MASTER THESIS

MITIGATING ENVIRONMENTAL IMPACTS OF SURGICAL PRACTICES IN A DANISH HEALTH CARE CONTEXT

AALBORG UNIVERSITET

STUDENTERRAPPORT

Environmental Management and Sustainability Science, Department of Planning

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Abstract:

The health care sector in Denmark, as well as on a global scale, is caught in a paradox where its efforts to ensure the health and well being of people lead to environmental impacts, which have damaging effects on human health. Surgical procedures are identified, through a state-of-the-art literature review, to be one of the most promising areas to achieve effective mitigation results to global warming. Circular transitions from single-use medical devices to reusable devices are a key strategy to achieve this. The case of the Regionshospital Nordjylland is chosen as the basis for investigating the research question of this thesis, which is:

What circular transitions are relevant to implement to improve the sustainability of the surgical consumption practices at the Regionshospital Nordjylland?

To answer this a consequential LCA of a routine laparoscopic hernia surgery at the hospital is conducted. Additionally, a qualitative assessment of the surgical consumption practices is made to define these practices and explore how they affect the potentials for implementing circular transitions. Based on the identified environmental footprint and main environmental impacts causing damage to human health, it is most relevant to transition the single-use drapes and gowns into their reusable alternatives. It is also recommended to further prepare the organization at the hospital with small scale incremental circular transitions and investments in the center of sterilization (SCT). Transitions towards a greater share of reusable devices will put pressure on the SCT, making it a high priority to ensure they acquire the necessary capacity both in terms of time, hands and capital goods.

Resumé

Den danske samt globale sundhedssektor er havnet i et paradoks hvor dets helbredende og forebyggende aktiviteter har negative konsekvenser for miljøet som kan medføre skadevirkninger på menneskers sundhed. Global opvarmning anslås som en af de største trusler mod menneskers sundhed på globalt plan, og sundhedssektoren står for en væsentlig andel af de globale drivhusgasudledninger. Gennem en state-of-the-art litteratur review er operationsområdet angivet som et af de kritiske punkter der er årsagen til en væsentlig del sektorens drivhusgasudledninger og affaldsproduktion. Cirkulære forandringsprocesser anses som en central strategi til at afværge de negative miljøpåvirkninger der skyldes produktforbruget på de danske hospitaler, herunder også operationsafdelingerne. Særligt forandringsprocesser fra engangs- til flergangsprodukter vurderes til at have det største potentiale. Med udgangspunkt i Regionshospital Nordjylland som case, undersøges der i dette speciale hvilke cirkulære forandringsprocesser der er relevante at implementere for at gøre forbrugspraksisserne i forbindelse med operationer mere bæredygtige. De miljømæssige påvirkninger og deres årsager kortlægges ved hjælp af en livscyklus analyse af en laparoskopisk brokoperation, der er en af de mest hyppige operationer udført på hospitalet, for at identificere hvilke produkter der har størst afværge potentiale. Derudover analyseres forbrugspraksisserne i forbindelse med en operation gennem en række interviews og observationer for at afdække hvordan disse påvirker mulighederne for at implementere cirkulære forandringsprocesser.

Resultaterne fra livscyklusanalysen viser at de primære miljøpåvirkninger stammer fra forbruget af engangsprodukter, særligt engangskitler og -afdækning samt plastemballage, og affaldshåndteringen af restaffaldet. Dette medfører skadevirkninger på menneskers sundhed svarende til 4,97E-05 DALY, svarende til tabte sunde leveår, på grund af miljøpåvirkninger på luftkvaliteten, global opvarmning og akkumulering af giftstoffer i den menneskelige fødekæde. På baggrund af den kvalitative analyse af interviewene med forskelligt sundhedspersonale, der både er direkte og indirekte forbundet med produktforbruget på operationsområdet, er forbrugspraksisserne defineret i forhold til deres bagvedliggende opfattelser, motivationer og en postfænomenologisk forståelsesramme af menneske-teknologi relationer.

Heraf kan det konkluderes at engangskitler og -afdækning er mest relevante at omstille til flergangsalternativer, men at yderligere tiltag er nødvendige for at modne hospitalet organisatorisk til at kunne implementere opskalerede cirkulære forandringsprocesser. Dette kan gøres ved at lave flere mindre omstillingsprojekter, vidensdeling og formidling af bæredygtighedsfremmende projekter på tværs af Regionerne samt investeringer i hospitalets sterilcentral.

Mitigating environmental impacts of surgical practices in a Danish health care context

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Abstract The health care sector in Denmark, as well as on a global scale, is caught in a paradox where its efforts to ensure the health and well being of people lead to environmental impacts, which have damaging effects on human health. In this thesis the surgical procedures are identified to be one of the most promising areas to achieve effective mitigation results to global warming, based on a state-of-the-art literature review. Circular transitions from single-use medical devices to reusable devices are a key strategy to achieve this. The case of the Regionshospital Nordjylland is chosen as the basis for investigating the research question of this thesis, which is:
What circular transitions are relevant to implement to improve the sustainability of the surgical consumption practices at the Regionshospital Nordjylland?
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Acronyms

CE circular economy

DALY Disability-adjusted life years

GHG Greenhouse gas

LCA life cycle assessment

MIS minimally invasive surgery

OR operation room

SCT center of sterilization

SUD single-use medical devices

1 Introduction

Climate change poses a great threat to the global health and is expected to lead to an increased number of death caused by the rising temperature driving an expansion of disease vectors and spread of viral and bacterial infections as well as heat stress and malnutrition (D'Alessandro et al., 2024; Rizan et al., 2020; Cunha and Pellino, 2023; WHO, 2022). Besides posing a risk to health, climate change may also be a barrier to health promotion with risk of infrastructure break downs due to extreme weather (Drew et al., 2021; Cunha and Pellino, 2023; WHO, 2023). This will especially be the case for developing countries and low income populations, where mitigating the consequences of climate change is hampered by environmental and economical conditions (Thiel et al., 2017; WHO, 2023). This is further problematized by the paradox of the health care sector itself being a significant cause to climate change, as the sector was responsible for 4.4 % of global Greenhouse gas (GHG) emissions in 2014 (Karliner et al., 2019). Moreover, the impacts of the sector are larger in high income countries and are considered a necessary cost to the delivery of quality care (Talibi et al., 2022; Karliner et al., 2019).

Within the sector, surgery is one of the activities causing most GHG emissions and generating most waste (de'Angelis et al., 2023; Cunha and Pellino, 2023; Rizan et al., 2020). The main processes leading to this are the energy use for maintaining the operation room (OR) environment (heat, ventilation and air-conditioning), anesthetics, pharmaceuticals and con-

sumption of medical devices, especially single-use medical devices (SUD) (de'Angelis et al., 2023; Rizan et al., 2020; Drew et al., 2021; Friedericy et al., 2022). de'Angelis et al. (2023) indicate that the majority of waste related to the OR is generated before the surgical procedure in the preoperative period. Some of the common waste types connected with OR are SUD, personal protective equipment, drapes and plastic wrappers (de'Angelis et al., 2023). Additionally, the OR is among the most energy-intensive sites on a hospital, consuming three to six times more energy than the rest of the hospital as a whole (Rizan et al., 2020). Thus, Drew et al. (2021) identifies surgical and anesthetic care to be the most promising areas to achieve effective mitigation results to global warming within the health care sector.

2 Problem analysis

D'Alessandro et al. (2024) show that there has been an increase in academic interest in how circular economy (CE) is and can be implemented in health care since 2016. These studies have a predominant focus on waste management by implementing the R-strategies (refuse, reduce, reuse, recycle, etc.), which can be explained with waste being the most visible form of environmental impact of the sector (Thiel et al., 2015). Health care waste has also been rising during recent decades caused by a growth in demand of health services and increasing use of SUD (van Straten et al., 2021). Medical device companies have developed their business models to ensure the lowest barrier of use for practitioners in the health care sector, promoting the consumption of SUD's (KPMG, 2023). This consumption trend is further pushed along with the technological development and introduction of minimally invasive surgery (MIS). The patient benefits of MIS are currently at the cost of a number of high technological SUD which have followed in the wake of MIS, and studies have indicated that they may have larger environmental impacts compared with traditional open surgery (Woods et al., 2015; Thiel et al., 2015; Cunha and Pellino, 2023), however these studies do not consider the post-operative period.

Stainless steel is a valuable resource and one of the most used and recycled metals, as it does not loose any of its key properties during recycling, and is beneficial both in terms of economic, resource and energy savings (Johnsona et al., 2008; Yellishetty et al., 2011). However, this is rarely the case for stainless steel surgical devices used in health care despite significant environmental and cost saving potentials (van Straten et al., 2021; Enzor and Pierce, 2012). The EU Medical Device Regulation states that devices must be disposed of in a safe manner validated and described by the manufacturer in the instructions for use. Thus, to enable circular pathways for the devices, including recycling, this must be reflected in the instructions for use. Often these instructions only cover how to clean and recycle the batteries of SUD but not the device itself (KPMG, 2023). Clarity on the preparation for recycling is important for how the waste may be classified and thus its possibilities for recycling (KPMG, 2023).

Recycling, however, is only one of many pathways to achieve a CE, which can be defined as a regenerative system that retains and maximizes the intrinsic value of material resources as well as minimizing waste and pollution (Ellen MacArthur Foundation, 2021). The primary CE strategies are shown in figure 1. Jørgensen et al. (2018) argue that CE strategies mainly focused on closing resource flows, like recycling, will have limited value. Instead resource efficiency is better ensured by focusing on the slowing and narrowing strategies, like reuse and refurbishing (Jørgensen et al., 2018).

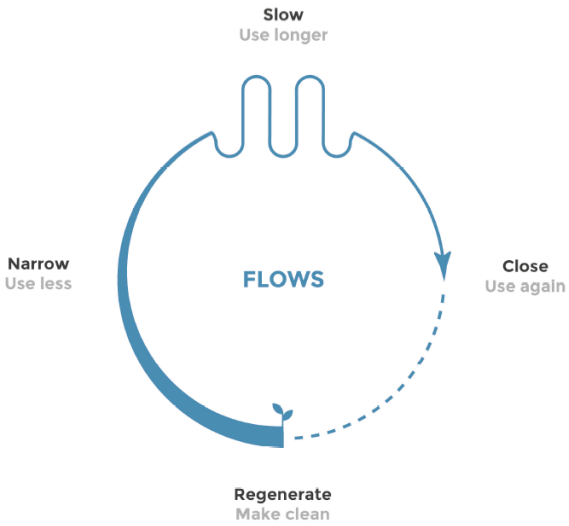

Figure 1: Circular economy strategies of narrowing, slowing, closing and regenerating resource and energy flows, by (Konietzkoa et al., 2020).

Moreover, the environmental impacts of health care and surgery have also been under increased academic scrutiny in recent years. Several life cycle assessment (LCA) and carbon footprinting assessments have been made for different types of surgical procedures in addition to a variety of medical devices (de'Angelis et al., 2023; Drew et al., 2021). LCA is an established method for identifying and validating environmental impacts of products and processes across all life cycle stages from cradle to grave. Thus, LCA can be applied in various ways as a tool to support decision-making in sustainable product designs and developing mitigation strategies. Additionally, an LCA can also be used to estimate the resulting damages to human health due to various

environmental impacts. For example, Eckelman et al. (2020) finds that the activities of the health care sector resulted in approximately 388.00 Disability-adjusted life years (DALY) in 2018 in the US due to particulate mater formation, ozone pollution and GHG emssions.

A state-of-the-art literature review conducted in connection with this thesis identified nine studies done on various surgical procedures, with only four of these being actual LCA's. However, several of these studies find remarkably different results, which is due to a large difference in scope, detail and methods used across the studies. For example, (de'Angelis et al., 2023) found cataract surgery to be one the most studied procedures with a carbon footprint ranging from 6-151.9 kg CO_2e. Many of the studies exclude pre- and postoperative processes, capital goods, water use, reprocessing of reusable medical devices as well as patient and staff travelling. There is a general lack of transparency of assumptions and some are also unclear about the functional unit. Thus, the external validity of these studies are compromised and they are unsuitable to make any general conclusions related to surgical practices in the Danish health care sector (Rizan et al., 2020).

2.1 The North Denmark Region

The efforts to de-carbonize this sector must be combined with disease prevention strategies to be effective in the long haul (MacNeill et al., 2021). Drew et al. (2021) argue that *"Minor incremental improvements in the system, however, are likely to be counteracted by the projected increase in demand for surgical services associated with population growth, aging demographics, the growing burden of chronic disease, the apparent rise of unnecessary procedures, and worsening impacts of planetary disruption on human health"*. This has already been the case in the UK where the growing demand for health services has offset carbon reductions efforts (MacNeill et al., 2021).

Similar trends are forecasted for the Danish health care sector, where a growing elderly population is linked to an increase in the number of chronic and complex diseases which consequently leads to increased demand, costs and pressure on the Danish health care sector. (Højgaard and Kjellberg, 2017; Lægeforeningen, 2022; Robusthedskommission, 2023). Thus, disease prevention strategies are instrumental to abate this projected development and can be argued to be an equally important part in the de-carbonization efforts as circular transitions and transitions to renewable energy. Lægeforeningen (2022) and Robusthedskommission (2023) also highlight the importance of prioritizing disease prevention as a means to manage the expected increase in demand of health services.

However, surgical procedures remain a relevant area to prioritize in mitigation efforts to reduce the carbon footprint of the sector. This is also expressed in the national strategy for reducing GHG emissions of the Danish hospitals by Danske Regioner (2024). The strategy highlights both the importance of transitioning to CE consumption practices and reducing GHG emissions and waste generated in the OR (Danske Regioner, 2024). The North Denmark Region is one of the five Danish regions who are part of this strategy. Besides this, the region also has its own climate goal of a 40% reduction of their GHG emissions in 2030 compared to 2018. The primary contributor to the Region's carbon footprint is the consumption of medical devices and products, which make up 45% of the total of 172.700 tons CO_2e in 2022 (Region Nordjylland, 2023). One of the Region's main strategies to reduce these emissions is to make circular transitions from SUD to reusable medical devices.

To assess mitigation potentials of circular transitions within the OR a consequential LCA will be conducted of the surgical practices of a routine MIS at the Regionshopital Nordjylland. One of the most common surgical procedures performed at the hospital is a hernia surgery which are done multiple times each day. Furthermore, this type of surgery is increasingly performed by laparoscopy which is a type of MIS. The LCA allows for the identification of hotspots that can help direct the strategic work in the continued pursuit of carbon reductions and improved sustainability of the health care services delivered by the North Denmark Region. Thus, the research question this thesis will attempt to answer is the following:

> *What circular transitions are relevant to implement to improve the sustainability of the surgical consumption practices at the Regionshospital Nordjylland?*

In this endeavour, these additional sub-research questions will assist to direct the analysis.

- What are the environmental and human health impacts and hotspots of a laparoscopic hernia procedure at Regionshospitalet Nordjylland?
- What defines the consumption practices of the health care professionals during a surgical procedure?
- How do these practices affect the potentials for implementing circular transitions in surgical procedures?

3 Conceptual framework

The ontological and epistemological basis of this thesis is founded in the postphenomenological branch of

theory of science. Postphenomenology is a philosophy of technology, which posits a close intertwining relationship between humans, technology and the world, where humans and technology shape each other (Ihde, 1990). The concept of technology from this perspective can be defined as artifacts of material culture which are not merely inert neutral matter (Ihde, 1990). Like with classical phenomenology, postphenomenology does not make claims of absolute truths nor the essence of an object. Instead claims rooted in this theory of science perspective are embodied and situational, based on empirical and practical matters (Rosenberger and Verbeek, 2015). Hence, postphenomenology represents a certain style of interpretation of the relations between science, technology and culture which investigates how humans are bodily-perceptually engaging the world through technology and how the relation between humans and technology constitute a specific *"world"* (Ihde, 1990).

Practice theory and be related to postphenomenology through the common element of human-technology interaction, as defined by Askholm and Gram-Hanssen (2022). Practice theory is a relevant framework to apply to explorative consumption studies, as it may shed light on the dynamics between agency and structure which condition the consumption practice (Jaeger-Erben and Offenberger, 2014). Practices can be described as different repeated habits and routines of doings and sayings which reproduce social structures and contributes with a sense of ontological stability (Gram-Hanssen, 2009). Hence, practices are socially shared, though each individual can be characterized as a carrier of practice (Askholm and Gram-Hanssen, 2022). Practices can be divided in two categories; dispersed and integrated practices. Dispersed practices are based on know-how, embodied habits and rules, whereas integrated practices are more complex and build on knowledge and teleo-affective structures (Gram-Hanssen, 2009, 2021). In general, the concept of practices are based on a series of elements, of which the most relevant for this thesis are:

- General understanding
- Teleo-affective structures
- Technologies (Askholm and Gram-Hanssen, 2022)

General understanding in theory of practice can be defined as that *"which lies across the tacit, the reflected and the embodied"* and encompass the notions of values, knowledge and beliefs which connect different practices (Askholm and Gram-Hanssen, 2022). Discourse is closely related to general understanding and can *"translate into practices by practitioners drawing on, miming from or arguing by them"* (Gram-Hanssen, 2021). Teleo-affective structures also play an important role in understanding what holds a practice together. The concept can be defined as what guides the practice towards a meaningful goal and is a defining aspect of the integrated practices (Gram-Hanssen, 2021).

Furthermore, changes in practice occur due to changes in the elements which hold the practice together (Askholm and Gram-Hanssen, 2022). In a case study by Gram-Hanssen (2009) on household standby energy consumption, knowledge, motivation and technological rearrangement were key elements for enabling changes in practice. However, the *"technology configurations and design and to housing arrangements combined with lack of motivation"* were the main reasons for a lack of change (Gram-Hanssen, 2009). This suggest that understanding the human-technology interaction is essential to determine the degree and scope of changes possible to enable in consumption practices. In line with this, agency is also a relevant aspect to analyse as the practitioners can have different types and limitations of agency to actually change their consumption practices. This is also argued by Sahakian (2014), who introduce the concept of material agency in relation to changing consumption practices, which shares the same ontological understanding of technology as postphenomenology.

Finally, the concept of sustainability is central to this thesis and answering the research question. This concept has become opaque due to its many different definitions and connotations, however, in this thesis it is defined according to the definition proposed by Morelli (2011) for environmental professionals. Thus, sustainability in this context refers to *"meeting the resource and service needs of current and future generations without compromising the health of the ecosystems that provide them"* (Morelli, 2011). The carrying capacity of ecosystem services systems are given a delineating role with this definition, however, it should also be recognized that compromising the health of ecosystems with pollution and disruptions may cause harm to human health and welfare of both current and future generations (WHO, 2022; European Environmental Agency, 24/4 2024). Hence, the definition is expanded to also include the relation to human health.

Together these theories and concepts constitute the conceptual framework of this thesis. The framework will be applied to conduct a qualitative analysis of the consumption practices of the health care professionals, and how the human-technology interactions may enable or block practice changes. The elements which define the practices of the health care professionals and their agency will thus be investigated to determine the barriers and opportunities for changes that can enable circular transitions.

4 Methods

4.1 Case study

The research question of this thesis will be investigated through a mixed-methods approach which combine both the quantitative LCA method with the qualitative methods of interviews and observations within the methodological framework of an embedded single-case study. Applying a single-case study method to this thesis research allows for a close examination of the situational phenomena and practical conditions which constitute the surgical practices and dictate the potentials and barriers for implementing circular transitions in a Danish health care context. Figure 2 illustrates how the case study framework is defined in this thesis and which methods are used to analyze the two units of analysis.

The context of the case is defined as the circumstances and possibilities for implementing circular transitions. This will be investigated by using the Regionshospital Nordjylland as a case, which can be characterized as a typical case since the hospital is representative of the 54 public hospitals in Denmark within the given context. Furthermore, sub-units of analysis allow for more extensive analysis and insight into the case, and as such two sub-units are chosen (Yin, 2014). The first unit of analysis explores where circular transitions can achieve the most effective environmental impact mitigation potentials for a laparoscopic hernia procedure. The other unit of analysis examines the product consumption practices of the health care professionals taking place during surgical procedures. By using an embedded case study approach there is an inherent risk of having a narrow focus on the sub-units, in effect reducing the overall case to the context instead of target of the study (Yin, 2014). This is deterred in this thesis by interviewing different actors from different positions in the organizational structure around the hospital, but all relevant in potential circular transitions, though they are not directly part of the surgical procedure nor the consumption practices.

4.2 Observations

A number of observations have been conducted in different settings, both as direct participatory observations during meetings concerning possibilities for circular transitions and non-participant observations of the product consumption and handling post-use during laparoscopic surgeries. The observations have provided a deeper insight into the practical interactions between the health care professionals and the technologies used in the OR. The surgical observations also allowed for primary data collection needed to conduct the LCA. Moreover, the observations of different meetings were also part of the author's professional activities as a student employee within the North Denmark Region. This position has assisted in providing contextual knowledge to the research regarding the development of the general sustainability agenda in the Danish regions, current circular transition projects conducted in the regions and organizational structure of the North Denmark Region. Field notes of the various observations can be found in appendix B.

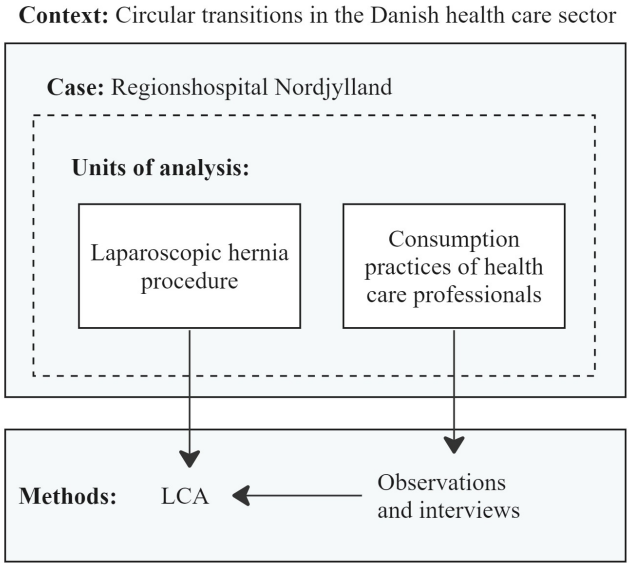

Figure 2: Embedded single-case study framework based on Yin (2014)

4.3 Interviews

Answering the research question of this thesis requires an understanding of the relations between the health care professionals and technologies used during surgical procedures, which a series of semi-structured interviews have helped to accomplish. Various health care professionals are directly and indirectly connected to the consumption practices taking place in the OR, thus a surgical nurse as well as reprocessing and infection control personnel have been interviewed. The surgical nurse interviewed, referred to as Søndergaard, has worked at the gastrointestinal surgical department at Regionshospital Nordjylland for six years and graduated as a nurse in 2012 after working many years in the medical sector. The second interviewee, Nielsen, is also educated as a nurse but has worked at the center of sterilization (SCT) since 1997. Lastly, Nielsen and Madsen both work in the infection hygiene department of the North Denmark Region after more than 19 years of working as nurses in different departments, including surgical departments. The interviews have been transcribed in an intelligent verbatim manner and can be

read in appendix C, D and E.

The focus of the interviews have been on identifying the general understanding, teleo-affective structures and agency of the interview participants, to analyze how the consumption practices can be changed to enable circular transitions and what barriers might exist.

4.4 System description

Hernia surgeries are a very common procedure at the hospital, and they are increasingly done by laparoscopy. Before the procedure starts the patient has been dressed in hospital clothes and shaved in the operating area. When the anaesthetic team has put the patient to sleep, the procedure begins with the nurses unpacking the reusable and SUD procedure packs, preparing all the instruments for the surgeon and sorting the packaging waste. The type of hernia operation studied for this thesis is an inguinal hernia, which have a duration of approximately 80 minutes of active surgery and lasts around 120 minutes from the patient arrive in the OR and leaving the OR. The procedure packs for an inguinal hernia consist of 36 individual SUD and 36 reusable devices, though there is some uncertainty to the extent and type of additional devices used for the procedure. The procedure begins with the patient's abdomen being insufflated with CO_2 and three trocar ports are inserted, through which the procedure is conducted. When the procedure is completed the SUD devices are sorted for waste treatment and the reusable devices are packed for reprocessing at the SCT at the hospital. The patient is sent to a ward for waking and can leave the hospital within the same day.

4.5 Goal and scope

To determine what type of circular transitions may improve the sustainability of the Regionshospital Nordjylland by mitigating environmental impacts, a consequential process-based LCA is conducted to identify these impacts and their causes. The LCA is based on the general structure of ISO 14040:2008 and includes all cradle-to-grave processes of the products used to perform a laparoscopic hernia procedure. Due to the limited activities performed pre- and post-surgery, the product system is confined to the operating activities in the OR, as shown in figure 3. Thus, the functional unit of this LCA is one laparoscopic hernia procedure.

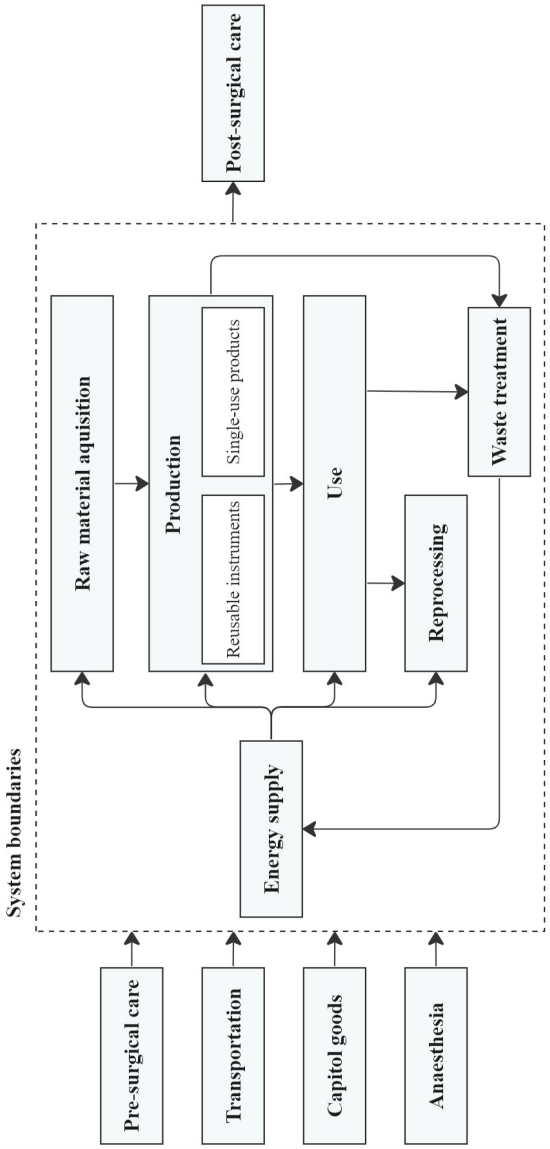

Figure 3: Product system and system boundaries.

With the definition of sustainability applied in this thesis, the relevant impact categories to report are as follows:

- Global warming potential
- Stratospheric ozone depletion
- Ionising radiation
- Ozone formation
- Fine particulate matter formation
- Human carcinogenic toxicity
- Human non-carcinogenic toxicity
- Damage to human health

These impact categories represent the environmental consequences which can cause damages to human health, measured in disability-adjusted life years (DALYs). The DALYs metric covers both the overall mortality and disease burden which lead to years lost in full health due to a specific cause (Institute for health metrics and evaluation, 15/5 2024). The impact pathways from the environmental impact to damages on human health are shown in appendix A.

4.6 Life cycle inventory

The impact assessment is performed with the software Simapro v9.5 and Ecoinvent v3.9 inventory database. To report on the above impact categories, the characterization method used is Recipe 2016 for both midpoint [H] and endpoint [H]. The different production processes chosen from the database are based on rest-of-world and global markets due to the long complex global supply chains of the sector.

The primary data is collected through a post-operative assessment of the products consumed which include weighing the reusable devices and a waste audit. It is assumed that 30L of CO_2 is used for the insufflation of the patient's abdomen, based on an estimation by the surgical nurse. Data concerning the reprocessing is collected through the manufacturers and interview with reprocessing personnel. The reusable devices are packed within two trays, and both the washing machine and autoclave can be loaded with a maximum of five trays at a time, hence only 2/5 shares of the reprocessing are contributed to the product system. Furthermore, the lifespan of the reusable devices are estimated based on LCA studies of similar products where the container and trays are estimated to last for 5000 uses (Friedericy et al., 2022), the simple instruments 4000 uses (Ibbotson et al., 2013) and the laparoscopic instruments 500 uses (Rizan and Bhutta, 2021).

The energy consumption of the surgical procedure is based on data supplied by the hospital for the climate accounting report for 2023, and thus covers the whole hospital for a one year period. Similar studies have previously calculated the energy consumption based on the proportion of the area of the OR and duration of the surgery, multiplied by a factor of two due to the generally high energy consumption of the OR (Morris et al., 2013; Power et al., 2012).

The primary data is summarized in table 1 and a more detailed account of the composition of the product categories is provided in table 2 along with the source used to model the product composition. Data regarding small product attributes like tape, labels and pigments have not been possible to gather and are also considered negligible in this inventory analysis.

Product	Weight (kg)	Share of total product consumtion/ waste generation
Reusables	9,615	67% / 0%
Plastic	0,666	5% / 14%
Paper	0,368	3% / 8%
Hazardous	0,121	1% / 3 %
Solid waste	3,575	25% / 76%
Total	14,345	

Table 1: Product and waste fractions weight and distribution.

Category	Description	Sources
Reusables	- Container (2,967 kg) - Blue wrap (0,199 kg) - Simple instruments — Clamps — Scissors — Forceps - Laparoscopic instruments — Cable diatermi monopolar — 5 handles — 5 inner pieces (scissor, clamps) — 5 outer pieces	Container: (Friedericy et al., 2022) Blue wrap: manufacturer Simple instruments: (Ibbotson et al., 2013) Laparoscopic: (Rizan and Bhutta, 2021)
Plastic	Packaging	Material composition report of plastic packaging at Aarhus Universitetshospital (2017)
Paper	Packaging	Based on observation
Hazardous	3 syringes, needles, medicine glass bottle, 3 trocar ports (60g)	Trocar ports: (Rizan and Bhutta, 2021) Syringes: (Honkoop, 2022)
Solid waste	Drapes (10,18 m2), gowns, personal protective equipment, tube, respiration bag, packaging, tissue	Tube: (Liang, 2019) Gloves: (Rizan et al., 2021) Masks: (Rizan et al., 2021) Drapes: (Tobin, 2022) Gowns: (Tobin, 2022)

Table 2: Overview of the product consumption and the respective sources used to substantiate the estimations of the material composition in the reference model.

4.7 Sensitivity analysis

The life cycle inventory analysis is based on a number of assumptions and estimations, which have been necessary due to a lack of detail in the primary data. For this reason a comprehensive sensitivity analysis is conducted to evaluate the influence of these assumptions on the impact assessment results. The sensitivity analysis includes several evaluations of different material composition distributions of the laparoscopic instruments, miscellaneous waste and plastic waste fraction. To do this, the particular system process is modelled based on alternative LCA studies to the ones used in the reference model.

The estimations of energy consumption are associated with a high degree of uncertainty, and is thus part of the sensitivity analysis as well. The sensitivity is assessed by modelling the energy consumption of the OR to be twice as large as what has been calculated.

Moreover, it has not been possible to acquire accurate information of the origin of the products used during the surgery, which is why transport is outside the system boundaries. However, this is a potential process hotspot due to the global supply chains of medical products, and thus the sensitivity analysis also features an estimation of the degree of impacts caused by transport. This is done by using four of the common suppliers as a proxy to represent the suppliers for the products consumed during the surgery, and applying the CERDIseadistance database (Bertoli et al., 2016) to identify the transport distances.

5 Results

5.1 Life cycle impact assessment

The results of the impact assessment are presented in figure 4, figure 5 and the distribution of impacts are summarized in table 3. These show that the primary hotspot of one laparoscopic hernia surgery is the consumption of SUD, which account for an average share of 82% of the impacts across all impact categories. The following waste treatment of general municipal solid waste is also one of the main hotspots for the human carcinogenic and non-carcinogenic impact categories. Reprocessing of the reusable instruments in the SCT and energy consumption in the OR also account for a noticeable share of the environmental impacts, whereas the consumption of reusable instruments, medicine and CO_2 used for insufflation are shown to have negligible impacts.

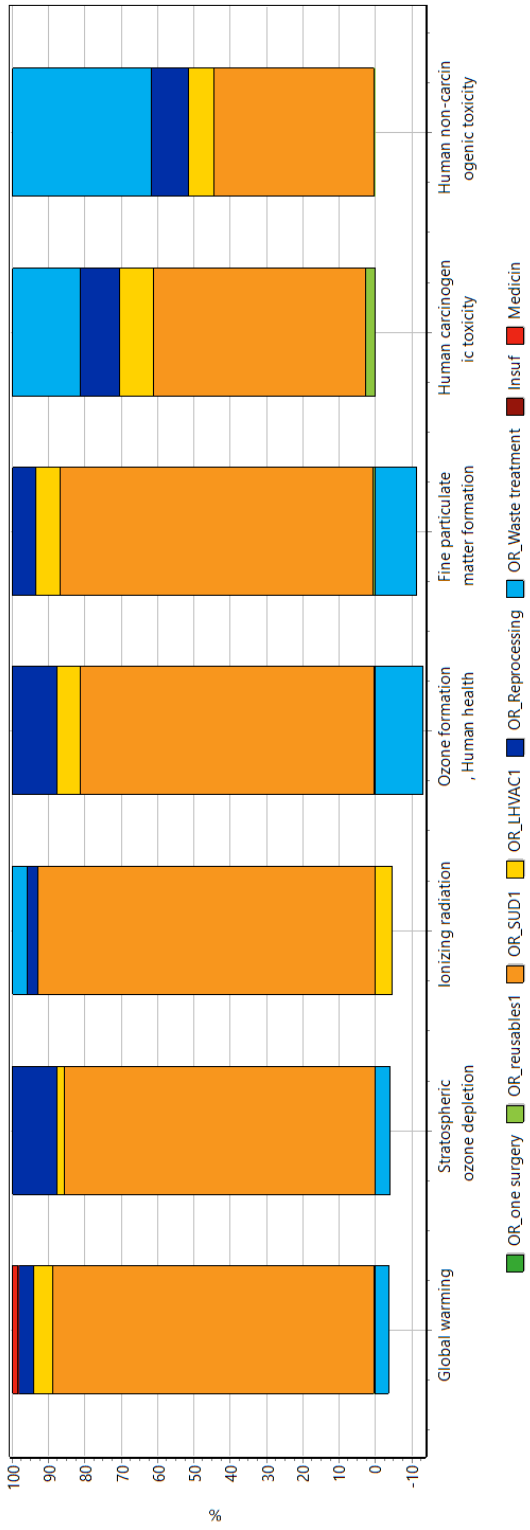

Figure 4: Life cycle impacts assessment midpoint characterization results for one laparoscopic hernia surgery.

The environmental footprint of one laparoscopic hernia surgery is mainly comprised of 20 kg CO_2e, 0,03 kg PM2,5 and a total of 35 kg 1,4 DCB. A network analysis show that these emissions are caused by the production of packaging film, viscose fibres for the single-use drapes and non-woven polyester for the single use surgical gowns, see figure A.32 in appendix A. Consequently, these environmental impacts lead to damages to human health, primarily due to air pollution from fine particulate matter formation, which can give respiratory symptoms and lung damage. However, global warming and human non-carcinogenic toxicity are also some of the main causes of damage to human health as increasing temperatures will change disease distribution and create extreme weather events and the accumulation of human toxicities in the human food chain will lead to increased disease incidents, see figure A.1 in appendix A. Overall the damages to human health from one laparoscopic hernia surgery correspond to 4,97E-05 DALY. On a yearly basis this will correspond to approximately 0,02 DALY, assuming that this type of hernia surgery is done twice a day, four days per week for 52 weeks.

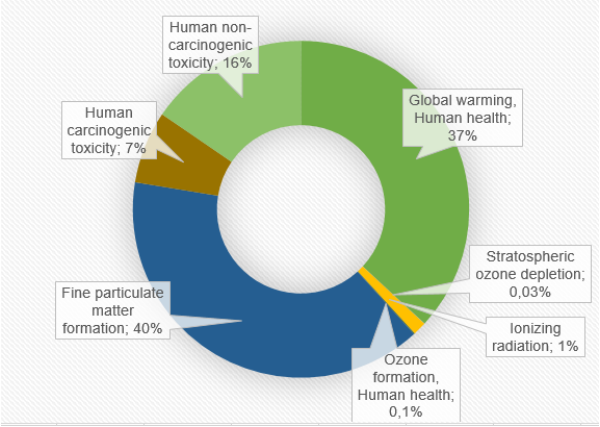

Figure 5: Distribution of DALY endpoint life cycle impacts assessment characterization results for one laparoscopic hernia surgery.

Impact category	Unit	Total	Reusables	SUD	LHVAC	Reprocessing	Waste treatment	Insufflation	Medicine
Global warming	kg CO2 eq	19,9	0,08	18,3	1,09	0,8	-0,8	0,06	0,3
Stratospheric ozone depletion	kg CFC11 eq	2,5E-05	3,7E-08	2,2E-05	5,0E-07	3,2E-06	-1,0E-06	N/A	N/A
Ionizing radiation	kBq Co-60 eq	0,8	2,1E-04	0,7	-0,04	0,2	0,03	N/A	N/A
Ozone formation, Human health	kg NOx eq	0,05	1,8E-04	0,04	3,3E-03	6,4E0-3	-6,8E-03	N/A	N/A
Fine particulate matter formation	kg PM2.5 eq	0,03	2,1E-04	0,03	2,4E-03	2,3E-03	-3,9E-03	N/A	N/A
Human carcinogenic toxicity	kg 1,4-DCB	1,05	3,0E-020,03	0,6	0,1	0,1	0,2	N/A	N/A
Human non-carcinogenic toxicity	kg 1,4-DCB	33,9	0,1	14,9	2,4	3,5	12,9	N/A	N/A

Table 3: Life cycle impacts assessment midpoint characterization results for one laparoscopic hernia surgery.*LHVAC* refers to light, heat, ventilation and air-conditioning.

5.2 Sensitivity analysis

The sensitivity analysis is composed of five alternative models of the product system, where adjustments have been made to one of the system processes. The results of the sensitivity analysis is depicted in figure 6, and in appendix A.4. The model which shows the overall greatest effect on the impact results is the inclusion of transportation from suppliers to the Regionshospital Nordjylland, which increased the total impact results with an average of 10%. Thus, the activity of transport can be considered an important element to include in an LCA for this type of product system.

The results of the impact assessment show less sensitivity to the other models where doubling the energy consumption produces an average increase of impacts of 5%, which is also the case for changing the material composition of the plastic waste fraction. In the reference model it is polyethylene high and low density granulates which make up the largest share of the of the plastic waste fraction, compared to the sensitivity model where these two make up the smallest share, and polypropylene and polyethylene terephthalate granulates and nylon make up the largest share.

The impact assessment results show the least degree of sensitivity towards model changes to the material composition of the laparoscopic instruments, which lead to an overall average decrease of 0.3%, and the single-use drapes and gowns, which correspond to an an overall average decrease of 3%. The sensitivity model of the laparoscopic instruments is based on an LCA study by López-Muñoz et al. (2023) of endoscopic instruments and a study by Boberg et al. (2022) on different trocar systems. Both the material inputs, and number of inputs, of these instruments vary between the reference and sensitivity model. Likewise, the source used to substantiate the estimation of the material composition in the reference model is based on Rizan and Bhutta (2021), who uses data from the manufacturer to model their laparoscopic instruments. Boberg et al. (2022) have used estimated data based on information from similar products to model their single-use trocar system and López-Muñoz et al. (2023) uses direct measurements to determine the material properties of the endoscopic instruments.

Moreover, the sensitivity analysis of the drapes and gowns are based on information from the manufacturer's own product brochure and an LCA study by Vozzola et al. (2018) which uses market representative product averages in their modelling. However, the reference model is based on a study by Tobin (2022) which has been conducted in collaboration with the drape and gown manufacturer, who are the same manufacturer to the products used in the laparoscopic hernia surgeries in Regionshospital Nordjylland. Consequently, the material composition of the different sources are likewise very different in scope and detail. Among others, the viscose fibres of the drapes in the reference model, which carry a high degree of the environmental impacts, is substituted with non-woven polypropylene and polypropylene granulates. Moreover, the non-woven polyester of the gowns in the reference model, which also carry a high degree of the impacts, are lower in the sensitivity model as several other materials are also used for the production of the gowns.

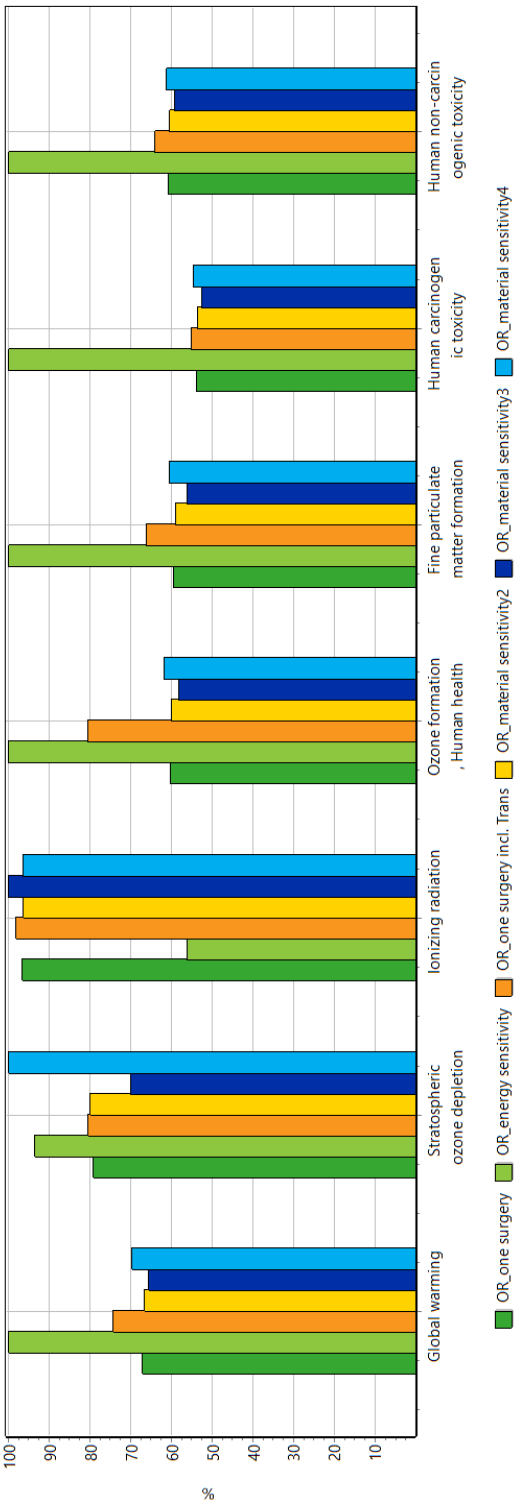

Figure 6: Sensitivity analysis of energy consumption, transport, alternative material composition of laparoscopic instruments (material sensitivity 2), drapes and gowns (material sensitivity 3), and finally the plastic waste fraction (material sensitivity 4).

5.3 Consumption practices

The current linear consumption practices in the OR at the Regionshospital Nordjylland are the result of a strategic change made on a structural level some 20 years ago to prioritize economic sustainability in the Region's hospitals (Nielsen and Madsen). The main argument behind this move was to reduce the costs connected to the reprocessing of devices and ease the pressure on the sterilization departments. A concrete example of the effect on the consumption practices based on this decision, is the consumption of sterile gauze tampons. Nielsen has worked in the SCT at the hospital close to 30 years and explains how in the early days they would spend a lot of time packaging bags with sterile gauze tampons in a variety of sizes, depending on the needs of the different hospital departments and surgeries. However, now these are delivered in sterile procedure packs by external global manufacturers in standardized sizes, which generate unnecessary extra waste as it is not possible to customize the sizes depending on local needs (Nielsen).

"That is what is cheapest and then we can use what we need and the rest is disposed of" (Nielsen).

This is exemplary of how the linear waste producing consumption practices has become embodied over the last couple of decades and entrenched in the general understandings among the health care professionals as expressed by Søndergaard:

"I dont know if a lot of thought goes into whether it is reusable or single-use - also because we have single-use and if you are not used to it being reusable then it cannot be differently".

The underlying teleo-affective structures and general understandings of this practice will be presented in the following, and the relationship between the material agency of the technologies, structures and agency of the practitioners will be explored to gauge what spaces for actions towards circular transitions exist.

5.3.1 Teleo-affective structures

During the interviews the different teleo-affective structures of the health care professionals became apparent as a natural extension to what they were explaining about their procedures and reflections. As can be expected, the meaningful goals guiding their practices are centred around the patient's best interest, which is implied both by the wish to finish the reprocessing of the instruments in time so the surgery is not cancelled (Nielsen), achieve satisfactory surgical outcomes (Søndergaard) and ensuring certain hygiene

standards for the patient's safety (Nielsen and Madsen).

However, a pronounced emerging motivation also steering the consumption practices in the OR is expressed, following the continuous tightening of budgets; protecting the department's economic sustainability (Søndergaard). For example, Søndergaard explains how she strategically attempts to choose the cheapest alternative when faced with two or more similar products. When the health care professionals in the OR are expected to change some practices, Søndergaard also underlines that is is very important that the purpose of this is communicated in an understandable and transparent way.

5.3.2 General understanding

There are several similarities between the general understandings conveyed by the health care professionals. One of the themes echoed by the interviewees is the superiority of SUD. This was either articulated in terms of costs, functionality, sterility or efficiency. This is illustrated by the response to the suggested transition to reusable drapes:

"Well I really don't hope that we'll return to reusable drapes, because then I picture something from a war zone and I will think are you completely sure this is sterile and closed off - and fastened with clamps! But that might also be my lack of knowledge which make me say that [...] Because the purpose of drapes is that it absorbs liquids and blood and body fluids so you don't dirty the patient's clothing or anything else. Because if it will leak, do we then have to change the patient's clothes before they leave the OR? There is always more things to think about. If we do it will we then loose what we gain? But again transparency is relevant, because we can think that we are doing good but then it is not the best option after all" (Søndergaard).

Nielsen and Madsen also expressed that drapes are among the most difficult products to transition. However, their explanations are based on the assumption that contemporary reusable drapes are like the ones used decades ago which would leak, be fastened with clamps (which were very uncomfortable for the patients) and some would have a plastic layer that you had to separate from the textile post-use; making the handling of the product difficult. Both Nielsen as well as Nielsen and Madsen mentioned the price and ease of handling to be the main advantageous of SUDs. Especially the efficiency and optimized work flows achieved by using SUDs, which are packaged ready to use and only has to be sorted correctly post-use, are factors that Nielsen and Madsen believe to have had a transformative effect on the practices and which are difficult to do without:

"So you have to assess what has the progress achieved. What is it that we don't want to return to? [...] think of what we have gained. You have a completely different flow than we had previously" (Nielsen and Madsen.)

Furthermore, the extra manual work procedures and logistics that follow reusable devices are perceived to be economically unsustainable or not competitive to SUD alternatives (Nielsen and Madsen and Søndergaard). This is expressed as difficult to navigate in when the sector is continuously reminded to reduce spendings, and produces a sense that the sustainability discourse sometimes goes too far (Nielsen and Madsen).

However, all interviewees also convey a general understanding and desire for the hospital to implement sustainability initiatives to mitigate environmental impacts. Nielsen mentions that the more the overall discourse on environmental protection increase the more aware she becomes of the extensive resource consumption of the hospital, and especially the amount SUDs and packaging waste. Likewise, both Søndergaard as well as Nielsen and Madsen have the impression that there is a growing resource awareness among the health care professionals and an increasing tendency for trying to minimize resource consumption by not breaking the sterile packaging barrier before it is needed.

5.3.3 Human-technology interactions

The OR is a highly technological textured environment and as such the technologies are likely to have a large influence on shaping the consumption practices of the health care professionals. The general development in recent years have resulted in an accelerated work flow, due to the easy handling of contemporary devices, but has also resulted in standardized single-use procedure packs, which are the source of the waste generation (Nielsen and Madsen). The fact that many procedure packs are single-use means there is a high turnover of these which generate increased amounts of packaging waste combined with the standardized contents, which means they include large manuals on instructions for use in multiple languages and surplus devices than what the local needs may be (Nielsen and Madsen and Nielsen). Because these are delivered by large global corporations it is not possible to customize these to local needs, as already mentioned. Consequently, this means that the health care professionals have limited agency in changing the product consumption related to the single-use procedure packs.

Changing the content of the procedure packs is also a long and complicated procedure as it must be based on a consensus among the practitioners and the changes must be confirmed by a surgeon (Søndergaard). Likewise, there are a number of rules regarding the procurement process of new products and contracts last four years and are managed by the personnel in the procurement department (Nielsen and Madsen). Thus, the health care professionals do not only have limited agency, but also only indirect agency regarding the consumption practices in the OR.

The SUDs are designed to be single-use by the manufacturers which also leave the health care professionals with no other options post-use than to sort the products for waste treatment. According to Nielsen and Madsen as well as Nielsen this is the easy choice for the manufacturers because marketing a medical device as reusable requires a comprehensive series of tests and certificates to ensure an appropriate hygiene standard can be achieved. Based on Statens Serum Institut (2019) and the regional infection hygiene guidelines, a device cannot be reprocessed for reuse without proper instructions for use on decontamination from the manufacturer (Nielsen and Madsen).

Moreover, the general development mentioned before has also entailed a deprioritization of the hospital's SCT. Nielsen explains how it is only in recent years that the SCT have become more visible and investments are starting to be made after many years of being neglected and overlooked. This change is due to an increased awareness of the importance of infection hygiene standards and guidelines. This means that the current infrastructures at the hospital do not have the needed capacity to support various large scale circular transitions.

Finally, it should be noted that even though both Søndergaard as well as Nielsen and Madsen declared that they had no preference whether a device is reusable or single-use, they showed an intuitive bias towards SUD when it comes to personal protection equipment like drapes and gowns as well as syringes.

5.3.4 Barriers

A number of barriers for implementing and enabling circular transitions are indicated by the interviewees. Nielsen and Madsen argue that the reprocessing and preparation of reusable devices will require more time and hands. This is also the main barrier identified by Nielsen, since the number of employees have decreased during the course of her time at the STC. Thus, for large scale circular transitions to be achieved more personnel and extended opening hours in the STC are needed. Nielsen also point out that the autoclaves in the SCT may not have the necessary programming to sterilize textiles if the hospital should transition to reusable drapes and gowns. This leads to another barrier which is the physical surroundings and reprocessing infrastructure of the hospital which have not been renovated and updated sufficiently over the years, as the hospital's plans for constructing a new building, which will include a new SCT, have been postponed for many years (Nielsen). As such the SCT do not have space for adding additional reprocessing machines before they are relocated.

Additional barriers include the lack of knowledge and first-hand experience with contemporary reusable product alternatives as well as lack of information and knowledge dissemination of previous and ongoing circular transition projects and strategic plans within the Region and the other Regions. Søndergaard mentioned multiple times the lack of knowledge sharing and dissemination concerning product alternatives, costs and impacts which complicate decision making.

Moreover, one of the main purposes of the department of infection hygiene is to interpret the national guidelines into regional guidelines and make sure these are implemented across the Region's hospitals (Nielsen and Madsen). The national guidelines make a lot of recommendations which the department of infection hygiene, however, interpret as demands as illustrated in the following:

"Well, "should" is mentioned a lot in the national guidelines, where they reference to best practice and literature so you interpret "should" as "must" and that is also something that we are being very much challenged on in these years. Because when it says "should" then people think that they can just do something else" (Nielsen and Madsen).

Researcher Karin Bundgaard Mikkelsen has stated in a study by Andersen (2024) that some of the national guidelines regarding reprocessing are not based on empirical evidence but best practice and industry recommendations, and knowledge gaps exist related to the effectiveness of different reprocessing procedures. Consequently, this may pose as a barrier if proposals for circular transitions are denied based on national recommendations that may not be based of empirical evidence.

6 Discussion

6.1 Impact interpretation

The LCA identified the main environmental impacts damaging to human health from a laparoscopic hernia procedure at the Regionshospital Nordjylland to be

the formation of fine particulate matter, global warming and human non-carcinogenic toxicity. These impacts are primarily caused by the demand of SUDs and waste treatment of the municipal solid waste, containing the single-use drapes, gowns and plastic packaging film. Consequently, the LCA show that the consumption and product demand for this type of surgery lead to 4,97E-05 DALY.

The primary purpose of the surgical drapes, gowns and plastic packaging is to reduce the risk of surgical site infections for the patients. Such infections can have great implications for patients and society at large (Koek et al., 2019). Cassini et al. (2016) estimate the overall DALY burden surgical site infections on a EU level to correspond to 0,5 DALYs per surgical site infection in general in 2011-2012. Koek et al. (2019) further details these findings by assessing the extent of DALY caused by surgical site infections for three different type of surgeries conducted in the Netherlands in 2011, finding that colectomy, which is a type of gastrointestinal surgery like hernia, are associated with 1,5 DALY per surgical site infection.

In this perspective the DALY caused by the product consumption of a surgical procedure, like a laparoscopic hernia procedure, can be argued to be insignificant, however over time and aggregated for all the types of surgery that necessitates the use of surgical drapes, gowns and plastic packaging this might accumulate to a relative large share of DALY, which potentially can be reduced through circular transitions.

An LCA study by Thiel et al. (2017) of a specific cataract surgical procedure in India show how highly circular and resource-efficient surgeries can have a significant effect on the associated carbon footprint. The consumption practices in the Indian cataract procedure are based on mainly reusable medical devices where they delineate between contaminated devices which are sterilized after each use (instruments, syringes, needles and phaco tip) and devices that can be directly reused without any risk to the patient, which are then sterilized or sorted for waste treatment at the end of the day (phaco wiring and tools, blankets, masks, gowns, table draping and plastic covers).

The autoclave cycles carried out in between surgeries are short 30 minutes flash cycles, reducing the energy consumption and reprocessing time, followed by a more comprehensive decontamination and long autoclave cycle at the end of the day. Moreover, the surgeon's gloves are sterilized between patients with an antiseptic gel and discarded after approximately 10 procedures. The majority of all the waste generated in this procedure is recycled locally and hazardous waste incinerated (surgical gloves, cotton swabs, patient cap, needles, face drape and intraocular lens).

As a results of this practice, and a very high throughput of patients, this type of cataract surgical procedure has a remarkably low carbon footprint compared to cataract surgeries performed in the UK, at the same time as having lower complication rates compared to the UK (Thiel et al., 2017).

All in all the environmental impacts of product demand and consumption can be difficult to comprehend as they are invisible to the naked eye and are displaced across time and space making them abstract. Likewise, the dynamics of expert social systems, like the sectors responsible for the production and consumption of medical devices, can be argued to build on the disembedding mechanisms of modern society defined by Giddens. These mechanism lift the social systems out of their local contexts of interaction to be restructured over long time-space distances. To fully comprehend the complex relationship of impacts between production and consumption are thus rendered *"beyond the interpretative capabilities of any single individual, whether expert or layperson"* (Gram-Hanssen, 2009). Hence, all such disembedding system rely on trust (Jemberie and Kumar, 2029), but for socio-technical systems related to the health care sector a precautionary principle also exist, which is embedded in the teleo-affective structures the health care professionals related to patient safety. Based on a case study of Aalborg Universitetshospital and the North Denmark Region by Andersen (2024), the precautionary principle is an institutionalized part of the discourse in the Region and play a determining role in the decision making processes.

6.2 Achieving effective mitigation

The analysis of the consumption practices highlights multiple limitations and constraints of the health care professionals to make immediate changes in practice and enable circular transitions. Some of these barriers are related to the reprocessing infrastructure at the hospital, but also structural and cognitive embedded constraints of the human-technology interactions. From a postphenomenological perspective, humans and technologies shape each other and, though limited in their agency, the health care professionals can be argued to still possess some power in shaping their interaction with the technologies in the OR.

Like the surgical drapes, various medical devices can be said to have stabilized as SUD at the Regionshospital Nordjylland. As SUD these technologies impose their material and normative constraints on the agency of the health care professionals. These are also reproduced by the health care professionals and strengthened with their perception of an absent technological development of old fashioned reusable devices, creating a cognitive lock in of the technological stability of the SUDs.

However, actors within the Region, like the infection hygiene, indirectly affect the consumption practices in the OR by making product demands in the procurement processes, which is one avenue where the health care professionals can channel their agency to enable circular transitions. In order to achieve effective mitigation of environmental impacts changes must be made to the products designs towards modular and hybrid designs if not fully reusable.

With the adoption of the Ecodesign for Sustainable Products Regulation in the EU, a paradigm shift in product design might be approaching, though it is unclear when and to what extent this will apply to medical devices (European Commission, 2022; Silver, 29/5 2024). However, even if medical devices will be exempt from this regulation there might still be a likelihood of a spill-over effect on the health care industry if a persistent push from health care professionals remain. These types of product demands and regulations illustrate of how humans also shape technologies.

6.3 Recommendations

Based on the interviews and observations in this investigation further efforts to mature the hospital for circular transitions are needed. This can be done through small scale incremental circular transitions and improving the sharing of knowledge and experiences between the different Regions. The strategy by Danske Regioner (2024) is an important step in this direction, but it is important that the goals, purposes and knowledge from the initiatives part of this strategy, as well as the Region's own strategies, are disseminated across the entire organization to ensure transparency and motivation, which Søndergaard also called for.

Mitigating the environmental impacts of the consumption practices in the OR will likely require a combination of different actions, as suggested in a study of different carbon reduction strategies of a laparoscopic surgery by Thiel et al. (2018). The study assesses the effectiveness of mitigation strategies related to anesthetics, medical devices and energy consumption. The results show that interventions in the use of anesthetics to be most effective and recycling and occupancy sensors to have the least effect. However, combining all the different interventions of only using sevoflurane gas as well as reducing and reusing medical devices hold great potentials for significant reductions in GHG emissions (Thiel et al., 2018).

For laparoscopic hernia surgeries at the Regionshospital Nordjylland, the results of the LCA point to the surgical drapes and gowns as the most relevant circular transitions to implement. This will reduce the generation waste by 25%, and other LCA studies show significant reductions of environmental impacts by using reusable gowns and drapes compared to single-use alternatives (Vozzola et al., 2020, 2018; Overcash, 2012). Furthermore, there is no empirical evidence suggesting that single-use drapes to offer any greater protection against surgical site infections compared to contemporary reusable drapes (Kiesera et al., 2018). However, further investigations of the capacity of the autoclaves at the hospital's SCT to sterilize textiles as well as costs related to such a transition are needed to determine the economic sustainability.

Finally, it can be recommended to prioritize investments in the SCT so that they have the possibility to hire additional staff and prolong their opening hours to accommodate for future large scale circular transitions. In line with this it could also be pertinent to make critical assessments of the possibilities to delineate between different reprocessing needs for the various devices. According to the national strategy by Danske Regioner (2024) multiple large scale future circular transitions are warranted, and as such it may be relevant to explore ways to optimize the reprocessing procedures of the SCT both to moderate the increase in energy consumption of the SCT, which will follow such transitions, and to shorten the reprocessing time as this will also moderate the need for a larger stock and storage of devices. Like in the study by Thiel et al. (2018), some devices or protective equipment may be identified to be safe to change at the end of the day instead of at the end of each procedure. This will, however, require an adjustment to the general application of the precautionary principle in trying to navigate between the need for precaution and need to reduce the product consumption.

6.4 Limitations

A number of assumptions are made in the life cycle inventory analysis which leads to a degree of uncertainty of the results. Especially the estimations of the energy consumption of the surgical procedure are to a large degree based on assumptions and thus very uncertain. However, comparing the carbon footprint of the energy consumption of this laparoscopic hernia surgery with the results from the LCA studies in the state-of-the-art literature review show three studies with larger carbon footprints from the energy consumption than in this thesis (Tan and Lim, 2021; Thiel et al., 2017; Morris et al., 2013), and two studies with an equivalent carbon footprint from the energy consumption (Latta et al., 2021; Thiel et al., 2015). The reason behind these differences are the relative large share of fossil based energy sources used in the national energy mixes compared to Denmark in two of the studies (Tan and Lim, 2021; Morris et al., 2013), and the majority of the medical devices being reusable in the third study (Thiel et al., 2017).

The material composition of the various devices, and lifespan of the reusable devices, are also based on assumptions, as it has either not been possible to gather data to this detail or it has not been possible to quantify directly. The data gathering process has been complicated due to the nature of the product system, consisting of expensive equipment which must be kept sterile before use and is contaminated post-use. Overcoming this barrier would require a more comprehensive research set-up and closer cooperation with the health care professionals, than have been the case in this investigation. Instead data from previous LCA studies on similar devices has been used to substantiate the estimations of the material composition and lifespans of the devices, which is also identified as a common research practice in the state-of-the-art literature review.

In general it is difficult to compare the results from the LCA in this thesis with other LCA studies of surgical procedures, as the LCA methodology allows for a great extent of variances in modelling approaches, use of databases and characterization methods. For the nine LCA and carbon footprint studies of surgical procedures identified in the state-of-the-art literature review, three are based on economic input-output modelling approaches, two use a process-based approach and three use a hybrid modelling approach - and none use a consequential methodology. There are advantages and disadvantages associated with each of the different modelling approaches, thus it is important that the chosen approach aligns with the goal of the LCA (National Academies of Sciences and Medicine, 2022). The process-based approach is deemed most suitable for the LCA in this thesis because it offers greater granularity for identifying process improvement specific to the case under investigation. This is a key aspect of the goal of this LCA, and it is not possible to obtain the same level of detail and specificity with the input-output approach as it is based on aggregated sector-wide economic transaction (National Academies of Sciences and Medicine, 2022).

Due to the lack of comparable studies it is not possible to properly contextualize the quantitative results of the LCA in this thesis. Overcoming this knowledge gap will require a multi-case study design to assess the impacts of different consumption practices for the same type of surgery across different hospitals, or different types of surgeries at the same hospital. This could allow for both a valid contextualization and comparison of impact results, as well as identifying ways to improve the sustainability of consumption practices without risking ethical compromises nor organizational barriers.

Moreover, the interviewees are all highly relevant to the case based on their many years of experience in their field and different positions in the organization of the Region. Capturing the perspectives from actors with different relations to the consumption practises taking place in the OR provide a broad institutional perspective on the development of the practices and the mechanisms maintaining them. However,the qualitative assessment of the consumption practices in the OR can be limited by the relative low number of interviews and observations conducted. Additional relevant interview persons include personnel from the procurement department in the Region, surgeons and personnel from the anaesthetic team.

7 Conclusion

The health care sector in Denmark, as well as on a global scale, is caught in a paradox where its efforts to ensure the health and well being of people lead to environmental impacts which have damaging effects on human health. Surgical procedures are identified, through a state-of-the-art literature review, as one of the main activities within the sector to cause most GHG emission and waste generation. To mitigate the negative environmental effects from the Danish hospitals and surgical consumption practices, circular transitions from SUD to reusable devices are a key strategy. The case of the Regionshospital Nordjylland is chosen as the basis for investigating what circular transitions are relevant to implement to improve the sustainability of the surgical consumption practices. This is achieved by conducting a consequential LCA of a routine laparoscopic hernia surgery at the hospital. Additionally, a qualitative assessment of the surgical consumption practices is made to define these practices and explore how they affect the potentials for implementing circular transitions.

The results of the LCA showed the main environmental impacts damaging to human health from a laparoscopic hernia procedure at the Regionshospital Nordjylland to be caused by the product demand of SUD, especially the use of single-use drapes, gowns and plastic packaging film, and waste treatment of the municipal solid waste. Consequently, these environmental impacts lead to damages to human health primarily due to air pollution with emissions corresponding to 0,03 kg PM2,5, global warming with 20 kg CO_2e and human toxicity with a total of 35 kg 1,4 DCB. The overall effect on human health of this type of surgery correspond to 4,97E-05 DALY.

Moreover, the interviews with different health care professionals and observations showed that the linear waste producing consumption practices have become embodied over a long time period due to a structural change made to prioritize the economic sustainability in the Region's hospitals. These practices are supported

by teleo-affective structures centered around the patients' best interest and a general understanding of a general superiority of SUD either in terms of costs, functionality, sterility or efficiency. All interviewees also expressed a general understanding of the need and value of sustainability initiatives at the hospital, but because of limited agency due to technological and structural factors, as well as the intransparent cost effectiveness of different consumption patterns, this motivation towards sustainability is impeded from being translated into action.

Based on these results, it is the single-use drapes and gowns which are most relevant to transition into their reusable alternatives. However, it can also be recommended to further prepare the organization at the hospital with small scale incremental circular transitions and investments in the SCT. Transitions towards a greater share of reusable devices will put pressure on the SCT, making it a high priority to ensure they acquire the necessary capacity both in terms of time, hands and capital goods.

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