visualization is used. As it is expected of hospitals to enter data for all processes, emission data for all processes is displayed. Both absolute and normalized emissions are shown, for all entered years or hospitals. Contributions to the total emissions can easily be identified in this figure, as well as absolute emissions.

To showcase the data visualization feature of the carbon footprint tool while not having complete data submission, unknown data was roughly estimated. An "unknown" value was created based on the average emissions of the available data points. If possible, this was scaled to the amount of operation rooms. This figure is intended only to showcase the possibilities of the external comparison of the tool, not in any way to estimate real emissions of these hospitals.

2.23 What differences do different calculation methods for greenhouse gas emissions of Dutch OR departments make?

To assess the differences in the identified calculation methods, a sensitivity analysis is performed on these choices. These fall into three categories of model choices:

1. System definition: Different system definition choices make for different calculation results. The inclusion or exclusion of certain processes will influence both absolute and relative emissions, as will the time horizon over which these emissions are calculated. This relates to modelling choices made for sub question 1.

2. Emission factors: different emission factors have been identified in the literature. These calculate different emission results, and the differences between these emission factors can be expressed as differences made in modelling choices regarding sub question 2
3. Consumption data: in some cases, different emission factors require different consumption data as well. For example, the carbon footprint of sterilization can be calculated through energy requirement or through the weight of sterilized material. This explains differences between modelling choices made regarding both sub question 2 and 3

2.24 Sensitivity to different system definitions

2.24.1 Sensitivity to use of internal monitoring system and external comparison system

There is some difference in the system definition between the model of internal monitoring and external comparison. This is due some data collection being too variable in nature to ensure fair data comparison. Only the processes for which this system definition makes a change will be examined closely. These are:

- Scope 1: no differences
- Scope 2:
  - Space heating (calculated gas use values not included in external monitoring)
- Scope 3:
  - Sterilisation (only sterilization direct energy use is included in external comparison)
  - Medical products (these are split up into more categories with internal monitoring)

The differences between these modelling choices are compared by calculating the total emissions per process in both systems. This was done for all hospitals that were able to submit process data on the respective process. As per procedure normalization data was not available for all hospitals, the amount of OR's was used as a normalization denominator. Normalized data are compared to assess sensitivity to the two different system definitions. Total emissions of the LUMC data for both systems are also displayed.

2.24.2 Sensitivity to use of GWP20 vs GWP100

As discussed in the literature review, GWP100 is the generally accepted characterization factor to calculate climate change impact scores. This expresses all greenhouse gas emissions relative to the radiative forcing generated by CO2 over a 100-year period. While this is commonly used as well as agreed upon in the Kyoto protocol, it is not the best tool for all purposes (Qin et al., 2013). It creates a level playing field for policymaking, but some emissions are relatively more severe in shorter time horizons. Volatile anesthetic gases are in this category (Özelsel, Sondekoppam, & Buro, 2019). As they are part of this study, the sensitivity to changes in the calculation time horizon are examined by using GWP100 as well as GWP20.

It is only meaningful to compare characterization time horizons if the composition of the greenhouse gas emissions is known. For the processes calculated through LCA databases, this is the case. For the processes calculated through economic estimation models, emission factors are already expressed as GWP100 CO2-equivalent emissions. The actual composition of these emissions remains unknown. To convert this to a GWP20 value would be meaningless, as the actual emission composition is not equivalent to CO2; it is only that way for GWP100.

Thus, we can only assess the differences in GHG emission by using a different characterization time horizon for the use of anesthetic gases, HVAC electricity and heating, and sterilization processes. The last two of these processes are calculated using the CML GWP20 characterization instead of the CML GWP100 characterization method within CMLCA. For the anesthetic gases, relative differences from Özelsel et al. (2019) are used, in comparison with GWP100 values from Sulbaek Andersen et al. (2010). Practically, these are changes in emission factors found in Table 26. Emission factors for each process in the tool, both GWP100 and GWP20, are also summarized in Appendix 1.3.

Unit process	**GWP100 emission factor**	**GWP20 emission factor**	**Unit**
Electricity use	0.646 (CML)	0.707 (CML)	kgCO2eq/kWh
Natural gas use	0.0689 (CML)	0.0829 (CML)	kgCO2eq/MJ
Steam use	0.283 (CML)	0.304 (CML)	kgCO2eq/kg
Sevoflurane	130	479	kgCO2eq/kg
Isoflurane	510	1869	kgCO2eq/kg
Desflurane	2540	7873	kgCO2eq/kg

Table 26: GWP100 and GWP20 emission factors of the processes that change depending on the characterization time horizon. Electricity, natural gas and steam use are based on CML2001 GWP100 and ReCiPe GWP20 values. based on values from (Sulbaek Andersen et al., 2010)*, and changes calculated in* (Özelsel, Sondekoppam, & Buro, 2019).

2.25 Sensitivity to emission factor choices

2.25.1 Sensitivity to electricity mix

The carbon intensity of electricity varies greatly. To examine the model's sensitivity to changes in this, the Dutch average 2019 electricity mix carbon intensity was compared to the carbon intensity of Dutch wind electricity generation (Wernet et al., 2016). Additionally, the respective carbon intensities claimed by the electricity sellers of the trialed hospitals was also included. Differences are expressed in normalized per operation room kgCO2-eq emissions, as Hospital A did not provide procedure amount data.

2.25.2 Sensitivity to use of pharmaceuticals using different economic emission factors

De Graaff & Broeren and Belkhir & Elmegili calculate different emission factors for pharmaceuticals. These differ greatly, as Belkhir & Elmegili do not include scope 3 emissions. These are difficult to calculate, but judging on the work by De Graaff & Broeren this part is likely close to 80% of total emissions. Therefore, emissions due to changing between these two calculation methods are expected to change by 80% as well.

2.26 Sensitivity to consumption data collection choices

2.26.1 Sensitivity to use of economic emission factor of product use vs factors from waste audit

To test the sensitivity to differences in calculating product use through expenditures versus a waste audit, both expenditure data and waste audit data needs to be available from the same hospital. This was only the case for the LUMC. Emission data calculated from expenditures using both emission factors from Belkhir & Elmeligi (2019) and de Graaff & Broeren (2018) were compared with waste audit data that was calculated with emission factors from MacNeill et al. (2017). Large differences are expected, as de Graaff & Broeren include scope 3 emissions and are specific to the medical industry. Belkhir & Elmeligi do not include scope 3 emissions, so a much lower emission is expected in this calculation. Lastly, the data calculated with waste audit data and emission factors from MacNeill et al. are also expected to be much lower, as the data they use are not specific to the medical industry. Therefore, emissions per kilogram of product are likely an underestimation and values will be much lower than those that are calculated with the emission factors by de Graaff & Broeren. Additionally, these numbers only calculate emissions from products that end up in the waste streams. Implants are therefore not included.

2.26.2 Sensitivity to energy use of sterilization vs factors from kg product sterilized

To test the sensitivity to differences in calculating emissions due to sterilization when using energy use data collection vs kg product sterilized annually. In the first case, the amount of steam that is used annually is collected. Subsequently this consumption is characterized using ecoinvent data for steam production. This results in a CO2-equivalent emission due to the use of steam to sterilize products. Additionally, the use of electricity for the sterilization process is characterized using the ecoinvent data previously mentioned. These two together account for the direct energy requirement of the sterilization process.

Alternatively, the total emission can be calculated through the total weight of products sterilized. A study on the energy and water use of steam sterilization in hospitals estimated the total electricity use at 1.9 kWh/kg and water use at 58 L/kg (McGain et al., 2017). In this study however, the steam was generated with electricity. In Dutch systems, this is usually achieved using natural gas. Therefore, the 1.9 kWh/kg is the total direct energy requirement of the sterilization process.

Data from the LUMC was gathered to test the sensitivity to both these methods. LUMC could not provide electricity use of the sterilization machines. However, the steam production numbers and total kg products sterilized were available. As the bulk of the energy requirement of steam sterilization is in heating the water to steam, this comparison can still be useful. However, it is expected that the method using the direct energy use calculates a slightly lower indicator result, as it does not include the non-heating energy use portion of the sterilization process.

2.26.3 Sensitivity to energy use of economic estimation vs factors from kg pharmaceuticals

The model's sensitivity to the calculation method of the emission of pharmaceuticals was tested. This sensitivity can be calculated either from spends and the economic estimation factors based on (de Graaff & Broeren, 2018), or from pharmaceutical weights multiplied by their respective LCI data (Parvatker et al., 2019). It should be noted that this second method calculates emissions only for the cradle to gate emissions of active pharmaceutical ingredients (API) in drugs. Therefore, it does not account for further processing, packaging and transport of the actual administered drug. These steps will add a widely varying emission on top of the emission associated with the API production, dependent on processing steps, concentration of API, packaging material per kg API and transport distance.

Additionally, emissions made by the pharmaceutical company in processes not directly involved in the production process of the API are not included. These include emissions related to office space, research and development, general overhead, capital goods, etc. Therefore, the emissions calculated from this second method are expected to be lower than those calculated from the emission factors calculated by de Graaff & Broeren (2018). In terms of costs, manufacturing of API's ranges from 10-50% of total costs for pharmaceutical companies (Basu et al., 2008). If emissions were proportionally divided over costs, this would mean that calculation through API LCI data would calculate between 10-50% of the total emissions associated with pharmaceuticals. However, it can be expected that emissions are not proportionally divided over costs, as for example there are relatively more emissions during the manufacturing process than during general overhead processes.

From the list of pharmaceuticals for which LCI data is calculated, seven were also used in the OR of the LUMC. For these 7, the total spends in euro's was calculated and multiplied with the emission factor by de Graaff & Broeren (2018). For the same seven pharmaceuticals, total API weight was calculated by multiplying the concentration (usually in mg/ml) by the volume (usually in ml) and the amount consumed. This weight was then multiplied by its respective GHG emissions per kg API as calculated by Belkhir & Elmeligi (2019) to calculate an emission for that respective pharmaceutical.

The total weight of these pharmaceuticals is also multiplied by the average GHG emission per kg API found by Belkhir & Elmeligi (2019). As the 7 pharmaceuticals that are used in the LUMC do not represent the average of the examined list in Belkhir & Elmeligi (2019), the reader is urged to also consider this number.

2.27 How can these greenhouse gas emission calculations be used to decrease greenhouse gas emissions of Dutch OR departments?

To answer this question, a carbon footprint calculation tool was developed to calculate greenhouse gas emissions of Dutch OR departments. This was adapted based on the results of the trial, literature review and sensitivity analysis. Due to this adaptation, the tool now has two modes. A detailed summary of all the included processes for each mode can be found in Appendix 1.3 or in the tool:

> - Internal monitoring mode: this includes more detailed carbon footprint calculation, but data collection for these may differ between hospitals. For internal monitoring, the method for data collection and calculation needs to be the same for each year. When done properly, changes in CO_2 emissions can be identified and linked to policy changes. It can be used as a communication tool towards employees. Depending on the available data, choices can be made to include a more complete selection of the operation rooms carbon emissions than the set used for external comparison
>
> - External comparison mode: this includes a smaller selection of carbon footprint calculations, but data collection for these is more equal throughout different hospitals. For external comparison, the method for data collection and calculation needs to be the same for each hospital. To achieve this, it is recommended to use only data that is marked as suitable for external comparison. When done properly, differences in CO_2 emissions between hospitals can be identified and linked to different practices at these hospitals. Hospitals can learn from each other, and employ each other's practices.

2.28 Tool development

The tool is based on the system presented in the introduction. It is further separated into three scopes, as per the GHG protocol and the MacNeill study (MacNeill et al., 2017; Ranganathan et al., 2004). In each scope, there are different processes that make up the total emission for that scope. The tool is designed around this principle. Each type of process has a dedicated sheet for entering consumption data for that type of process. Emission factors are displayed on this sheet, as well as the calculated emission. Different data entries may be used to calculate emission results suitable for internal monitoring only, and for external monitoring. This is clearly indicated beside each data entry point. The consumption data entry sheets are all grouped into their respective scopes.

The second part of the data tool is designed around data and calculation presentation. First, a summary of each scope's carbon footprint is presented for both internal monitoring results and external comparison results. Then, in a separate monitoring sheet, these internal monitoring results can be copied and compared throughout the years. Both absolute emissions and normalized emissions are shown. Similarly, in an external comparison sheet, external comparison results can be copied and compared between hospitals.

3 Results

3.1 How can greenhouse gas emissions of Dutch OR departments be accurately calculated?

Regarding this question, trial results and feedback from environmental coordinators returned the following relevant items:

- Environmental coordinators were not able to provide all information themselves; they needed to communicate with other departments within the hospital. The level of acquaintance with people at these departments proved paramount in the speed and quality of the data collection. For example, some environmental coordinators had personal contacts within the pharmacy department who could quickly produce a total spend for the OR department. Others, who did not, struggled to contact the right person who could and was willing to produce this number. Of course, it did not help that coordinators could not physically visit the departments in question due to the COVID-19 outbreak. However, it is recommended to develop personal contacts within each relevant department.
- The departments required to consult are similar in most hospitals, but do not all have the same level of available data. For example, some energy coordinators could easily produce natural gas use data for the OR specifically, while others could not. Some procurement departments could separate different product categories, while others struggled. In some cases, this was due to structural differences in either the information systems or the building, but in other cases, it was due to the required time investment.
- Some of the returned data differed by orders of magnitude from the base data collected during the LUMC study. This was due to ambiguities in the data or scope requested, as well as differences in data collection methods.
- Some of the required information was not available in some hospitals, creating empty entries

Based on the trial questionnaire, literature review and sensitivity analysis, the scope of this study has been adapted to two different systems: the internal monitoring system and the external monitoring system. The internal monitoring system is identical to the flowchart shown in the methods section, but the external monitoring system has been adapted to Figure 3. For space heating by natural gas, only measured numbers are allowed in this system. As can be seen in the figure, the HVAC electricity use for the sterilization department have been placed outside the system boundary. Because during the data collection trial and feedback session, it was concluded that the data collection results for these processes from different hospitals yielded incomparable results. Additionally, disposables production, implants production and other products production have been lumped together under medical products production as the separation of these was found to be difficult.

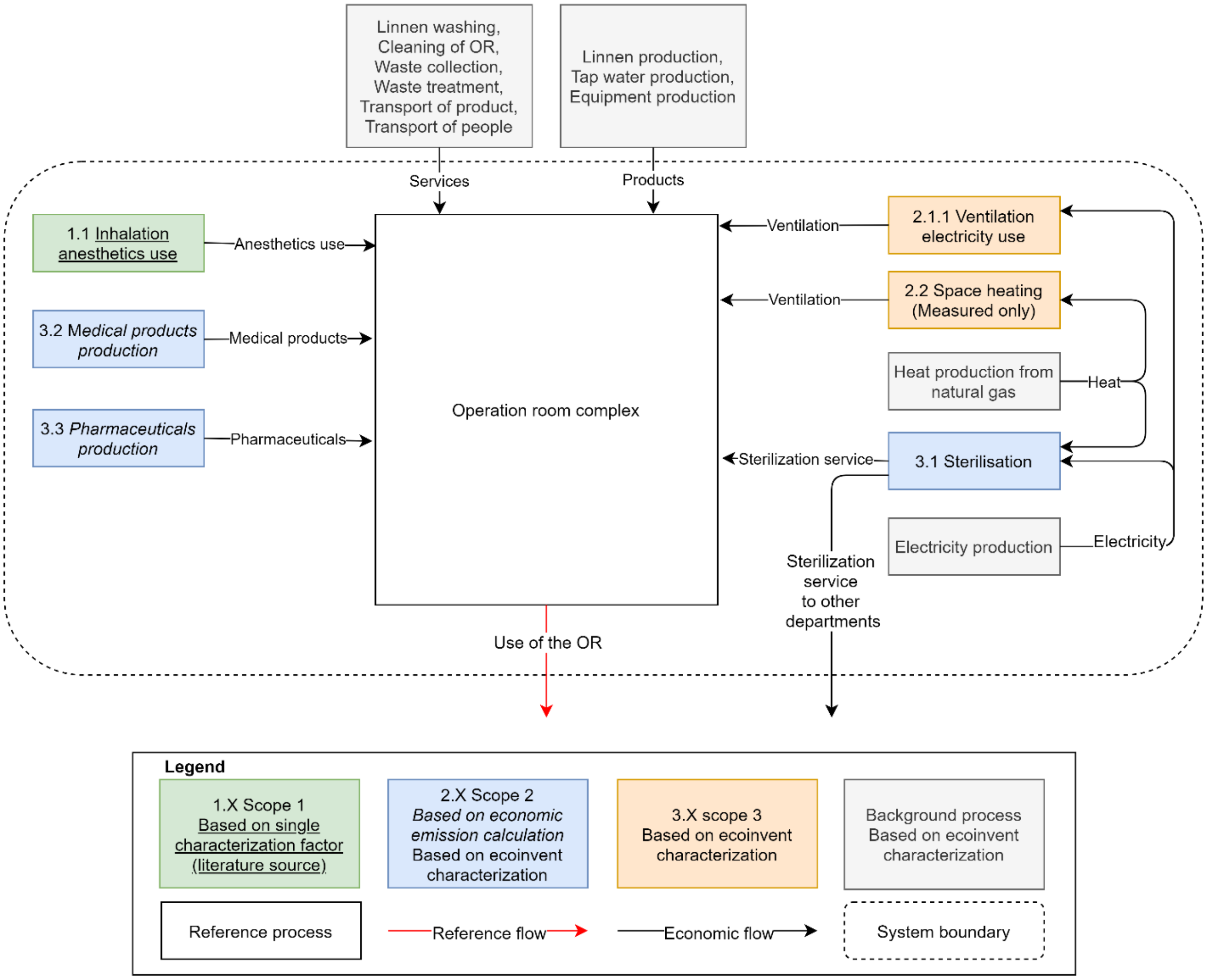


Figure 3: Flowchart and system boundaries of the system used to calculate external comparison carbon footprint.

3.2 What are the CO2 footprints of services and goods yearly consumed by ORs?

In the literature and methods section, multiple emission factors for consumed goods and services are explored. Appendix 1.3 summarizes all emission factors used in the carbon footprint calculation tool. It is also indicated if emission factors are deemed suitable for external comparison or only for internal monitoring.

3.3 What are the consumed goods and services and how can data on the use of these within Dutch OR departments be repeatably collected?

Data collection trial responses are summarized in Appendix 1.4. Based on feedback from environmental coordinators, the data collection method was changed. For external comparison data collection, a stricter data collection procedure was designed to ensure the data is comparable. For internal monitoring data collection, more flexibility was added to the data collection procedure. This allows more data to be submitted when structures are different in separate hospitals. It is assumed that within the same hospital, the gathering of data will be performed in the same harmonized and systemic way over the years. The renewed data collection procedure can be found in the tool user's guide (Appendix 1.5), which can be used in conjunction with the tool (Appendix 1.6). In Table 27, the amount of valid responses is summarized per process type.

Scope	Process type in questionnaire	Valid responses (out of 16 approached)
1	Anesthetics use	7
2	HVAC electricity use	3
2	Space heating energy use	3
3	Sterilization energy use	2
3	Disposables consumption	3
3	Implants consumption	3
3	Other procurement products consumption	3
3	Pharmaceutics consumption	2

Table 27: Amount of valid responses in the data collection trial per process type

3.4 How can the results of the calculations be reported transparently and effectively to hospitals?

While no full-size data collection of all hospitals was completed, the trial did return at least one data point of sufficient data quality per process. These have been summarized in the graphs below, to showcase the capabilities of the tool and the comparisons it can make. All data are normalized to improve comparability. If possible, the normalization denominator used is the number of procedures completed annually. If this data is lacking, the number of OR's is used.

3.5 Scope 1 emissions

3.5.1 Inhalation anesthetics

Due to the simplicity of the data collection for the anesthetics use, there were relatively many responses with sufficient data quality for this process. Five out of the seven hospitals approached in the first round were able to submit this data, while two out of the nine hospitals approached in round two returned this data. As can be seen in Figure 4, the total emissions of most hospitals are much higher than those that are calculated at the LUMC. This is to be expected, as the LUMC has stopped using the more emission-intensive isoflurane and desflurane some years ago. The other hospitals all use at least one of these still, and use more anesthetic gases in general. It is also shown that when normalized to a per-procedure emission, LUMC still performs the best, but Hospital C performs relatively better than Hospital B. Most hospitals should be able to reach emissions per procedure similar to those found at the LUMC by reducing the use of anesthetic gases in general, and isoflurane and desflurane in particular.

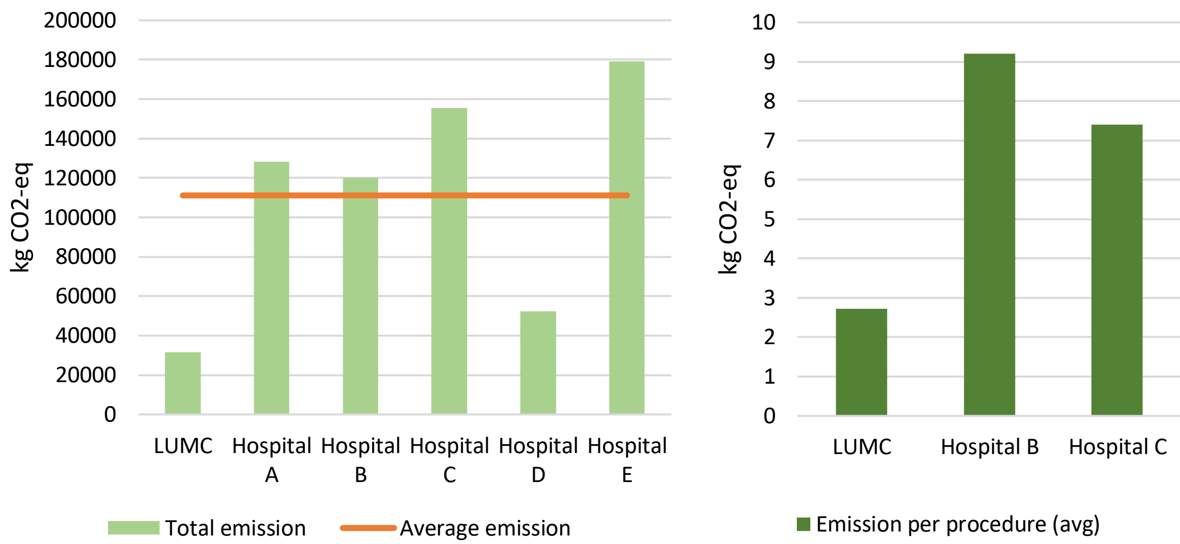


Figure 4: The total CO2-eq emission due to inhalation anesthetics use in 6 Dutch hospitals (left), and the normalized per-procedure emission of three of those hospitals (right). GWP100 emission factors are used.

3.6 Scope 2 emissions

3.6.1 HVAC electricity

Using the Dutch average electricity emission factor, climate change impact scores due to HVAC electricity use for three hospitals were calculated (Figure 5). Only hospital C had direct measurements of a part of the HVAC electricity use, which could be extrapolated to the whole system. LUMC and Hospital A used rated system power to calculate total electricity use. Hospital C emissions are higher, but this hospital is also larger than the other two. LUMC and Hospital A have 20 and 16 operation rooms respectively, while Hospital C has 32. Likewise, Hospital C performs almost twice the amount of operations the LUMC performs. Normalized, emissions are more similar, though Hospital C still has a higher emission per operation performed. As it is known that the LUMC HVAC system is old and runs 24 hours a day, this comparison is an indicator that Hospital C's HVAC system can also be improved.

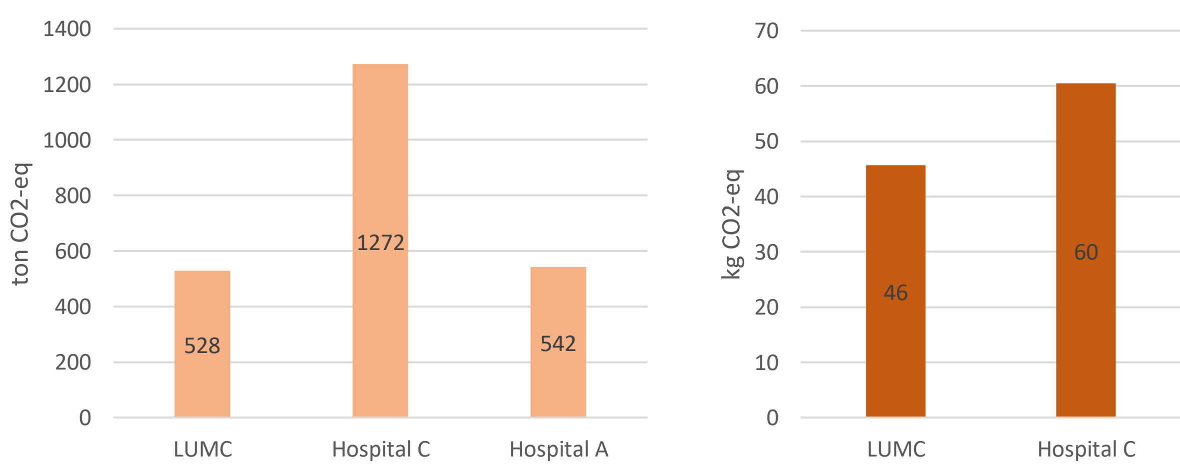
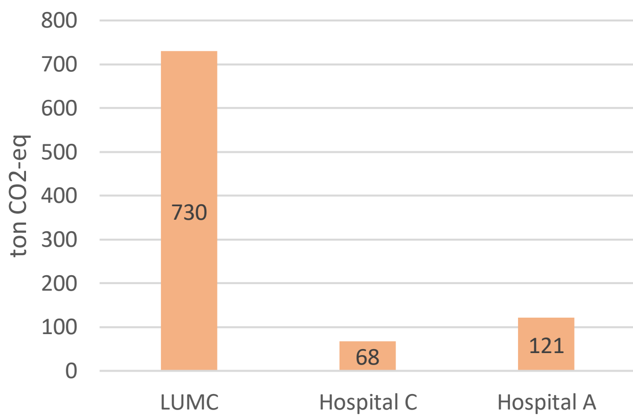


Figure 5: Total absolute emissions due to HVAC electricity use of three hospitals (left) and normalized per procedure emissions (right) due to HVAC electricity use of two of those hospitals.

3.6.2 Gas (space heating)

The trial responses for space heating were limited, as hospitals struggled to separate OR specific natural gas use from their total gas use. Only Hospitals A and C were able to submit a value, albeit with limited confidence. Both had to make estimations based on the total gas use of the hospital. As can be seen in Figure 6, the calculated emissions of these two hospitals were much smaller than the ones calculated at the LUMC. This large variation motivated the decision to move the calculated energy use of space heating outside the external comparison system boundary. Measured values are acceptable.



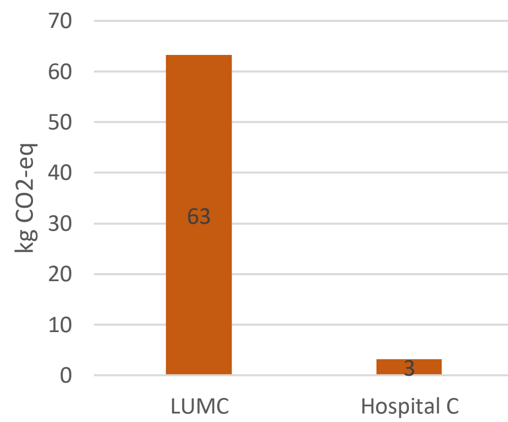
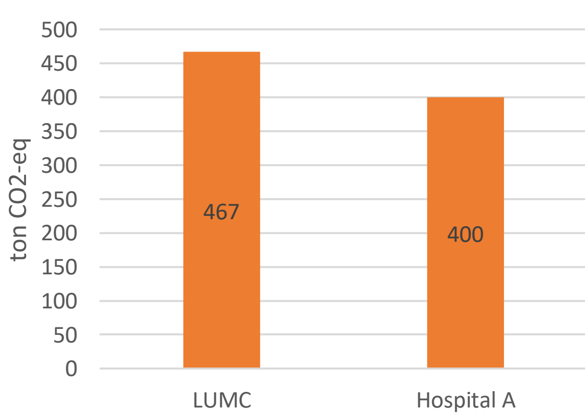


Figure 6: Total absolute emissions due to the energy use of space heating of three hospitals (left), and normalized per procedure emissions (right) due to HVAC electricity use of two of those hospitals.

3.7 Scope 3 emissions

3.7.1 Sterilization

Data collection proved challenging for the sterilization data as well. Only one hospital was able to deliver reliable data during the trial. This hospital made use of an external sterilization company, which had fairly detailed data. However, transport to and from this company was not included. Figure 7 shows that Hospital A has a similar emission as the LUMC. Hospital A did not provide per procedure normalization data, so this data has been normalized per operation room. The OR departments of the LUMC and Hospital A are of similar size (20 versus 16 OR's respectively). When normalized, the data still show similar emissions per operation room.



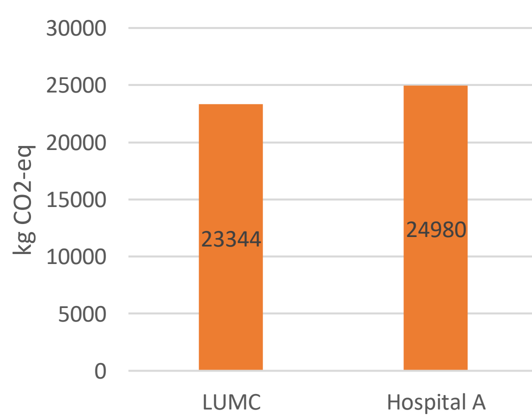


Figure 7: The total ton CO2-eq emission due to sterilization in two Dutch hospitals (left), and the normalized per operation room emissions in kg CO2-eq (right).

3.7.2 Medical products

For medical products, it proved difficult for most hospitals to separate procurement data into the different categories (disposables, implants and other medical products). Therefore, only two hospitals were able to return procurement data. Hospital E did not submit per procedure normalization data, so the number of operation rooms was used as the normalization denominator in this case. There is greater variability between the individual categories of these procurement emissions than there is for between the totals (Figure 8). This was due to procurement departments grouping products in different ways. For example, in one hospital suture thread may fall under suture materials (disposables) while in the other it may fall under miscellaneous items (other products). For this reason these were grouped together in the external comparison system, different categorization systems do not matter if all products are lumped together.

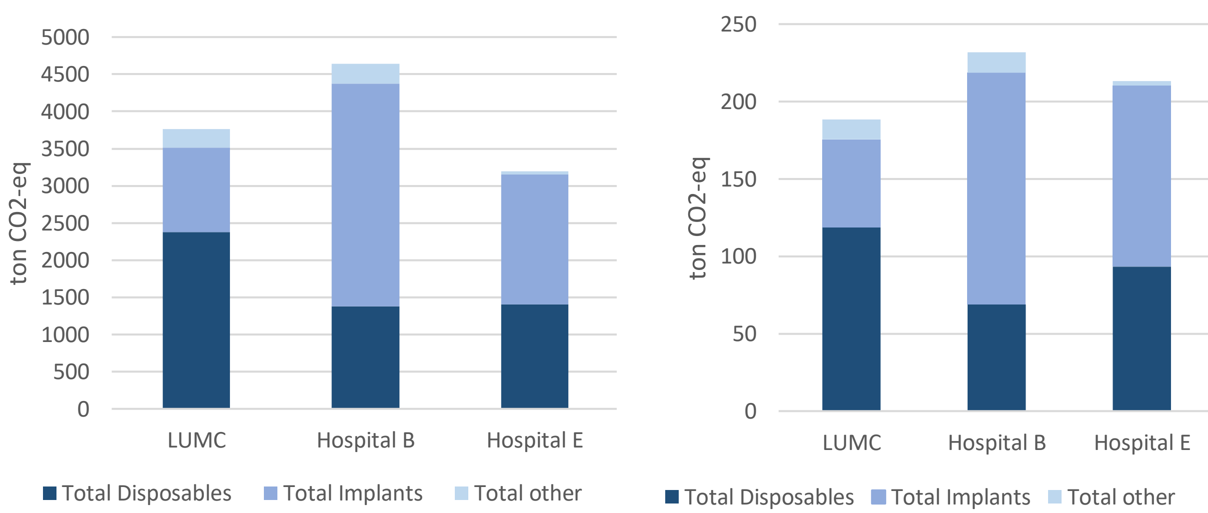
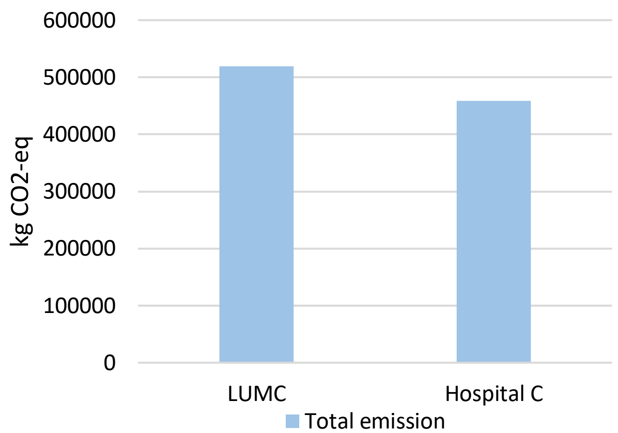


Figure 8: Absolute total emissions and normalized emissions per OR due to the production of medical products.

3.7.3 Pharmaceuticals

The LUMC and Hospital C have similar climate change impact scores due to pharmaceutical use, though Hospital C is much larger. It is not obvious from the data collection process why these two are similar, given that hospital C is much larger, therefore, further research is required. It could be that these differences arise from structural differences in whether pharmaceuticals are generally administered within the OR or outside of it, or the administration of these pharmaceuticals. Additionally, differences could lie in the nature of operations performed or the tendency of doctors to use certain pharmaceuticals.



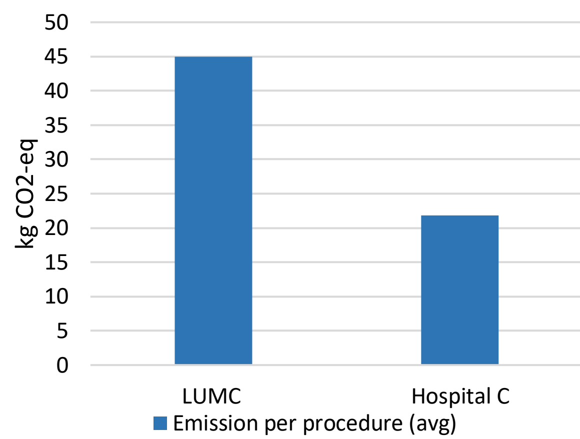


Figure 9 The total CO2-eq emission due to the use of pharmaceuticals in two Dutch hospitals (left), and the normalized emission per procedure of two of those hospitals (right).

3.8 Data visualization in the carbon footprint tool – internal monitoring

The results as they are shown in figures 4-9 above are all calculated using the carbon footprint tool. The figures have been adapted to show only the relevant hospitals and processes, to increase clarity. Within the carbon footprint tool, this can be carried out manually. However, by default the monitoring and comparison sheets will display all processes for all entered years or hospitals. It shows both internal monitoring results and external comparison results. Below, a visualization of the internal monitoring results is given. In this figure, real data (2018) and invented data are used to showcase this possibility (Figure 10).

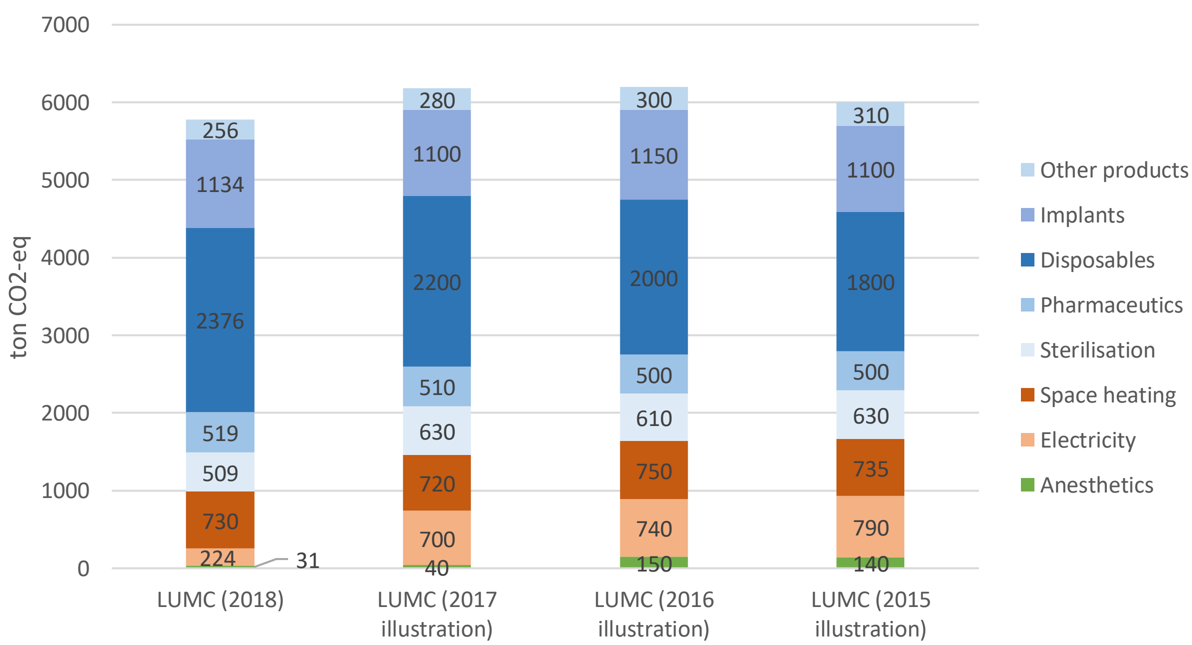


Figure 10: Showcase of internal monitoring visualization. Only LUMC (2018) data are real, the other data are invented to showcase the visualization.

3.9 Data visualization in the carbon footprint tool – external comparison

As explained in the methods section, unknown data was estimated to be able to showcase the data visualization capabilities of the carbon footprint tool (Figure 11). Important to note is that these estimations are very rough, and intended only as a showcase for the visualization method. They are not an accurate estimation of the actual emissions of the hospitals.

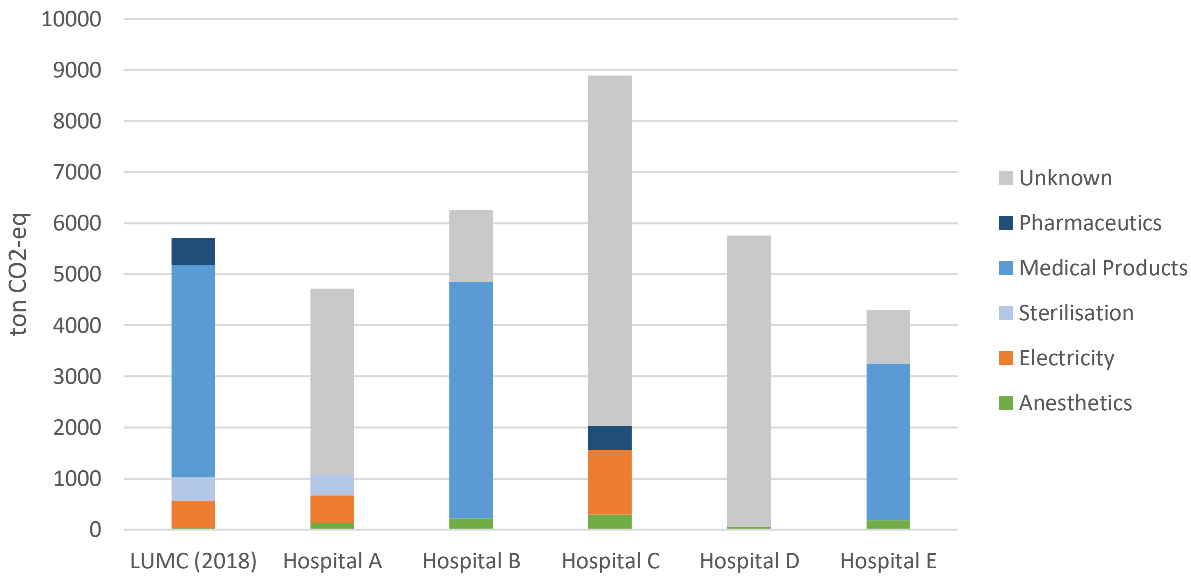


Figure 11: example of external comparison visualization. Unknown data are roughly estimated, this figure is only meant as an illustration of the visualization. These emissions are not intended as accurate estimations of the emissions of these hospitals.

3.10 What differences do different calculation methods for greenhouse gas emissions of Dutch OR departments make?

3.11 Sensitivity to different system definitions

3.11.1 Sensitivity to use of internal monitoring system and external comparison system

Sensitivity to the different system definitions in the tool was checked by comparing the total emission results and the emission results of the processes that are changed by this definition. Scope 1 is defined the same for both systems. In scope 2, calculated values of space heating is either included (internal monitoring system) or excluded (external comparison system). Figure 12 shows the normalized per OR emissions of the external comparison system (space heating excluded) is more similar between hospitals than those of the internal monitoring (including space heating). Judging from feedback from environmental coordinators, space heating was more challenging to calculate accurately. Therefore, space heating is excluded from the external comparison unless its energy use is directly measured. However, as it can be a significant part of the scope 2 emissions, it is recommended to include it in internal monitoring if possible.

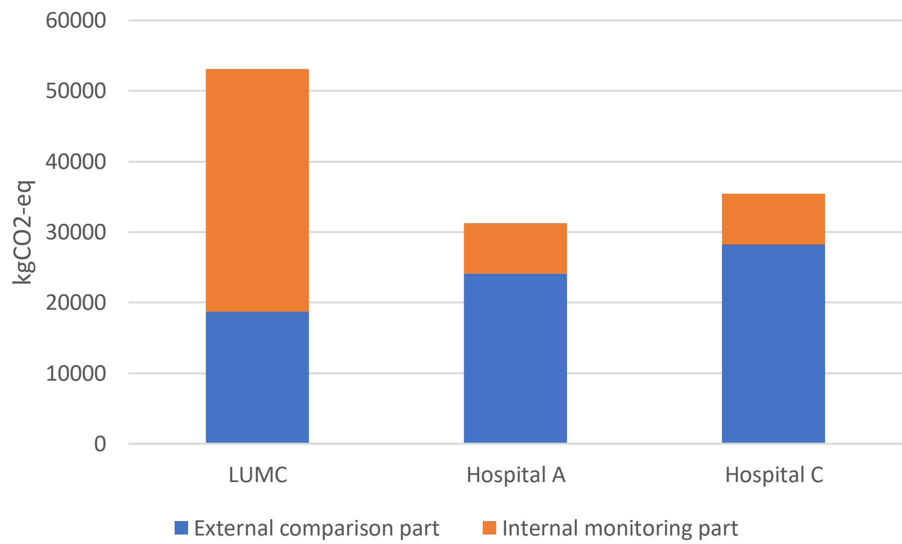


Figure 12: Results of scope 2 emissions sensitivity analysis. Normalized emissions per OR of the external comparison part (HVAC electricity) as well as the internal monitoring part (space heating) are displayed. It can be seen that there is less variability between the external comparison part, as data collection for this is more robust.

Scope 3 consists of emissions due to the sterilization process and emissions due to the procurement of products. Emissions due to the sterilization process are in part due to direct energy use emissions and in part due to the space heating and HVAC at the sterilization department. This last part is excluded in the external comparison system, as it proved challenging to collect this consumption data. In Figure 13, the normalized per OR emissions of both the external comparison system (excluding space heating) and the internal monitoring system (including space heating) are displayed. For Hospital A, space-heating data was not available. There is little variation between the two normalized external comparison emissions, indicating that this factor is indeed robust. However, only two hospitals were able to submit this consumption data.

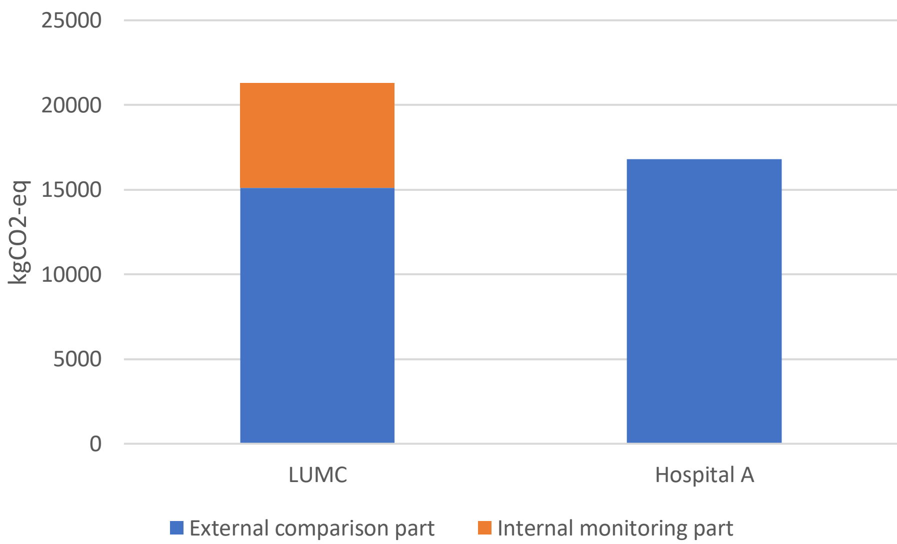


Figure 13: Results of scope 3 sterilization emissions sensitivity analysis. Normalized emissions per OR of the external comparison part (direct energy use of sterilization process) as well as the internal monitoring part (space heating and HVAC) are displayed.

Scope 3 product consumption data are calculated differently for both systems. In the external comparison system, the total procurement expenditure is multiplied by a weighted average emission factor. In the internal monitoring system, the total procurement expenditure is separated into different categories, each with their own emission factor. This creates more insight into the types of products that create these emissions, at the expense of extra labor required to prepare this data. As shown in Figure 14, total emissions change slightly when changing the system type. However, these changes are below 10% for each hospital tested. Thus, while the internal monitoring calculation is more precise, the external comparison method is a reasonably accurate substitute.

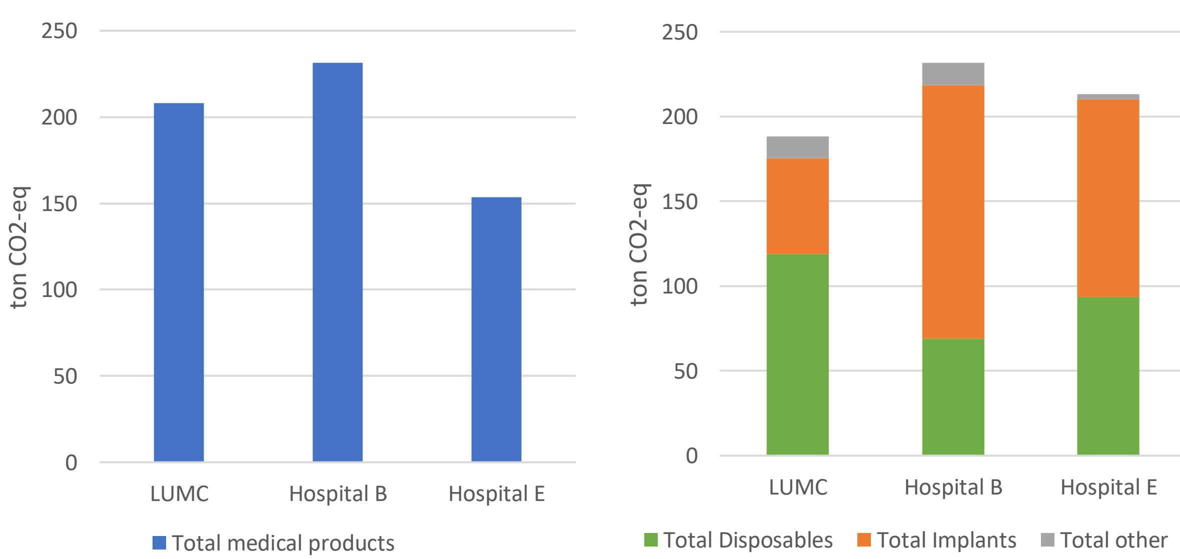


Figure 14: Results of scope 3 medical products emissions sensitivity analysis. Normalized emissions per OR of the external comparison part (left graph) and the internal monitoring part (right graph) are displayed.

Summing up all these emissions, and including the unaffected processes, the total emissions are shown in Figure 15. Most notably, space heating is absent in the external comparison system and the medical products are split up in the internal comparison system. Total calculated emissions are 493 ton lower in the external comparison system, a change of 8% (Figure 15).

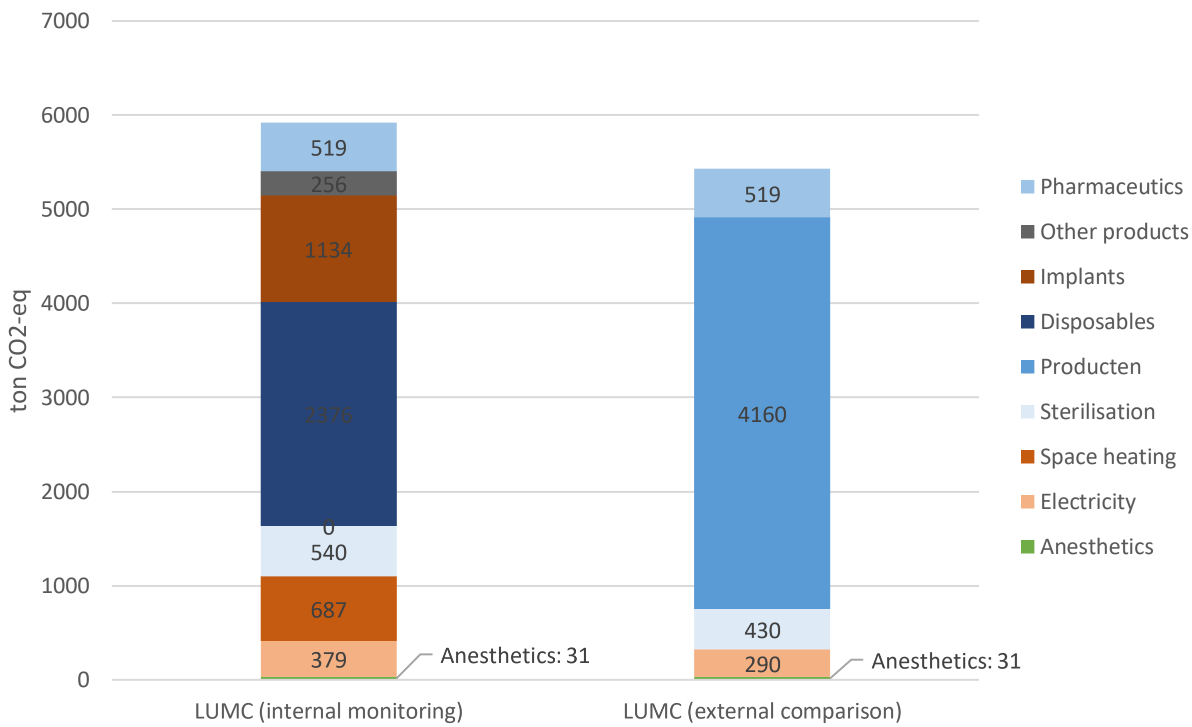


Figure 15: Total annual emissions for the LUMC OR complex when using the internal monitoring system definition and the external comparison system definition.

3.11.2 Sensitivity to use of GWP20 vs GWP100

When changing the emission impact time horizon from GWP100 to GWP20, for all relevant processes the emissions in CO2-equivalent emissions increased. Total emissions from relevant processes for the LUMC increased from 91 ton to 106 ton, in Hospital A from 79 ton to 107 ton, and in Hospital C from 54 to 85 ton (Figure 16). The impacts for sterilization, space heating and electricity increased with 11%, 10% and 16% respectively. The impact of anesthetic gases increased with 255%.

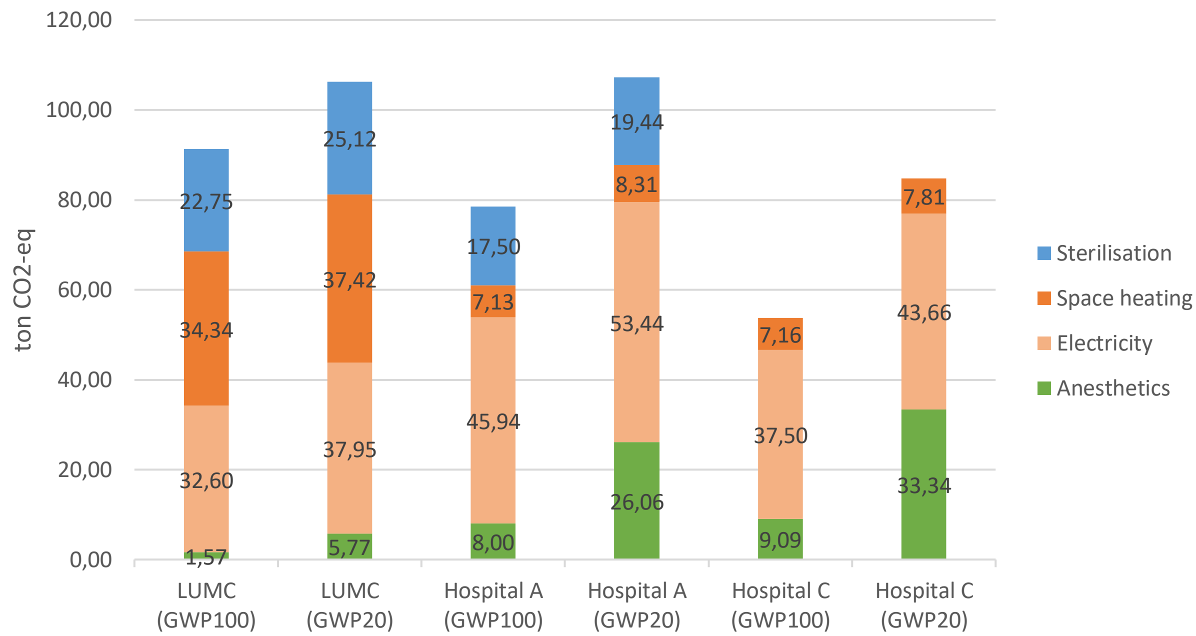


Figure 16: kgCO2-eq emissions normalized per operation room of four highlighted processes at three hospitals, compared for a GWP100 time horizon as well as a GWP20 time horizon.

3.12 Sensitivity to emission factor choices

3.12.1 Sensitivity to the use of electricity mix emission factors

As can be expected based on the changes in emission factors (between 0.646-0.0137 kgCO2eq/kWh), emissions due to electricity mix choice vary greatly. Only the sterilization and electricity processes are influenced by this modelling choice, but emissions in these categories change drastically based on this decision. LUMC emissions from electricity use change from 34529 ton to 727 ton (-98%) when using wind energy emission factor and to 11225 (-67%) when using the electricity provider emission factor (Figure 17). Emissions for the sterilization are impacted less, as they also have a part that is not influenced by this model choice. They are reduced from 23344 ton to 17150 ton (-27%) and 19077 ton (-18%). The numbers for Hospital A show similar reductions. These reductions are scaled linearly with the reduction in emission factor. In terms of total model sensitivity, for the LUMC the total score is impacted between -7% and -11% depending on these emission factors compared to the Dutch average.

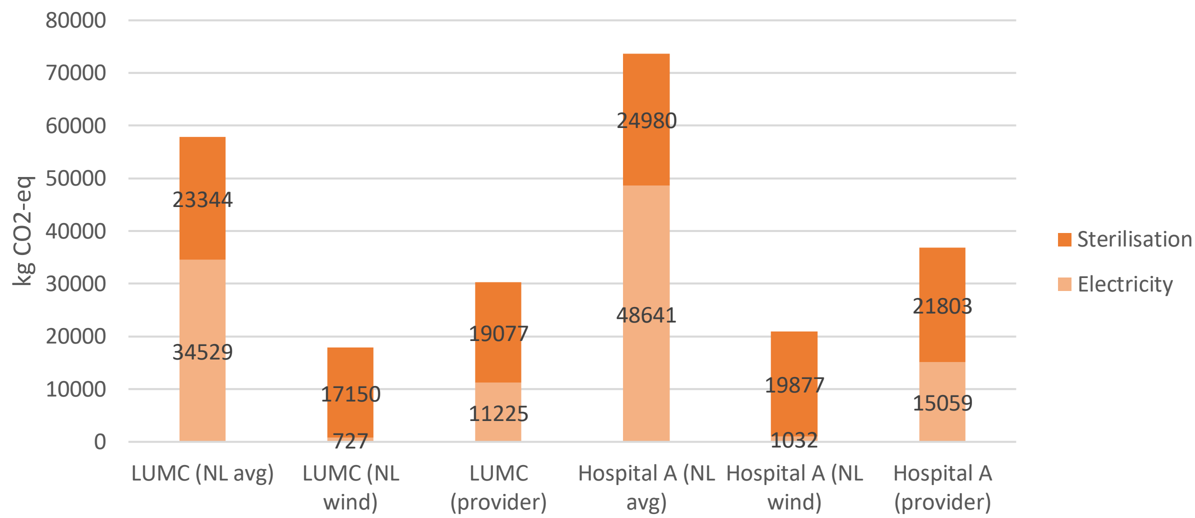


Figure 17: Normalized per OR emissions in kgCO2eq for the sterilization and electricity use of two hospitals, when using different electricity emission factor choices (NL avg, NL wind, Provider).

3.12.2 Sensitivity to use of pharmaceuticals using different economic emission factors

As shown in Figure 18, emissions due to pharmaceuticals are 428 ton lower (-82%) when using the Belkhir & Elmeligi emission factor. As this factor does not include scope 3 emissions, this is to be expected. Therefore, this emission factor is not used in the calculation tool. It would seriously underestimate emissions due to missing scope 3.

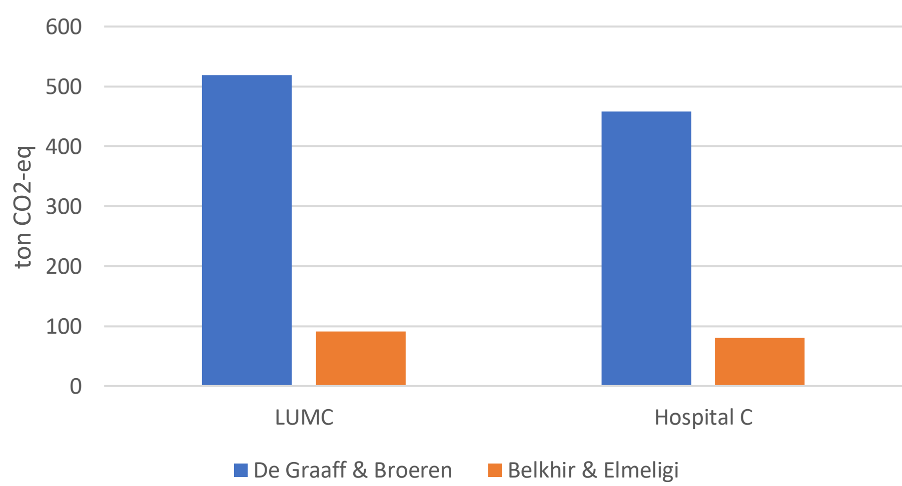


Figure 18: Absolute emissions in kgCO2-eq for the use of pharmaceuticals in two hospitals, calculated using two different emission factors. It must be noted that Belkhir & Elmeligi emissions do not include scope 3 emissions.

3.13 Sensitivity to consumption data collection choices

3.13.1 Sensitivity to use of economic emission factor of product use vs factors from waste audit

Figure 19 shows that the emissions are 3153 ton lower (-84%) when using the emission factors by Belkhir & Elmeligi (2019). It must be noted that the emission factor by Belkhir & Elmeligi does not include scope 3 emissions, and is therefore expected to have lower indicator results.

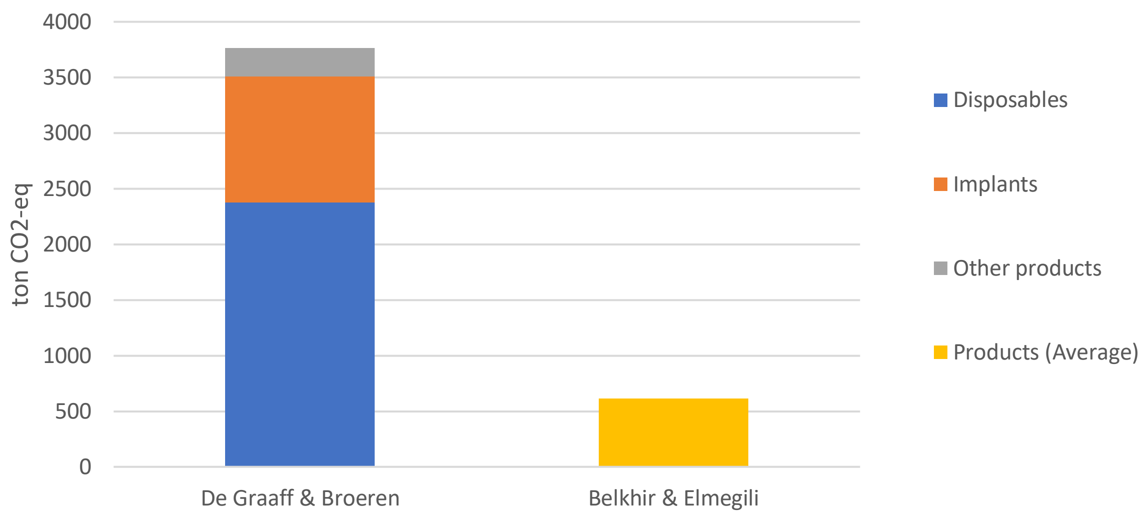


Figure 19: Results of sensitivity analysis to consumption data collection. De Graaff & Broeren and Belkhir & Elmegili results are both calculated from expenditure data. It must be noted that the Belkhir & Elmegili emission factor does not include scope 3 emissions.

Emissions using the waste collection audit numbers are 2066 ton lower (-78%) than the emissions calculated with procurement expenditures (Figure 20). This is likely due to these emissions being calculated with generic industry emission factors instead of emission factors specific to the medical industry. Only the method using procurement data and the emission factor by de Graaff & Broeren (2018) is able to include scope 3 and be specific to the medical industry, so using this method is recommended.

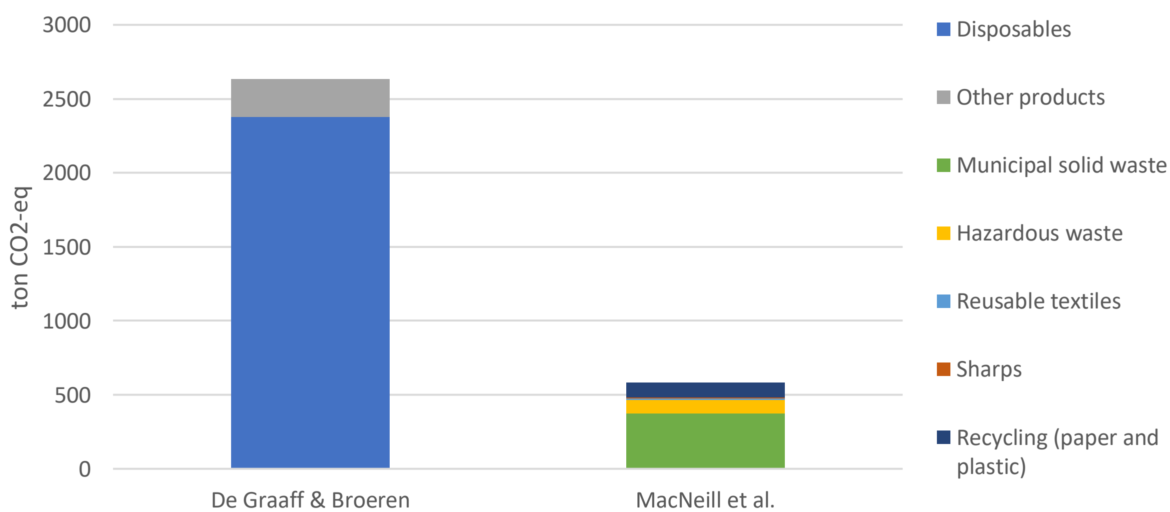


Figure 20: Results of sensitivity analysis to consumption data collection. De Graaff & Broeren results are calculated from expenditure data, while Macneill et al. results are calculated from waste data. As implants do not end up in the waste stream, these are not included in the figure.

3.13.2 Sensitivity to energy use of sterilization vs factors from kg product sterilized

The results of the sensitivity analysis on the emission data of the emissions associated with the direct energy use of the sterilization process show that when using the weight of sterilized material, a 39.5 ton lower (-13%) emission is calculated for the LUMC. Causes for this difference will be discussed in the conclusions and discussions sections. While the observed difference is too small to discard the option of calculation through weight of sterilized material, it is inferior in terms of scope. This comparison is only about heat energy used in the sterilization process, it does not include non-heating electricity use. Additionally, the weight of sterilized material emission factor uses electricity as a heat source instead of gas. In the option that calculates sterilization emission through energy use, these issues can be accounted for. Therefore, it is closer to reality and the preferred modelling choice.

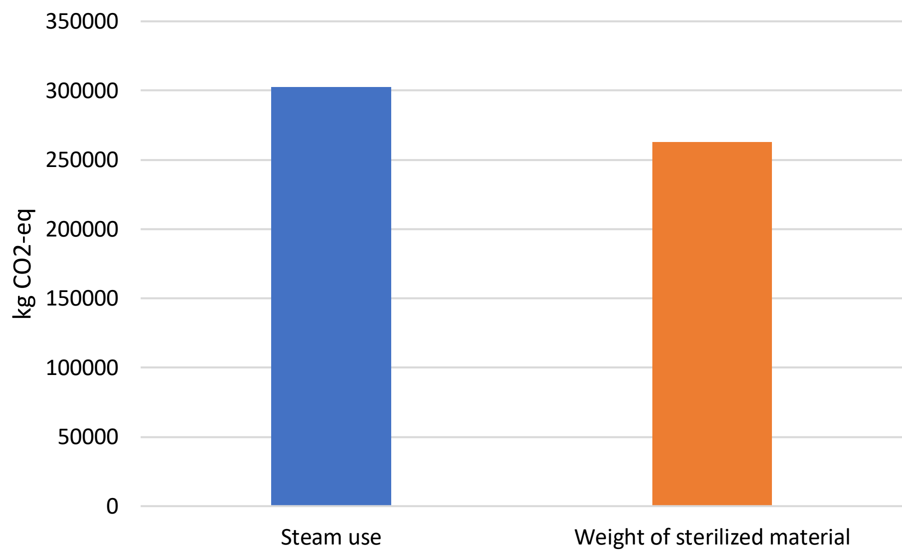


Figure 21: Emissions due to direct energy use of the sterilization process in the LUMC in 2018. Calculated through steam use (left) and weight of sterilized material (right).

3.13.3 Sensitivity to energy use of economic estimation vs factors from kg pharmaceuticals

Using both economic estimation and LCA calculation methods, a kgCO2-eq indicator result can be calculated for each pharmaceutical. The results show a large variety of impacts, ranging from 0.02% to 3.13% of the spend-based calculation (Table 28).

Pharmaceutical	**Indicator result in kgCO2eq (mass based)**	**Indicator result in kgCO2eq (spend based)**	**Percentage (mass based indicator result / spend based indicator result)**
Ketamine	44,0	10344	0.43%
Remifentanil	1,0	8728	0.01%
Fentanyl	0,2	919	0.02%
Ropivacaine	28,6	2417	1.18%
Lidocaine	27,5	1199	2.29%
Bupivacaine	0,9	298	0.31%
Propofol	314,4	10051	3.13%

Table 28: Indicator results of two calculation methods for the emissions associated with the production of 7 selected pharmaceuticals. Mass based indicator results only include the production of the Active Pharmaceutical Ingredient (API) based on (Parvatker et al., 2019)*, while spend based indicator results include cradle to gate scope 1, 2 and 3 emissions for the pharmaceutical industry based on* (de Graaff & Broeren, 2018).

Even still, the results in Table 28 are all calculated for 7 of the pharmaceuticals that have relatively low GHG emissions per kg API calculated in (Parvatker et al., 2019). These 7 range from 21-140 kgCO2eq/kg API with an average of 64, while in the study by the 20 examined pharmaceuticals range from 11-3006 kgCO2-eq/kg API with an average of 340 (Parvatker et al., 2019). Using the 340 kg average, the calculated mass-based result is 21% of the spend-based result. The observed gap is likely due to the Parvatker numbers not including the life cycle after the production of the API, which includes packaging, distribution etc.

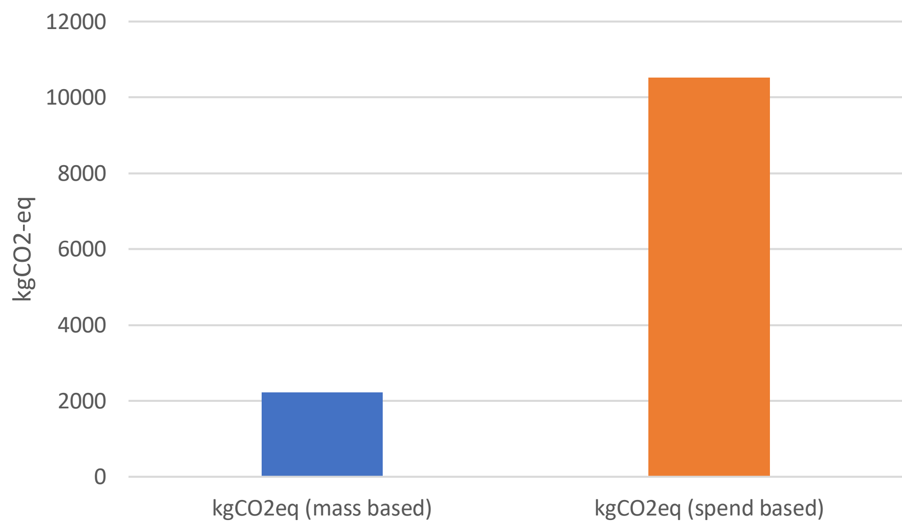


Figure 22: Indicator results of two calculation methods for the total emissions associated with the production of 7 selected pharmaceuticals. Mass based indicator results only include the production of the Active Pharmaceutical Ingredient (API), using the average GHG emission factor found in (Parvatker et al., 2019)*. Spend based indicator results include cradle to gate scope 1, 2 and 3 emissions for the pharmaceutical industry based on* (de Graaff & Broeren, 2018)*.*

3.14 How can these greenhouse gas emission calculations be used to decrease greenhouse gas emissions of Dutch OR departments?

Results such as the ones shown in chapters 3.5-3.7 can be used to inform decision making within hospitals. Policy changes can be monitored and compared with other hospitals. However, it is important to realize that the results calculated in this tool only calculate the CO2-impact of the processes that are described. They should always be placed in context, both in terms of other environmental impacts, as well as medical, economic and other relevant context.

4 Discussion

4.1 How can greenhouse gas emissions of Dutch OR departments be accurately calculated?

This study intends to develop and test a CO2-footprint calculation tool. This tool is designed around its users, which requires some simplifications, but should also hold up in terms of scientific rigidity. To remain scientifically accurate as well as include a reasonable scope of processes, the internal monitoring system is the most complete. In the internal monitoring system, most emissions are accounted for. When comparing the internal monitoring system to the LUMC study, the scope is narrower (Hendriks et al., 2020):

- The production phase of the HVAC system is not included
- The production phase of light bulbs is not included
- Tap water use is not included
- Cleaning of the OR is not included
- Product transport is not included
- Waste treatment is not included
- Linen production and washing is not included
- Procurement of goods is separated into less categories

However, taken together these processes amount for only 9% of the emissions calculated in the LUMC study. Therefore, using the internal monitoring system, 91% of the emissions calculated using the full LCA method are still included. It must be mentioned that both methods do not include the transport of patients and employees to and from the OR. Depending on the definition used for the scope of a carbon footprint analysis, this should be taken into account as well. Hospital-wide, travel of employees contributes to 7.8% of the total emissions in the LUMC (LUMC, 2017). Travel of patients to and from the hospital amounts to 15.5% of the total emissions for the LUMC (LUMC, 2017). Likely, part of this travel would be attributable to other departments than the OR, but both these travel emissions are likely to add a sizeable amount to the OR emissions if included.

Comparing the internal monitoring system to the study by MacNeill et al. (2017):

- Sterilization emissions are included
- Emissions related to products are calculated using procurement data instead of waste data
- Waste treatment is not included

In terms of processes that might be missed in each scope within this study:

There is currently no indication, either in the literature or from findings in this report, that major scope 1 emissions were missed in this methodology.

Scope 2 emissions for the internal monitoring system consist of three parts: HVAC electricity use, space heating and other electricity use. In other electricity use, electricity use from other processes can be added to the user’s discretion. If electricity use from lighting, appliances and medical equipment is all included, scope 2 emissions are complete as well. From this follows that for the external monitoring system, scope 2 emissions are not complete: space heating and other electricity use are not included in this system.

Scope 3 emissions are more challenging to check for completeness. These are indirect emissions, and the nature of our defined functional unit makes it difficult to assess the completeness of scope 3 emissions. As the use of the OR for one year makes use of hundreds of processes completed by dozens of different people, one can only try to include all relevant emissions by consulting literature, consulting employees, and by reasoning. It is assumed that all major scope 3 emissions are included in the internal monitoring system scope, excepting the transport of people to and from the OR. In the external monitoring system, indirect energy use for sterilization such as space heating and HVAC electricity are not included.

4.2 What are the CO2 footprints of services and goods yearly consumed by ORs

Scope 1 emissions are calculated by using emission factors based on Sulbaek Andersen et al. (2010). Other options have been identified in the literature review. The radiative forcing calculated by Sulbaek Andersen et al. are considered the best calculations for the anesthetic gases around. Some argue that the values, which are now expressed in kgCO2-eq per kg anesthetic should be expressed in CO2 emitted per hour (Hanna et al., 2019; Özelsel, Sondekoppam, Ip, et al., 2019). This seems to be the main reason for different emission factors used throughout the literature. Most are indirectly still based on the radiative forcing calculated by Sulbaek Andersen et al. Therefore, scope 1 emission factors seem fairly robust.

Scope 2 emission factors are more complex, as they include emissions from electricity as well as burning of natural gas. Electricity emission factors especially proved to be a point of contention, as there are large differences between green, gray and average electricity mixes. Additionally, many hospitals buy (partly) green energy. This was dealt with by including all these emission factors as selectable options. However, for the comparisons in this report, the average Dutch electricity mix was used to represent the Dutch electricity system as honestly as possible. It may be argued that in reality, the average mix bought by hospitals has a lower emission factor than the Dutch average. However, the information acquired in the data collection trial was not large enough to make this estimation accurately. Additionally, emission factors claimed by electricity providers may not be calculated in the same way.

Scope 3 emission factors were in part based on the same factors used in scope 2. Differences lie in the emission factors used for the calculation of emissions due to medical products use and pharmaceutical use. Both the emissions from medical products use and pharmaceutical use are calculated using emission factors from de Graaff & Broeren (2018). Conceptually, these emission factors make the most sense of the identified possibilities. They are specific to the medical industry, and include scope 3 emissions. Additionally, they require procurement expenditures instead of waste volumes, which is preferable from a practical point of view. However, these emission factors from de Graaff & Broeren (2018) are not published in peer-reviewed literature. They do align with numbers found in peer-reviewed literature, as emission factors for the pharmaceutical industry excluding scope 3 found by Belkhir & Elmeligi (2019) combined with scope 3 proportions found for the manufacturing industry by Hertwich & Wood (2018) almost exactly match their findings. Ideally, emission factors would be used that are specific to the medical industry, and include scope 1, 2 and 3 emissions, and are from a peer-reviewed source. However, this information is currently not available and the emission factors from de Graaff & Broeren, (2018) were deemed most suitable for this study.

4.3 What are the consumed goods and services and how can data on the use of these within Dutch OR departments be repeatably collected?

Data on the amount of consumed goods and services were collected in a data collection trial. Responses to this trial were minimal, in part due to the Covid-19 outbreak but also due to factors that can be improved upon. These were briefly touched upon already in the methodology and results sections. It proved difficult to collect comparable data reliably for some of the processes (e.g. natural gas use, separated medical products use). The data collection procedure has since been improved for some processes. For other processes, this was not possible and these were moved to the internal monitoring system. This aims to clear up differences in data collection, at least for the external comparison part.

From the trial, it became clear that hospitals do not have the resources to spend much time on the collection and preparation of the required input data for a tool such as this one. The new procedures and carbon footprint tool have been designed to ease the collection and preparation requirements, while maintaining most of the informational value. However, this is always a tradeoff. Collecting more data will offer more detailed insights, and can in turn guide policymaking choices more precisely. However, a choice must be made between the resources spend researching and monitoring the carbon footprint, and the resources spent on reducing these. This type of calculation tool can identify large possible CO_2 savings, but it will not save any CO_2 until policy changes are made based on it. This goal should always be kept in mind, as discussion on data collection and accuracy of calculation does not actually make a difference until policy choices are made and emission-reducing actions are taken in the workplace.

4.4 How can the results of the calculations be reported transparently and effectively to hospitals

In order to report the results in a transparent and effective way, the data analysis tool displays the calculations and results in both absolute and relative terms. Additionally, the tool aims for full transparency by displaying the emission factors used and each calculation step and intermediate result. It also offers a high degree of adaptability when systems are differently structured than expected.

However, there are limits to the tool. It is designed only for the functional unit of using an OR for a period of time. The tool is not a complete LCA software. It can only calculate emissions for the processes that have been discussed in this report. Other emission factors can be used, but doing so can defeat its purpose of comparability unless it is a communicated change.

The tool aims to create a carbon footprint as complete as possible for the function analyzed: the use of the OR. It is intended to be used by hospital employees such as environmental coordinators. They are likely to not have the time to fully read this report. A more concise user's guide file in pdf-format is included to guide users in the use of the tool. It also describes its goal, scope and calculation methods more concisely.

It is also important to realize that this tool is designed around the information currently available. As such, the assumptions discussed in the methods section are all in place. For example, this means GWP100 emission factors are used. For scope 1 emissions, this means they are relatively smaller than they would be when using GWP20 or even shorter time horizons. These choices have been made in this report and in the tool, but are not the only right choices. They could be made differently, especially if new data is published, or the UNFCC publishes new guidelines for policymaking characterization time horizons. Additionally, if the model is to be used years from now, its emission factors should be updated. There is currently no system in place to check for outdated emission factors or to centrally update these. Environmental coordinators that will use the tool have been notified of this issue.

It should also be considered and clearly communicated that this tool only calculates CO2-equivalent emissions. It does not include other environmental effects, such as ecotoxicity, while these can be just as relevant. Additionally, it does not include medical or financial aspects. It should therefore be used as an informative tool to decision-making, but not as the only information guiding any decision. Especially in the medical sector, these other factors will be at least as important as environmental effects, if not more.

Putting the tool's results into perspective to other decision-making factors can partly be done through normalization. The current normalization denominators used in the tool and this report are: annual procedures, amount of operation rooms, and total CO2-eq of the hospital. These are chosen to order to best rationalize and compare results while being easily available for hospitals, but are by no means the only or the best options. Depending on the audience, it might be better to include normalization denominators that are closer to the audience's expertise. Other denominators that could be useful include, but are not limited to; operation room surface area, average blood loss of operations, operating time and post-operation wound infections. Such normalization denominators could be used to compare hospitals that have different types of operations, buildings, procedures and medical success rates. Using such factors can also increase communicative strength towards doctors or other medical staff who might be more concerned with medical endpoints than environmental ones.

4.5 What differences do different calculation methods for greenhouse gas emissions of Dutch OR departments make?

Some differences have been observed when testing the sensitivity to different calculation methods. These differences have causes; to what extent they can explain the observed differences is discussed below in sections 4.6-4.8

4.6 Sensitivity to system definitions

4.6.1 Sensitivity to use of internal monitoring system and external comparison system

The two system definitions showed a limited sensitivity to overall emissions when changing from the use of the internal monitoring system to the external comparison system. However, part of the sensitivity was masked by the increase of the product-associated emissions. Especially scope 2 emissions change drastically when changing this system definition, as space-heating emissions are not included in the external comparison system.

However, this sensitivity analysis is only based on one hospital's data. This inevitable, as no other hospital was able to provide a full dataset during the trial questionnaire. The sensitivity to system definitions is likely to be different for other hospitals. As the model's calculations are transparent however, it is simple to identify these sensitivities. The external comparison does not include space heating, other electricity use and sterilization indirect energy use. Therefore, this sensitivity will be higher for hospitals that have these processes as larger contributors to their total emissions. Similarly, hospitals with larger contributions by product use will also have a higher sensitivity to this system definition change. The limited data from the other hospitals did not indicate that the sensitivity would drastically change.

4.6.2 Sensitivity to use of GWP20 vs GWP100

The system proved sensitive to changes in the time horizon. Especially anesthetic gases form a much larger contribution to the total emissions when GWP20 is used. As this tool is intended for policymaking, the UNFCC GWP100 standard is followed (Qin et al., 2013). It is still important to realize that especially in the medical context, shorter time horizons can calculate different results. These volatile gases cause extreme radiative forcing, but for a shorter time. It can be argued that using a 100-year time horizon is strange, as very few other decisions are made using such long time horizons. Most policy decisions are made with a time horizon of one to five years. In some sense, it is odd that climate change decisions are made using this much longer time horizon. This decision is made with a reason however, as radiative forcing will continue for many years, and future generations will be impacted by the choices we make now.

4.7 Sensitivity to emission factor choices

Emission factor choices are made based on the current available information. However, new information may be published with more precise or better fitting emission factors. These can be entered in the carbon footprint tool, though this should be done with care. The user must verify that the new emission factor matches the scope of the system. When comparing with other hospitals, the new emission factors need to be clearly communicated and used by all hospitals in the same way.

Additionally, emission factors based on monetary expenditures should be adjusted for inflation if the calculation tool is used for a long period. As expenditures will increase even if the acquired products remain the same, carbon emissions calculated by the tool would increase if emission factors were not adjusted. Assuming a 2% inflation rate, emissions from processes that use an economic estimation factor would be overestimated by 10% after 5 years.

4.8 Sensitivity to consumption data collection choices

4.8.1 Sensitivity to use of economic emission factor of product use vs factors from waste audit

This study makes use of economic emission factors of product use instead of factors from waste audits. In terms of data collection, this is easier as procurement expenditures are easier to calculate than waste volumes. However, waste volumes do not suffer from inflation as they are based on SI units. This makes them preferable from an LCA perspective, if the emission factor were to match the scope of the study. In the current state of data availability, this is not the case, but if life cycle emission factors specific for medical waste become available, this would be preferable.

4.8.2 Sensitivity to energy use of sterilization vs factors from kg product sterilized

From an LCA perspective, it is better to use data on real energy use than to calculate it from the amount of product sterilized using another study. This way, fewer calculation steps can be sources for errors. Thus, it is preferred to use real energy use data (either measured or calculated).

4.8.3 Sensitivity to energy use of economic estimation vs factors from kg pharmaceuticals

Large differences were observed between spend-based calculations and mass-based calculations. Again, from an LCA perspective it is preferable to use mass-based calculations if they align properly with the set goal and scope. At this moment, this is not the case. The number of pharmaceuticals for which LCI data is available is too small, and is currently only available on API level, not on a product level. Therefore, a large part of the life cycle is not included. The current data does not represent the whole life cycle of pharmaceuticals. As the range between GHG emissions per kg API is very large, the use of an average GHG emission for pharmaceuticals can also lead to mistakes.

5 Conclusions

5.1 How can greenhouse gas emissions of Dutch OR departments be accurately calculated?

The results of this study show that it is very important that the scope of the carbon footprint calculation is well defined. Strictly defining the scope while aiming for a full life cycle assessment turned out to be a double-edged blade. Defining the scope more strictly, while keeping data collection feasible, reduces the scope size. Thus, fewer processes can be taken into account. To combat this, a stricter scope was designed for external comparison carbon footprints, and a looser scope definition with optional data entries was designed to include a more complete life cycle for internal monitoring purposes.

For scope 1, the scope is defined identically for both internal monitoring and external comparison systems. It includes direct emissions from sevoflurane, isoflurane and desflurane anesthetic gases within the OR.

For scope 2, the scope is more precise, as only measured values of natural gas use for space heating are included. Non-HVAC electricity uses are excluded. In the internal monitoring system, this is expanded by including other electricity use and space heating non-measured values.

For scope 3, the external comparison system includes direct energy use for sterilization, medical product procurement and pharmaceutical procurement. In the internal monitoring system, this is expanded by including HVAC electricity and space heating gas use for sterilization, and the separating of medical product procurement into disposables, implants and other products procurement.

For a visual representation of these scopes, reference Figure 1 and Figure 2.

5.2 What are the CO2 footprints of services and goods yearly consumed by ORs?

The results of this study show that a clear definition of emission factors is very important to create a meaningful comparison, either between hospitals or between years. There is a large variation between the emission factors that can be used. There are no emission factors that perfectly describe the system of the use of an OR; there are only best substitutes. They are all flawed, and either underestimate or overestimate the real emissions. However, the strength of carbon footprint calculation lies not in the perfect accuracy of the calculations made, but in the comparisons that can be made with other hospitals or other years.

Such comparisons can only be made if there is a consensus on the emission factors used. The calculation tool presented alongside this report is proposed as a consensus for a calculation tool of Dutch OR carbon footprints. It is recognized that both the scope and the accuracy of emission factors are imperfect, but the usability and feasibility of data collection is deemed a worthwhile tradeoff. It is important to realize that this is not intended as a full-scale LCA study, but more an informing tool for policymaking. To this end, a realistic resource investment in the data collection is more important than the completeness of the system analyzed. Based on the results, the following emission factor model choices are made:

For scope 1 emission factors, GWP100 values were used for the carbon footprint tool (Sulbaek Andersen et al., 2010). While it is recognized that these may be an underestimation in the short term, GWP100 is the recommended time horizon since the Kyoto protocol for informing policy change (Qin et al., 2013). As this tool is designed to do just that, GWP100 emission factors are preferred above GWP20. GWP20 emission factors are therefore not included in the tool. The tool does allow for manual overrides of emission factors by inputting a deviating emission factor.

For scope 2 emission factors, more choices were available. For electricity use, the 2019 Dutch average mix is set as the default (Wernet et al., 2016). However, a custom emission factor can be entered to account for buying greener energy from electricity providers. For space heating, an emission factor for heat energy from natural gas is derived from the ecoinvent 3.6 life cycle inventory database (Wernet et al., 2016).

For scope 3 emission factors, sterilization energy use used the same emission factors as scope 2 emissions for electricity and heat production. For steam production, emission factors were derived from ecoinvent 3.6 (Wernet et al., 2016). For the procurement of disposables, implants and pharmaceuticals emission factors based on expenditures including scope 3 emissions were used (de Graaff & Broeren, 2018). Based on the same study, emission factors for average medical products and other medical products were derived (de Graaff & Broeren, 2018).

All of the emission factors used in the tool can be found in Appendix 1.3.

5.3 What are the consumed goods and services and how can data on the use of these within Dutch OR departments be repeatably collected?

Trial questionnaire responses on all processes except anesthetic use were very limited. From environmental coordinator feedback, this was mostly due to the unprecedented workload experienced by hospital employees due to the Covid-19 outbreak. This was a factor beyond the control of this study.

However, environmental coordinators also experienced difficulties with collecting data due to a lack of specificity in scope definition, or resources required to prepare or calculate data points. These have been dealt with by improving the data collection procedure, and separating the internal monitoring and external comparison systems.

5.4 How can the results of the calculations be reported transparently and effectively to hospitals?

For each of the scopes, it is explored whether conclusions can be drawn from the data of the data collection trial. As seen in the results, there have been a mixed number of responses for each scope, so conclusions are limited in some cases.

5.4.1 Scope 1: Inhalation anesthetics

Results showed that the use of inhalation anesthetics in most hospitals is responsible for between 30 and 180 ton CO2-eq emissions. Normalized, this varies from 3 to 9 kgCO2-eq per procedure. The reason for this variability stems mainly from the differences in inhalation anesthetic use. The LUMC hospital has reduced the use of inhalation anesthetics, and increased the use of intravenous anesthetics. Additionally, isoflurane and desflurane use have been phased out. The other hospitals still use these gases, which drastically increases their emissions due to anesthetics. On average, an emission of around

80 ton CO2-eq annually, or about 4 kg per procedure, can be saved by adopting anesthetic use practices similar to the LUMC hospital.

5.4.2 Scope 2: HVAC electricity

Results showed that electricity use for HVAC in all tested hospitals is similar to the electricity use at the LUMC. This indicates that all these hospitals are using older systems that run 24 hours per day. Modern systems can be turned on or off based on occupancy of OR's, saving electricity for the OR's that are not used during the nights or weekends. Assuming HVAC systems can be turned off for 8 hours a day on average, this would result in 33% emission savings for these hospitals. This would save between 96 and 233 ton CO2-eq per hospital.

5.4.3 Scope 2: Space heating

Reported space heating results did not hold enough reliable information to draw conclusions.

5.4.4 Scope 3: Sterilization

Results showed a carbon footprint of between 20 and 23 ton CO2-eq per operation room per year for the hospitals that submitted data. While this is a smaller emission than the emissions for disposable products, it does show that reusable products also have their associated emissions.

5.4.5 Scope 3: medical products

A an annual average carbon footprint of 94 ton CO2-eq associated to disposable production per operation room was observed in the results. While there is no indication in this study of the proportion of reusable versus disposable products used in the operation room, it seems obvious that disposables are more emission intensive. On a hospital annual basis, on average 1720 ton CO2-eq emissions are due to disposables.

Similarly, the production of implants adds another 1920 ton CO2-eq emissions to this. These cannot be replaced by reusable products, such as disposables might be. However, sustainable procurement and reduction of discarded implants may reduce this emission.

5.4.6 Scope 3: pharmaceuticals

Results showed an annual average footprint of 490 ton CO2-eq emissions per hospital. While pharmaceutical use in the OR is inevitable, it should still be realized that they cause a burden on the environment. Medical success will always be the priority, but special care should be taken in reducing the use of pharmaceuticals. Pharmaceutical waste should be reduced as much as possible and sustainable procurement can also reduce this emission.

5.4.7 Data visualization in the carbon footprint tool – internal monitoring

As can be seen in Figure 10, changes in total emissions as well as changes in process emissions can be monitored. For example, in the invented data the LUMC makes a switch from grey energy to their current energy mix, which decreases the electricity emissions. The use of disposables is gradually increasing, which can be seen in the visualization. This kind of information can be used in two ways:

- Big emission contributors can be identified and tracked to check if they are increasing or decreasing. This can incite targeted policy changes
- The effects of such policy changes can be tracked over time

5.4.8 Data visualization in the carbon footprint tool – external comparison

As can be seen in Figure 11, the external comparison visualization offers less detailed emission results than the internal monitoring visualization does. This is due to the decreased scope and separation of processes that had to be carried out to make data comparable. If data collection quality increases, figures more akin to the internal monitoring visualization could be possible. This can be achieved by installing OR-specific and sterilization department-specific electricity and gas meters, and by adapting procurement information systems to allow for extraction of categorized data.

However, it must also be taken into account that while the current external comparison system reduces scope and detail, it enables the direct comparison of different hospitals. Therefore, it is also a useful tool as it can be used to:

- Compare total emissions and contributing processes to other hospitals to identify large emissions within a specific hospital
- Hospitals with less emissions for certain processes can be interviewed, and their practices and solutions can be used in the other hospital and vice versa

5.5 What differences do different calculation methods for greenhouse gas emissions of Dutch OR departments make?

Different calculation methods have been identified in the methods section. They were all tested in the sensitivity analysis. Based on theoretical differences, sensitivity results, and data collection practicalities it was decided which methods were most suited to be used in the tool. These are summarized in Appendix 1.3 and are used in the tool (Appendix 1.6).

5.6 Sensitivity to system definitions

5.6.1 Sensitivity to use of internal monitoring system and external comparison system

The sensitivity analysis results showed that the system definition change from internal monitoring to external comparison only changed the total emission results by 8% (Figure 15). However, as the emissions due to medical products production is higher in the external monitoring system than it is in the internal monitoring system, the reduction of included emissions in the other processes is partly masked. Not counting the product emission, in a system where gas use is not measured, the reduction of the total emissions is 40%. This is mainly due to the exclusion of space heating in the scope, which accounts to 75% of this reduction. If space heating is measured, the reduction is only 10%.

It can be concluded that the external monitoring system does an adequate job of estimating total annual OR emissions, and of its contributing factors. However, if more detailed conclusions are required, the internal monitoring system is recommended. Especially emissions related to space heating and product procurement can be assessed in more detail when using this system definition. For emissions related to sterilization, the same applies but to a lesser extent as the majority of its energy use is evaluated in both the external comparison and internal monitoring system.

5.6.2 Sensitivity to use of GWP20 vs GWP100

The use of GWP20 compared to GWP100 on average led to an increase in impact scores. This indicates that, on average, gases with a shorter atmospheric lifespan than CO2 are emitted. Using GWP20, the impact scores of anesthetic gases increased by 255%, compared to 11%, 10% and 16% for the other categories. In total, annual impact scores per operation room increased between 15 and 30 ton CO2-eq (LUMC and Hospital C respectively). This is significant, as the total impact score per operation room for the LUMC is about 300 ton CO2-eq annually. However, these increases are expected in all processes. Relative changes are more important to consider in this context. The relative increase of anesthetic gas emissions indicates that in the medical context, some care must be taken with the selection of the emission impact time horizon. In shorter time horizons, anesthetic gases will have a much larger relative impact.

5.7 Sensitivity to emission factor choices

5.7.1 Sensitivity to the use of electricity mix emission factors

As can be logically expected, the electricity mix emission factor is highly influential in determining the emissions associated with electricity use. It can be seen in Figure 17 that both hospitals can save around 10 ton CO2-eq emissions per operation room by switching from their current provider to green energy. Using the 2018 Dutch average mix as a default, the electricity mix emission factors can induce a change of -4% to +7% to the total hospital emissions. This is a significant change, but it is a logical consequence of buying grey or green energy. Use of the emission factor of the Dutch average mix is recommended. However, if green energy is bought or the energy provider provides a cradle-to-gate life cycle emission factor for their specific electricity, this may be used in favor of the Dutch average.

5.7.2 Sensitivity to use of pharmaceuticals using different economic emission factors

The difference between the emissions calculated with emission factors from de Graaff & Broeren (2018) and Belkhir & Elmeligi (2019) are about -80%. This conforms to the expectations of scope 3 emission proportions found in the literature review. It exemplifies the importance in choosing emission factors carefully, and making sure it encompasses the scope that matches the research. Once again, due to this difference the emission factors from de Graaff & Broeren (2018) are used in the tool. These include scope 3 emissions.

5.8 Sensitivity to consumption data collection choices

5.8.1 Sensitivity to use of economic emission factor of product use vs factors from waste audit

As expected, emissions for product use are much lower (84%) when using the Belkhir & Elmeligi expenditure emission factor, as this does not include scope 3 emissions. This agrees with the numbers found in the literature review. Emissions calculated from the waste data using emission factors from MacNeill et al. are similar, and are much lower than the emissions that are specific to the medical industry. Implants are not taken into account here, as only products that end up in the waste streams described are. Observed differences between factors from waste audits and economic emission factors are large. There is no published work to indicate the difference in emissions per kilogram product between the medical and average industry. However, it is known that the pharmaceutical industry is very pollutant, in both research and development phase as well as the production phase (Belkhir & Elmeligi, 2019). All of these emissions are included in the de Graaff & Broeren emission factor, while only production emissions are taken into account in the MacNeill et al. emission factor. The model is very sensitive to changes in this emission factor, as emissions due to the production of products are the largest contributor to total emissions for all hospitals that submitted data. The emission factors based on de Graaff & Broeren (2018) seem to be the only ones that are specific to the medical industry and include all scopes. The emission factor seems to agree with the available, though limited, literature. Additionally, it requires procurement expenditures instead of waste volume data. As procurement expenditures are easier to collect, this is another argument for using this emission factor. Combining all these arguments, calculation of emissions due to product use is recommended by using procurement data in combination with emission factors from de Graaff & Broeren (2018).

5.8.2 Sensitivity to energy use of sterilization vs factors from kg product sterilized

A 13% reduction was observed when using the weight of the product sterilized. While this opposes the expectations, both calculations are very similar considering they are calculated completely separately. The differences observed could be caused by a number of reasons; the calculation methods stem from different sources. For the calculation through the weight of sterilized material, the energy requirements are calculated for a system that electrically heats water to steam. Additionally, it is mentioned that about 40% of the energy use is made during idling. The average load mass in this system is also much larger (21.2kg vs 4.5kg) which could explain efficiency differences. Generally in industry, scaling up means increased efficiency. Thus, the differences could be caused by efficiency differences in energy source, idling time and load mass. A 13% difference due to these factors is understandable. As differences such as the ones observed can be prevalent, it is recommended to use real (measured or calculated) energy use at location.

5.8.3 Sensitivity to energy use of economic estimation vs factors from kg pharmaceuticals

A 79% reduction of emissions was found when using the mass-based calculation method versus the spend-based calculation method. Such a reduction is possible, as emissions made outside of the production process of the API are not taken into account. However, this reduction was only valid for the 7 selected pharmaceuticals, using the average found by Belkhir & Elmeligi (2019). When zooming in on individual pharmaceuticals large differences, up to a factor 50, were found. There seems to be no relation between the cost of pharmaceuticals and the weight of the API, and therefore such discrepancies are found. It is likely that both methods align when using a larger subset of pharmaceuticals, ideally the same subset that is produced by the pharmaceutical companies is used to calculate spend based emission factors. At this moment, it is not possible to conclude what causes these differences and how accurate both numbers are in relation to each other. As the scope of the spend based factors aligns better with the goal of this study, the use of these is highly recommended.

5.9 How can these greenhouse gas emission calculations be used to decrease greenhouse gas emissions of Dutch OR departments?

This work offers a limited insight in the emissions of OR departments due to limited acquired data. However, some hotspots can be identified for improvement within Dutch OR's

- Anesthetic use is a relatively small emission for most hospitals, but when considering a shorter time horizon these become much more relevant. Changing the use of anesthetic gases is a relatively simple improvement that can save around 80 ton kgCO2-eq annually for each hospital on average, or about 4 kg per procedure.
- Scope 2 emissions are highly dependent on the electricity emission factor. As most hospitals buy (partly) green energy, this does not show very high emissions. It only shows that buying green energy is very positive when reducing carbon footprint. Switching from the Dutch average to Dutch wind energy, it saves between 700-900 ton CO2eq per hospital annually. Per operation, this is between 60-80 kg CO2eq. Still, energy use reduction is even better.
- Scope 3 emissions dominate the carbon footprint of the OR. Especially the use of disposables and implants are very large contributors to the total emission. Based on this, replacing

disposables by reusable products and reducing waste in general is a favorable progression. Sustainable procurement may also decrease the real contribution of scope 3 emissions. Small changes can make large differences; only a 10% reduction in disposables use can save between 150-240 ton CO_2-eq annually, or between 11 and 22 kg CO_2-eq per procedure.

The tool itself also offers possible pathways to improvement, by using the internal monitoring functionality, hospitals can:

- Identify and track large emission contributors within their OR, in order to check if they are increasing or decreasing. This can incite targeted policy changes.
- The effects of such policy changes can be tracked over time.

The internal monitoring system is more complete and more detailed than that of the external comparison system, but cannot be compared with other hospitals.

Apart from the internal monitoring functionality, the external comparison functionality can be used to:

- Compare total emissions and contributing processes to other hospitals to identify large emissions within your own hospital.
- Hospitals with less emissions for certain processes can be interviewed, and their practices and solutions can be used in your own hospital and vice versa.

However, the external comparison system is less complete and less detailed than the internal monitoring system.

Ideally, the internal monitoring system and the external comparison system should be the same. Currently, this was not possible due to large differences in data availability from different hospitals. Both technical as well as systemic differences were observed. If these differences are resolved, for example by installing energy use measurements or by improving information systems, both systems could be unified and a more detailed external comparison could be realized. It would also simplify the data gathering process and subsequently the use of the tool, thereby increasing its use. There are currently promising plans to continue this research and data collection, both from academics as well as from environmental coordinators at hospitals.

Additional Information

Appendix 1.1

Emission factor calculations for processes based on sector CO2 disclosure

code	Unit process	Spend on category in euro (sum of hospitals, 2018)	Emission factor in CO2eq/euro	Emission due to spend (kgCO2)
A	Medical equipment production	€ 688.122	0.14	96337
B	Diagnostics production	€ 154.071	0.225	34666
C	Reusables production	€ 1.902.380	0.14	266333
D	Disposables production	€ 15.174.486	0.34	5159325
E	Implants production	€ 13.058.462	0.45	5876308

Emission factors are based on (de Graaff & Broeren, 2018). Annual spends are based on LUMC 2018, Hospital A 2018, and Hospital E 2018 data.

Emission factor of average product was calculated by dividing the total emission of codes A, B, C, D and E over the total spend of those same codes. (=0.369 kgCO2eq/euro)

Emission factor of other product use was calculated by dividing the total emission of codes A, B and C over the total spend of those same codes. (=0.145 kgCO2eq/euro)

See also: Appendix_1-1_Products_EFs.xlsx

Appendix 1.2

Questionnaire and approached hospitals

Approached hospitals round 1	Approached hospitals round 2
UMC Utrecht	Antoni van Leeuwenhoek Amsterdam
Radboud UMC Nijmegen	Tergooi Hilversum/Blaricum
VU MC Amsterdam	OLVG Amsterdam
AMC Amsterdam	Sint Lucas Andreas Amsterdam
Maastricht UMC	MeanderMC Amersfoort
Erasmus UMC Rotterdam	Rijnstate Arnhem
UMC Groningen	Diakonessenhuis Utrecht
	MCL Leeuwarden
	Alrijne Leiden

Appendix_1-2_Questionnaire.docx

Appendix_1-2_Questionnaire.xlsx

Appendix 1.3

Summary of all processes, input units and emission factors used in this study

Appendix_1-3_Data_inputs_EFs.xlsx

Appendix 1.4

Summary of all data collected during the data collection trial

Appendix_1-4_Trial_Data_collected.xlsx

Appendix 1.5

User's guide to the tool

Appendix_1-5_Users_guide.pdf

Appendix 1.6

The tool developed during this study

Appendix_1-6_Carbon_Footprint_Tool.xlsm

Appendix 1.7

Example of categorization of procurement data

Appendix_1-7_Procurement_Categories_Example.xlsx

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