Material logistics infrastructure in a circular hospital

Design science research in academic hospitals Erasmus Medisch Centrum (Erasmus MC) & Leids Universitair Medisch Centrum (LUMC)

Msc Supply Chain Management thesis

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Abstract

Over the past thirty years hospitals have become more reliant on single use medical devices and their linear value chains. These linear value chains cause the healthcare sector to contribute significantly to environmental pollution that negatively impacts global health. Healthcare sectors, government institutions and academics all over the world have recognized that emergency action is needed. Hospitals should shift away from single use (SU) medical devices (MDs) to reusable (RER) MDs that are reprocessed, repaired and recycled to increase circularity, lower environmental impact and save on costs. In order to make this shift, the material logistics infrastructure of hospitals will need to be adapted which has not been studied before. This research fills this research gap by answering the following research question.

***RQ**: What are the implications on the material logistics infrastructure in a circular hospital?*

This design science research study designs solutions for Dutch academic hospitals by using both academic and management literature combined with observations, expert knowledge and archival documentation of Dutch academic hospitals Erasmus Medisch Centrum (Erasmus MC) and Leids Universitair Medisch Centrum (LUMC) and expert knowledge from business offering a solution and experts by experience of a solution. This study goes over three phases of the problem-solving cycle, being problem definition, analysis and diagnosis and solution design.

This study consists of four main deliverables that all contribute significantly to theory and practice. First, the results of all Life Cycle Assessment (LCA) (and Life Cycle Costing (LCC)) studies that compare a SU with a RER medical device in tables, showing that RER versions have most often lower environmental impact and/or costs. Second, a novel typology that identifies eleven different types of MDs that have different requirements on six material logistics infrastructure elements when switching from a SU to a RER version. Third, 70 problems based on this typology identified at either one or both case hospitals. Fourth, a solutions flowchart presenting the importance and order of the designed solutions that solve almost all identified problems. The most important solutions are solutions around the material logistics infrastructure element of tracking and tracing. When implemented, the designed solutions will help hospitals to move away from SU MDs to RER MDs, increase circularity, lower environmental impact and save on costs.

Limitations include minimal prior knowledge of and network in the healthcare sector of the researcher, the selected scope of the two case hospitals, existing LCA (and LCC) studies studies, interpreting LCA (and LCC) study results, and a limited time span.

Suggestions for future research include evaluation and investment costs of the designed solutions, more LCA (and LCC) studies, LCA (and LCC) study of a hospitals own reprocessing processes, how to use procurement to reach the goals of the green deal sustainable healthcare 3.0, and the social impacts of a circular hospital.

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Glossary

Al – Aluminum.

AI – Artificial Intelligence.

BLE – Bluetooth Low Energy.

CBM – Circular business model.

CE – Circular Economy. An economic system in which resource input and waste, emission, and energy leakage are minimised by cycling, extending, intensifying, and dematerialising material and energy loops. This can be achieved through digitalisation, servitisation, sharing solutions, long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling.

CE Certification – Certification required to bring new MDs or reprocessed SU MDs on the market.

CO – Cotton.

CO2 – Carbon dioxide.

CO2e – Carbon dioxide equivalents. A measure used to compare different greenhouse gases by their GWP.

Cu – Copper.

CSSD – Central sterile services department.

(E1) till (E17) – Reference to data that was gathered through a consultation with a respondent from Erasmus MC.

EEIO - Environmentally extended input-output, is a top-down approach of doing LCA that couples country data of monetary spend with emissions.

EL – Elastane

EOL – End of life.

EPS – expended polystyrene. More known as Styrofoam.

ePTFE – expanded polytetrafluoroethylene.

FTE – Full-time equivalent.

FU – Functional Unit. The selected unit of study of LCA (and LCC) studies.

GWP – Global warming potential. Most common used environmental impact category, measured in CO2e.

GDSN data pool – Global Data Synchronization Network data pool. Data pool from GS1 that tracks and traces information about different version of specific types of MDs.

HDPE – High Density Polyethylene.

IC – Intensive care.

JBZ – Jeroen Bosch Ziekenhuis.

(L1) till (L7) – Reference to data that was gathered through a consultation with a respondent from LUMC.

LCA – Life Cycle Assessment. Internationally standardized scientific approach used to quantify the environmental impacts of a product, process, or system, also called the 'functional unit' (FU), during all

phases of its life cycle, from raw material extraction, through energy production and manufacturing, to transportation towards the use phases and EOL treatment and disposal.

LCC – Life Cycle Costing. This method looks at the total cost of a product or system over its full life cycle, including its operating costs and EOL costs rather than only looking at the initial procurement costs.

LCI – Life Cycle Inventory are databases with materials showing their environmental impacts in each phase of the life cycle.

LCIA – Life Cycle Impact Assessment make comparisons between the impact of different products, processes or systems.

LDPE – Low Density Polyethylene.

LMA – Laryngeal mask airway.

MD – Medical device. Any instrument, apparatus, appliance, material or other article designed to be used, alone or in combination, for human beings for some specific medical purposes, specified in the EU MDR. Type of MD refers to T0 till T11 from the typology. Specific type of MD refers to e.g., a 'scissor' or a 'cystoscope'. Version of a specific type of MD refers to e.g., a SU, RER, or MOD scissor 'x' from a specific OEM. Unique MD refers to a MD that is traceable to its individual medical device e.g., it differentiates one scissor 'x' from another scissor 'x'.

MDR – Medical Device Regulations.

MOD – Modular. Consisting of different detachable subparts, that all have different cycles. Some subparts might be SU and others might be RER.

N/A – Not available.

Ni – Nickel.

OR – Operation rooms.

OEM – Original equipment manufacturer.

[P1] till [P70] – Observed problem at either one or both case hospitals.

PA – Polyamide (nylon).

PC – Polycarbonate.

PE – Polyethylene.

PET – Polyethylene terephthalate.

PO – Polyolefin.

PL – Polyester. Category of polymers of which PET is the most known type.

PPE – Personal protective equipment. In a healthcare environment used for protecting against infection risks. Also worn during reprocessing operations.

PU – Polyurethane.

PVC – Polyvinyl chloride.

RER – Reusable. Can be reused multiple times when reprocessed and/or repaired or without any of that (by wait and reuse).

RFID – Radio Frequency Identification.

(S1) till (S6) - Reference to data that was gathered through a consultation with a respondent of business offering a solution, or expert by experience of a solution.

SMS – Spunbond Meltblown Spunbond.

SS – Stainless steel.

SAP – Superabsorbent polymer.

SU – Single use. Also called disposable.

Si – Silicone

T0 till T11 – Types of MDs. Defined in the typology based on their requirements of material logistics infrastructure elements.

Ti – Titanium.

TTL – Triple tip line.

TBL – Triple bottom line.

WEEE – Waste Electrical Electronic Equipment.

WMS – Warehouse Management System.

Zn – Zinc.

1. Introduction

Pollution to air, water and soil is destroying whole ecosystems, contributing to climate change and therefore directly and indirectly negatively impacting global health (Figueres et al., 2018; World Health Organization, 2021). Extreme weather events such as heatwaves, storms and floods are happening more often, food systems are being disrupted and water quality is deteriorating. Moreover, pollution leads to an increased amount of zoonoses (for example SARS-COV-2 that caused COVID-19), food- water- air- and vector-borne diseases, mental health issues and non-communicable diseases (Figueres et al., 2018; Watts et al., 2021; World Health Organization, 2021). The World Health Organisation (2021) sees climate change as the single biggest threat to global health, expected to cause 250,000 additional deaths each year between 2030 and 2050, from malnutrition, malaria, diarrhoea and heat stress alone. The Lancet commission on pollution and health (Fuller et al., 2022) calculated that pollution is causing 9 million premature deaths each year. These negative health impacts are disproportionally being felt by the most vulnerable and disadvantages countries and communities, who contribute least to its causes (Watts et al., 2021; World Health Organization, 2021), with more than 90% of pollution-related deaths occurring in low-income or mid-income countries (Fuller et al., 2022).

Ironically, the healthcare sector itself contributes significantly to these problems, being responsible for 4.6% of global greenhouse gas emissions, and in high-income nations this is even more, for example 7.3% in The Netherlands (Steenmeijer et al., 2022; Watts et al., 2021). Moreover, the healthcare sector is resource-intensive, creating lots of waste of complicated compositions (World Health Organization, 2014). The Dutch healthcare sector consumes 13% of all materials and generates 4.2% of all waste (Steenmeijer et al., 2022).

Over the past thirty years, the healthcare sector of high-income nations has become increasingly reliant on single use (SU) medical devices (MDs), by reducing their internal material logistics infrastructure that is required to manage reusable (RER) MDs and transitioning to 'just-in-time' systems that represent a 'take-make-dispose' economy with linear supply chains (Macneill et al., 2020). Main reasons for this shift are assumptions on infection prevention, costs and convenience (Macneill et al., 2020). Most of the SU MDs and their packaging are plastics, made from fossil fuels and toxic plasticizers, that have a negative impact on the environment and health during each phase of its life cycle; extraction, manufacturing, distribution, use and disposal (Gamba et al., 2021; Sherman et al., 2020). In the current system, the sector is not considering or accounting for these negative impacts up and down stream on social, environmental and public health (Alami et al., 2023). Moreover, by relying on SU value chains and shifting to 'just-in-time' systems, the healthcare sector has become more vulnerable to supply chain disruptions, caused by natural disasters and man-made events, such as shortages, transportation problems, international trade dynamics and price shocks. During COVID-19, the vulnerabilities of linear supply chains became visible, causing disruptions in the supply of Personal Protective Equipment (PPE) kits, vaccines, MDs and pharmaceuticals. This shows that relying on linear systems might be convenient under business-as-usual circumstances, but when a supply disruption with a high impact happens it will only amplify the disastrous consequences (Macneill et al., 2020; Singh & Parida, 2022).

Therefore, academics, healthcare practitioners and government institutions, including the World Health Organization and the International Panel on Climate Change, are recognizing that emergency action is needed from the healthcare sector to battle the worlds planetary crises and protect global health and well-being (Alami et al., 2023; Atwoli et al., 2021; Hinrichs-Krapels et al., 2022; International Panel on Climate Change, 2023; Watts et al., 2021; World Health Organization, 2017). More than 200 clinical journals have simultaneously published the article of Atwoli et al. (2021), making an urgent call for action to limit global warming, restoring biodiversity and protect health. During the UN Climate Change Conference (COP26), 31 countries, including the Netherlands, have set targets on decarbonization, and thirteen more countries even pledged to aim for zero emissions on or before 2050, following the UK National Health Service that

was the pioneering country making such a pledge a year before the conference (Wilkinson, 2021). Alami et al. (2023), mention that even though the healthcare sector recognizes that financial and social performance metrics are important to protect our health and well-being, they are neglecting the fact that environmental impacts are forming a major threat to global health and well-being and therefore should also include environmental sustainability performance metrics into their decision making.

A crucial strategy to aim for environmental sustainability and to try and solve the previously mentioned social and economic problems that follow from current dominant linear 'take-make-dispose' economy is that of the Circular Economy (CE). A CE aims to eliminate waste and pollution, to circulate products and material at their highest value and to regenerate nature. By doing this economic growth is decoupled from resource consumption and a system is created that is beneficial for businesses, people and the environment (Ellen MacArthur Foundation, 2013a; Ellen MacArthur Foundation, 2013b; Ellen MacArthur Foundation, 2014). The European Commission and the Dutch government aim to be circular by 2050 (European Commission, 2020; Government of the Netherlands, 2016). Moreover, in the green deal sustainable healthcare 3.0 the Dutch government and the healthcare sector also set circular ambitions for the healthcare sector, aiming to reduce CO2 emissions with 55% compared to 2018 and to be climate neutral by 2050, for only 25% unsorted residual waste by 2030 and by 2026 already 25% less unsorted residual waste compared to 2018, for 20% RER MDs by 2026, for 50% less raw materials needed by 2030 compared to 2016, and for being fully circular by 2050 (Dutch Government & Healthcare sector, 2022).

Circular strategies in a hospital setting include reusing, repairing, reprocessing, or recycling so that the products or materials can be used again and is closely intertwined with waste management as it aims to reduce waste (Guzzo et al., 2020; Kane et al., 2018; World Health Organization, 2014).

There are multiple reasons why hospitals should aim for RER MDs and increase circularity. First, even though hospitals have moved away from RER MDs because of infection control reasons among others, there is no compelling evidence that using SU MDs lowers the risk of such infections (Macneill et al., 2020). Second, although the initial procurement price of SU MDs might be lower, studies show that the lifetime costs of many RER MDs are substantially lower (Boberg et al., 2022; Eckelman et al., 2013; Fargnoli et al., 2018; Hospodková et al., 2023; McGain et al., 2010; Sanchez et al., 2020; Sherman et al., 2018). Third, studies comparing the lifetime environmental impacts of SU versus RER MDs, show that the latter are significantly better for the environment (Eckelman et al., 2013; Fargnoli et al., 2018; McGain et al., 2010; Sanchez et al., 2020; Sherman et al., 2018). Fourth, improving environmental impact means improving global health impacts as discussed above and there might be elements that are beneficial to health into a product design, for example a carpet that cleans the air, improving the air quality (Ellen MacArthur Foundation, 2013a). Fifth, although less researched, there might be human rights violations arising in linear global value chains such as unequal- or under payment, poor working conditions and forced- or child labour, while in a circular value chains local meaningful jobs are created without these human right violations (Glade et al., 2018; Impact Economy Foundation, 2022). Lastly, creating circular healthcare value chains ensures security of supply therefore decreasing supply chain risks (Macneill et al., 2020; Singh & Parida, 2022).

Next to studies measuring environmental impacts and costs of MDs and services, circular MDs product design (Kane et al., 2018) and business models (Fargnoli et al., 2018; Guzzo et al., 2020; van Boerdonk et al., 2021) have been studied. However, what is lacking in literature and therefore has been mentioned by literature as an important area for future research, is research into what material logistics infrastructure solutions are required to support the shift from SU towards RER MDs and increase circularity (Macneill et al., 2020; Sherman et al., 2020; Viani et al., 2016; World Health Organization, 2014). Because, when circularity becomes a core strategy of hospitals and MDs are handled in a circular way, the material logistics infrastructure inside hospitals will need to be adapted. This study aims to design viable material logistics

infrastructure solutions that can be implemented by Dutch (academic) hospital managers inside their hospitals to move from SU towards RER MDs and increase circularity.

In chapter '2. Conceptual background', different concepts are defined in three sections '2.1. Sustainability and the CE', '2.2. Hospital material logistics infrastructure' and lastly in the combination of the two '2.3. the circular hosital'. In this last section the research gap that this study aims to fill is explained by defining the research question. Chapter '3. Methodology' describes the research methods that have been used to conduct this study. In chapter '4. Problem definition', Life Cycle Assessment (LCA) (and Life Cycle Costing (LCC)) studies are analysed and used to create a typology that presents eleven types of MDs that all have different requirements on six material logistics infrastructure elements when switching from a SU to a RER version. Chapter '5. Analysis and diagnosis' consist of an empirical analysis of the two case hospitals Erasmus MC and LUMC based on the created typology, were 70 problems are identified. In chapter '6. Solution design (plan of action) & intervention' solutions to those problems are presented. Chapter '7. Conclusion & discussion' consists of a conclusion by answering the research question, the theoretical contribution, practical implications, limitations, and suggestions for future research. Finally, the references and appendices are presented.

2. Conceptual background

This conceptual background chapter consists of three sections, that all present necessary background information to be able to perform this study. The first section '2.1. Sustainability and the Circular Economy', is introducing relevant terms and theories such as (regenerative) sustainable development, (positive) impact and how to measure that. The second section '2.2. Hospital material logistics infrastructure', discusses how healthcare supply chains are designed and zooms in on the material logistics infrastructure inside a hospital. The third section '2.3. The circular hospital', combines the two, discussing what is already known through academic and management literature on how to move towards circular material use inside hospitals.

2.1. Sustainability and the Circular Economy

This section discusses relevant terms and theories around sustainability and the CE. The first four sub-sections introduce concepts of sustainable development, triple bottom line (TBL) and triple top line (TTL), that all have led to the introduction of the concept of a CE. Then, the fifth sub-section describes why a CE is important by discussing its benefits. The sixth sub-section introduces LCC and LCA as methods to measure these benefits. Lastly, the seventh sub-section explains how monetizing impacts can be used to help organizations to integrate sustainability into their monetary decision making.

2.1.1. Sustainable development

The first industrial revolution, around 1800, marks the beginning of the Anthropocene, a new era where mankind is the main driver for global environmental change (Rockström et al., 2009). Ever since, (western) societies have been focussing on economic growth by using a linear model of consumption where companies take materials from the Earth, make products from them, and sell those to a customer, who will eventually dispose of them. Around 1960 the first flaws of this system have been shown. There was increasing evidence of environmental risks related to economic growth, such as climate change, biodiversity loss, ozone depletion and alterations in the nitrogen cycle (Carson, 1962; Meadows, 1973) This has led to a raise in environmental awareness and the creation of the term sustainable development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (The World Commission on Environment and Development, 1987).

2.1.2. Triple Bottom Line

Whilst the term sustainable development originally focused on the environment, it nowadays has many different definitions not only related to environmental dimensions, but also to social and economic dimensions. This is reflected by the seventeen interconnected Sustainable Development Goals (SDGs) that together strive at ending poverty, protecting the planet and promoting prosperity for all people by 2030, created in 2015 by the United Nations (UN General Assembly, 2015). The three dimensions of sustainable development, the environment, society and the economy, originate from the Triple Bottom Line (TBL) approach. Elkington (2014) acknowledges that economic growth, environmental destruction and inequality are intertwined and therefore should be on an organization's agenda. The term comes from the triplet of 'People, Planet and Profit' ('Triple'), the idea that one of these factors can impose negative externalities onto others ('Bottom') and captures that there are planetary boundaries ('Line') (Lodder et al., 2014). Planetary boundaries are thresholds onto Earth-system processes that if crossed, could generate unacceptable environmental change, including climate change, rate of biodiversity loss (terrestrial and marine), interference with the nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, change in land use, chemical pollution, and atmospheric aerosol loading (Rockström et al., 2009). Externalities are costs or benefits that impact an otherwise uninvolved party that did not choose to incur these costs or benefits (Buchanan & Stubblebine, 1962). Following the TBL approach, organizations should aim to minimize their negative externalities and their negative impact. To do that, an organization should aim for a combination of eco-efficiency, which relates to minimizing environmental resources and their negative environmental externalities, and social efficiency, which relates

to minimizing the negative social externalities, both resulting from an organization's economic activity (Figge & Hahn, 2004). Organizations can minimize negative externalities by 'internalizing' costs that were previously externalized to society and the environment (Elkington, 2014). Organizations can show that they are internalizing negative environmental externalities by using eco-labels and a Fair-Trade label for social externalities (Lodder et al., 2014).

2.1.3. Triple Top Line

McDonough and Braungart introduced the Triple Top Line (TTL) approach, which aims not only at efficiency but at effectiveness, increasing positive externalities on the environment and society and eliminates the concept of waste (2002b). Lodder et al. (2014) argue that following efficiency (TBL) approaches only, will result in sub-optimal solutions for the environment and society. Instead, they plea for a combination of efficiency strategies, decreasing negative externalities, and effectiveness strategies, increasing positive externalities, because this combination is needed to change the old linear economic system towards a system that is focussed on regenerative sustainable development that "emphasizes a co-evolutionary, partnered relationship between humans and the natural environment, […] that builds, rather than diminishes, social and natural capitals".

2.1.4. Circular Economy

The CE has been receiving increased attention from policymakers, businesses and academics worldwide ever since it has been taken up by the World Economic Forum in 2014 (Ellen MacArthur Foundation, 2014). It aims at changing the old economic system by describing a new type of economic system aiming for regenerative sustainable development, building forth on a variety theories and concepts that share the idea of a closed-loop system including Cradle to Cradle (McDonough & Braungart, 2002a), Laws of Ecology (Commoner, 1971), Looped and Performance Economy (Stahel, 2010), Regenerative Design (Lyle, 1994), Industrial Ecology (Graedel & Allenby, 1995), Biomimicry (Benyus, 2002) and the Blue Economy (Pauli, 2010). In this study the CE definition of Geissdoerfer et al. will be used, who define the CE as "an economic system in which resource input and waste, emission, and energy leakage are minimised by cycling, extending, intensifying, and dematerialising material and energy loops. This can be achieved through digitalisation, servitisation, sharing solutions, long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling" (Geissdoerfer et al., 2020).

This definition includes four generic strategies for a circular business model (CBM): cycling, extending, intensifying and dematerialising material and energy loops. Three of those build forth on circular business model strategies identified by Bocken et al., who talks about slowing (extending), closing (cycling) and narrowing (intensifying) material and energy loops (Bocken et al., 2017). Cycling refers to recycling of materials and energy within the system by reusing, remanufacturing, refurbishing and recycling. Extending aims for extending the use phase of a product and is achieved by long-lasting design, marketing, maintenance, and repair. Intensifying means making sure a product is used more often during its use phase and is achieved by sharing economy solutions. Dematerialising is a business model strategy where product utility is substituted by service or software solutions, for example by delivering the product-as-a-service (Geissdoerfer et al., 2020).

Geisendorf & Pietrulla (2018) explain that the 3Rs (reuse, reduce and recycle) are widely used to summarize a CE. A more specific classification consists of ten value retention strategies, the 10Rs, that are hierarchical from most value retention to least value retention; Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycling, Recovery (energy) and Re-mine (Reike et al., 2018). However, Geisendorf & Pietrulla (2018) also mention that focussing on these value retention strategies is only an approach for better waste management, and that a CE encompasses way more, including product and process design. This is also reflected in the CE definition of Geissdoerfer (2020) that is used in this study, including these value retention strategies, mostly as enablers of cycling, but also other enablers such as

product design, digitalisation, servitisation or sharing solutions that enable extending, intensifying and dematerialising.

A key influencer in the uptake of the CE is the Ellen MacArthur Foundation, that was created in 2010 with the aim of accelerating the transition towards the CE. They published multiple publications on the topic and engage with businesses, policy makers and academia. Their first three reports explain how a CE works and the potential benefits for the EU (Ellen MacArthur Foundation, 2013a), the fast-mover consumer goods sector (Ellen MacArthur Foundation, 2013b) and inside global supply chains where products are created from complex multi-tier components (Ellen MacArthur Foundation, 2014). Then there are also reports that explain the potential of how emerging digital technologies from the fourth digital revolution such as Intelligent Assets and Internet of Things (Ellen MacArthur Foundation, 2016) or Artificial Intelligence (Ellen MacArthur Foundation, 2019) could help to reach a CE. Moreover, some reports explain in detail how the CE has the potential to tackle certain crises such as the biodiversity crisis (Ellen MacArthur Foundation, 2021b), the climate crisis (Ellen MacArthur Foundation, 2021a) or the plastics crisis (Ellen MacArthur Foundation, 2017).

Businesses that are partnering up with the Ellen MacArthur Foundation are integrating circularity into their company DNA, including multinationals such as Google, Unilever and Renault (Bocken et al., 2017). Another example is healthcare technology company Philips who aims to achieve a CE through circular product design, circular operations and circular business models such as trade-in schemes, refurbished systems and delivering their products as a service (Ellen MacArthur Foundation, n.d.).

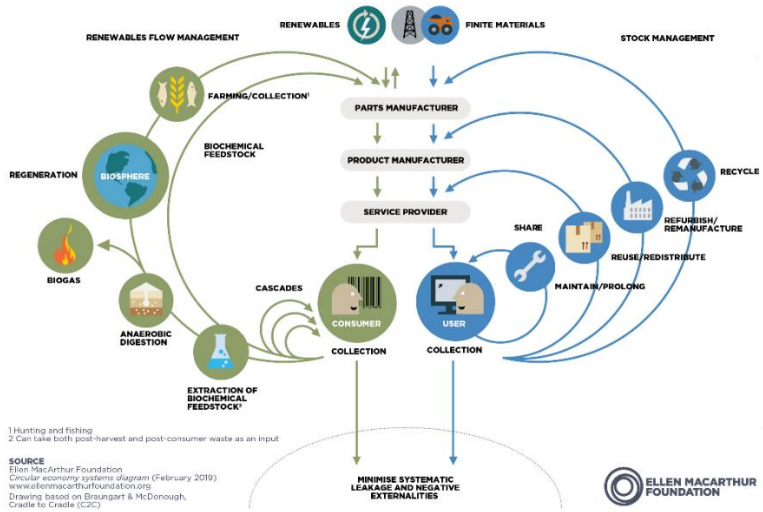
Policymakers at international, national, regional and local level are creating action plans with legislative and non-legislative measures to reach a CE. In 2015, The European Commission created such an action plan for the CE and recognize this as a critical element to reaching the European Green Deal of 2050, achieving climate neutrality by 2050 and stopping biodiversity loss (European Commission, 2020). The Dutch government has set a similar ambition to be 100% circular in 2050 (Government of the Netherlands, 2016). In China, laws and regulations to reach a CE are set on three levels. On a micro level, individual firms are encouraged to design more environmentally friendly products and production processes. On a meso level, eco-industrial parks are created that benefit both production as the environment by using strategies such as cascading, sharing infrastructure, exchanging by-products and recycling waste. On a macro level, whole eco-cities, -municipalities and -provinces are created that focus on bringing circular production and consumption to the attention of policy makers (Yuan et al., 2006).

Academic reviews and articles about the CE have grown exponentially since 2014 (Geissdoerfer et al., 2017). These academic reviews and articles consist of different research areas, including literature reviews on the CE (Geisendorf & Pietrulla, 2018; Ghisellini et al., 2016; Kirchherr et al., 2017; Lieder & Rashid, 2016), quantitative research on closed-loop supply chains and reverse logistics (Govindan et al., 2015; Guide & Van Wassenhove, 2009; Savaskan et al., 2004), research into circular business models (Bocken et al., 2016; Geissdoerfer et al., 2018; Geissdoerfer et al., 2020), and circular product design (Bakker, 2014; Hollander et al., 2017).

Following the terminology of The Ellen MacArthur Foundation (2013a; 2013b; 2014; 2016; 2019), a CE is based on three principles, driven by design: eliminating waste and pollution, circulating products and materials (at their highest value) and regenerating nature. By doing this, economic growth is decoupled from resource consumption like in the old economic system with a linear 'take-make-dispose' mentality, and a new system is created that is beneficial for businesses, people and the environment. Building forth on the concept of Cradle-to-Cradle design (McDonough & Braungart, 2002a), the butterfly diagram, a visualization of the CE system presented in figure 1, shows that there are two types of materials that circulate in two different spheres. These two spheres are called the Biosphere (on the left) and the Technosphere (on the right) (2013a; 2013b; 2014; 2016; 2019).

Figure 1

Butterfly diagram (Ellen MacArthur Foundation, 2014).



The Biosphere consists of all bio-based ingredients that are biodegradable and non-toxic so that after their use they can be safely returned to the biosphere, either directly or after cascading. Cascading means sequentially and consecutively re-using bio-based materials in different use cases (Campbell-Johnston et al., 2020). Consumables should be made mostly of ingredients from this sphere. Examples of bio-based materials are food, wood or natural textiles like cotton (Ellen MacArthur Foundation, 2014).

The Technosphere consists of all nutrients that cannot biodegrade and therefore are unsuitable for the biosphere. Durables are made from these technical materials and these materials should be kept in cycles for as long as possible through value retention strategies, such as those of Reike et al. (2018). Examples of technical materials are metals and most plastics. Important to notice is that customers are replaced by users implicating that products should be leased, rented or shared instead of sold (Ellen MacArthur Foundation, 2014).

2.1.5. Benefits of a Circular Economy

The Ellen MacArthur foundation identifies four sources of value creation compared to linear systems. The 'power of the inner circle' explains that by using tighter cycles, more financial, social and environmental gains can be achieved because more of the value embedded in the product is retained. The 'power of circling longer' explains a strategy that focuses on maximising the number and length of the cycles. The 'power of cascades' a strategy for the biological cycle, refers to finding reuse possibilities across industries. The 'power of pure circles' is especially important in the technical cycle and explains that by creating pure, non-toxic or easier to separate material streams, collection and redistribution efficiency as well as material productivity will improve (Ellen MacArthur Foundation, 2013a). These and other examples of value creation mentioned throughout their reports can be categorized into economic, environmental and social benefits.

Economic benefits include mitigating price volatility and supply risks, net material cost savings and stimulating innovation. First, commodity prices are rising, there is more volatility in prices and even some resources are risking depletion, a CE can be a solution to these and other price volatility and supply risks as resources are kept in closed-cycles, decoupling growth from the need for virgin materials. Second, the material savings resulting from circular activities will result in cost savings that are calculated to be 12-14% or 19-23% of total input costs in the European Union (EU). Third, rethinking product design and business models requires creativity and has been proven to be a stimulating factor for innovation (Ellen MacArthur Foundation, 2013a).

Environmental benefits are the most obvious. Using fewer virgin resources, non-toxic materials and renewable energy lowers the negative environmental impacts that arise during extraction, manufacturing, distribution, use and end of life (EOL) of a product (Ellen MacArthur Foundation, 2013a). Moreover, a CE not only aims for decreasing negative environmental impacts, but also aims at regenerating and restoring nature by eliminating threats to, leaving room for and enabling nature and biodiversity to thrive (Ellen MacArthur Foundation, 2021b).

Social benefits are the most overlooked and least researched, as most authors focus on environmental benefits of a CE (Bakker, 2014; Bocken et al., 2016; Rashid et al., 2013). Benefits to society for moving towards a CE include protecting human rights, creating local meaningful jobs and improving health and well-being. Global linear value chains today risk having human right violations, like child labour, forced labour, unequal or under payment. Creating local closed loop systems, will create local meaningful jobs without risking these social issues (Glade et al., 2018; Impact Economy Foundation, 2022). Moreover, improving environmental impact also results in improving global health and well-being as pollution and global health are intertwined (Figueres et al., 2018; World Health Organization, 2021). Again, a CE not only aims at reducing negative social impacts but also aims at increasing positive social impact, for example creating positive health impact by creating a carpet that cleans the air (Ellen MacArthur Foundation, 2013a). However, Murray et al. argue that it is unclear how a CE will lead to greater social equality (2017).

2.1.6. How to measure these benefits – or impact

Economic benefits of circular products or systems, compared to linear ones, can be calculated by using Life Cycle Costing (LCC) (Woodward, 1997). This method looks at the total cost of a product or system over its full life cycle, including its operating costs and EOL costs rather than only looking at the initial procurement costs. This is important because although the initial procurement costs of RER medical deivices might be higher, spreading these higher costs over multiple use cases can significantly lower the cost of the full life cycle of a product or system. Product-service systems are an example of a circular business model that can create lower Life Cycle Costs over the entire system (Fargnoli et al., 2018).

Environmental benefits can be measured by using LCA (also called 'cradle to grave' analysis). LCA is an internationally standardized scientific approach used to quantify the environmental impacts of a product, process, or system, also called the 'functional unit' (FU), during all phases of its life cycle, from raw material extraction, through energy production and manufacturing, to transportation towards the use phases and EOL treatment and disposal. A 'system boundary' explains how the scope of the LCA is defined, aiming for transparency. Life Cycle Inventory (LCI) are databases with materials showing their environmental impacts in each phase of the life cycle. Life Cycle Impact Assessment (LCIA) makes comparisons between the impact of different products, processes or systems. Economic and social impacts are typically out of scope, but health impacts resulting from environmental impacts are included for comprehensiveness (Finkbeiner et al., 2006; McGain et al., 2020).

Social benefits or impacts are the most difficult to measure. A way to measure social impact is by measuring the human right violations occurring in the value chain, but this data is difficult to gather (Impact Economy Foundation, 2022).

2.1.7. Monetizing impact

Monetizing impact is increasingly getting traction. By monetizing environmental and social impacts, all can be compared with the same measure, money, making it easier for decision making. Impact Economy Foundation is a public benefit organisation, that tries to create a common language for impact measurement and validation. They make use of a monetization factors that estimate the value of environmental or social impacts to a certain stakeholder. For example, a monetization factor of 0.157 EUR/kgCO2e is used based on the restoration cost to reach the two-degree target as set in the Paris Agreement. Using this monetization

factor makes it possible to see what the 'costs' are of the contribution to climate change (Impact Economy Foundation, 2022).

2.2. Hospital material logistics infrastructure

Where the previous section discussed sustainability and the CE, this section will discuss the context of this study, the material logistics infrastructure of hospitals. This section introduces healthcare supply chains and more specifically the material logistics infrastructure of MDs inside hospitals. Then in sub-section '2.2.2. Waste management' the different types of waste created by hospitals and the difficulties related to them are discussed.

2.2.1. Introduction into hospitals material logistics

Healthcare supply chains are mainly funded by the government and therefore a focus on cost optimization, without reducing the quality of service for patients, is one of the main goals (Božić et al., 2022). The most critical institution of a healthcare supply chain is the hospital, accounting for 29% of the total healthcare expenditures. Logistics activities account for more than 30% of those costs, making it the second largest costs category for hospitals after costs of medical staff. Most of the time, logistical activities are performed by medical staff. Therefore, optimising the material logistics inside hospitals cannot only help to reduce costs, but also increase the time that medical staff can spend on patient care, relieving them from logistical activities. Literature on material logistics in hospitals can be divided into four streams being supply and procurement, inventory management, distribution and scheduling, and holistic supply chain management. Especially distribution and scheduling literature will be important when designing solutions as this stream discusses the actual transport of materials inside hospitals and includes sterilization of MDs in order to reuse them again (Volland et al., 2017).

The hospital supply chain consists of three cycles in the external and internal supply chain, according to Castro et al. (2020). The first cycle consists of suppliers delivering supplies to a central warehouse of the hospital, that is closely linked to the central pharmacy department. The second cycle consists of delivering supplies from the central warehouse to the different hospital departments, like the operation rooms (OR), intensive care (IC), emergency care, infectious diseases, surgery, orthopaedics, transfusion, and other (Božić et al., 2022). The third cycle consists of delivering the supplies to the patient care locations. Suppliers are part of the external supply chain and from the warehouse till the patient care location is the internal supply chain. This study will focus on the material logistics infrastructure inside hospitals and therefore includes a part of the first cycle, from where products enter the hospital onwards, the full second and third cycle, and the fourth cycle waste management that will be explained in the next sub-section '2.2.2. Waste management'.

There are many different categories of hospital supplies such as food, medical drugs, pharmaceutical products (tablets and capsules), medical equipment, medical instruments for the operation rooms (OR) and medical materials (injections, syringes, gloves, surgical kits, surgical clothes and sterile tools), maintenance equipment for the hospital, bedding and different type of waste, as listed out by Božić et al. (2022), based on Moons et al. (2019), Ageron et al. (2018) and Castro et al. (2020). This study will look at medical equipment, medical instruments for the OR, medical materials and the waste resulting from those material streams. The broader term that will be used in this study, referring to all these categories is MDs. MDs are any instrument, apparatus, appliance, material or other article designed to be used, alone or in combination, for human beings for some specific medical purposes, specified in the EU MDR (The European Parliament and of the Council, 2017).

2.2.2. Waste management

Božić et al. (2022) suggest that waste management can be seen as the fourth cycle of the health care supply chain. This involves collecting, sorting and removing waste from the place of origin to the point of collection, where waste is taken over by companies specializing in waste disposal.

The healthcare sector is resource-intensive generating lots of waste and that waste consists of complicated compositions. Most of the healthcare generated waste around 85% is general non-hazardous waste (including packaging waste). The rest however, around 15%, is considered hazardous waste, including 10% sharps or infectious (including pathological) waste and 5% chemical, pharmaceutical, cytotoxic, or radioactive waste. An overview of these different categories of healthcare waste is presented in **table 1** (World Health Organization, 2014).

A frequently used indicator for the amount of waste generated in a hospital is the amount of waste per occupied hospital bed per day (kg/bd/day) (Hunfeld et al., 2023). In the US, a high-income nation, the average amount of general waste generated was 6.4 and 10.7 kg/bed/day for rural and metropolitical hospitals respectively and the average amount of infectious waste 2.03 and 2.79 kg/bed/day for the same hospitals (World Health Organization, 2014).

Waste segregation needs to happen as close as possible to the place of origin. The system that is used most often is the "three-bin system", with general non-hazardous waste in one container, potentially infectious waste in another and sharps into a third. The recommended segregation scheme is more differentiated by using different color coded and labeled containers for highly infectious waste, other infectious, pathological and anatomical waste, sharps, chemical and pharmaceutical waste, radioactive waste and general waste. Moreover, separating non-hazardous or general healthcare waste even further in recyclable wastes and biodegradable wastes is recommended (World Health Organization, 2014). This further separation of non-hazardous or general healthcare waste will be explained further in sub-section '2.3.6. Waste management', as further separation is required in a circular hospital.

Proper separation, disposal and treatment of hazardous waste is important as improper management can cause some serious health risks. Infectious and sharps waste might contain pathogenic microorganisms that can infect patients, hospital staff or others though an incidental cut, mucous membrane, inhalation, or ingestion. Chemical and pharmaceutical waste, including heavy metals inside medical equipment, might cause intoxication, corrosion, an explosion, inflammation, or a chemical reaction (World Health Organization, 2014).

Table 1

Overview of healthcare waste (World Health Organization, 2014)

Category name	Description
Sharps waste	Used or unused sharps (e.g. hypodermic, intravenous or other needles; auto-disable syringes; syringes with attached needles; infusion sets; scalpels; pipettes; knives; blades; broken glass).
Infectious waste	Waste suspected to contain pathogens and that poses a risk of disease transmission (e.g. waste contaminated with blood and other body fluids; laboratory cultures and microbiological inventories; waste including excreta and other materials that have been in contact with patients infected with highly infectious diseases in isolation wards).
Pathological waste	Human tissues, organs or fluids; body parts; fetuses; unused blood products.
Pharmaceutical waste, cytotoxic waste	Pharmaceuticals that are expired or no longer needed; items contaminated by or containing pharmaceuticals. Cytotoxic waste containing substances with genotoxic properties (e.g. waste containing cytostatic drugs – often used in cancer therapy; genotoxic chemicals).
Chemical waste	Waste containing chemical substances (e.g. laboratory reagents; film developer; disinfectants that are expired or no longer needed; solvents; waste with high content of heavy metals, e.g. batteries; broken thermometers and blood-pressure gauges).
Radioactive waste	Waste containing radioactive substances (e.g. unused liquids from radiotherapy or laboratory research; contaminated glassware, packages or absorbent paper; urine and excreta from patients treated or tested with unsealed radionuclides; sealed sources).
Non-hazardous or general healthcare waste	Waste that does not pose any particular biological, chemical, radioactive or physical hazard.

2.3. The circular hospital

This section combines the previous two sections by discussing CE benefits, measurement, product design and business models specifically this time specifically for the healthcare sector. The first four sub-sections discuss the environmental, economic, and social benefits and monetization of those benefits for the healthcare sector. Then a sub-section '2.3.5. Product design and business models for circular medical devices' discusses value retention strategies and circular business models for MDs. After this sub-section '2.3.6. Waste management' again discusses waste management, but this time from a circular economy perspective. Lastly coming forth from circular hospital literature, the need for research into solutions for the material logistics infrastructure in a circular hospital is explained in sub-section '2.3.7. Required material logistics infrastructure', and the research question of this study that is formulated to fill this gap is presented.

2.3.1. Environmental benefits

In a healthcare sector, LCA is also the most used tool to assess environmental impacts, compare those of alternative products, processes and systems, and with that inform healthcare decision-making. Healthcare sustainability science is an emerging field of research that identifies resource use of healthcare services and with that the environmental impacts, evaluating approaches that not only improve patient safety but also protect global health (Sherman et al., 2020). The *HealthcareLCA database* serves as an open-access repository for all healthcare-related LCA, supporting the evidence-based transition towards sustainable healthcare. The number of MDs and processes in this database have grown exponentially over the past two decades, showing the emergency field of 'healthcare sustainability science' (Drew et al., 2022; McGain et al., 2020).

LCA is used to assess healthcare services at multiple levels, from big to small; global supply chain, national health sector, health system, medical facility, clinical care pathway or basic materials, drugs and MDs (Sherman et al., 2020). Depending on the level of the FU, two main approaches can be distinguished: bottom-up and top-down.

A process-based, bottom-up approach involves measuring data on the material input of the FU and using LCI databases that report emissions associated with those materials. This type of research aims at understanding drivers and solutions to environmental emissions by making comparisons. This includes comparing the materials of MDs, comparing SU with RER MDs, comparing pharmaceuticals and comparing different clinical care pathways (Drew et al., 2022; McGain et al., 2020; Sherman et al., 2020).

An environmentally extended input-output (EEIO), top-down approach couples country data on monetary spend with data on pollution emissions to allow for approximation of different economic sectors. The FU are complex systems that would be impossible to study using a bottom-up approach. This includes national health sectors, health systems or hospitals, and aims at identifying areas of concern such as MDs or pharmaceuticals (Drew et al., 2022; McGain et al., 2020; Sherman et al., 2020).

As of December 2021, the *HealthcareLCA database* consists mostly of studies of MDs (40%), followed by pharmaceuticals (18%), procedures (11%), systems (11%), services (9%), medical interventions (5%), clinical investigations (3%), randomized controlled trails (1%), companies (1%), and industries (1%). Most of those studies follow a bottom-up approach (72%), some used a top-down approach (13%), and another section used a combination of bottom-up and top-down approaches (15%) (Drew et al., 2022).

2.3.2. Economic benefits

Viani, Vaccari & Tudor (2016) performed semi-structured interviews with stakeholders from hospitals in England and Italy to try and find the challenges of implementing circular value retention strategies from MDs, with a case study of the laryngoscope. In England, SU laryngoscopes where dominant because of perceptions on costs and infection prevention, while in Italy RER laryngoscopes that were being sterilized in-house after their use were still dominant. One of the common challenges they found is that having no good communication between departments, for example between procurement and waste management,

influences their perception on total LCC. What we can learn from this is that hospitals should use total LCC methods, using cost data from all departments to calculate financial benefits from circular business models. Multiple studies have proven that the LCC of RER MDs can be lower than SU MDs (Boberg et al., 2022; Eckelman et al., 2013; Fargnoli et al., 2018; Hospodková et al., 2023; McGain et al., 2010; Sanchez et al., 2020; Sherman et al., 2018).

Besides the direct financial benefits of RER versions compared to SU versions of MDs, being less vulnerable for supply chain disruptions is an additional benefit (Macneill et al., 2020; Singh & Parida, 2022).

2.3.3. Social benefits

In the healthcare sector, social benefits are also the least researched. A report on Circular Rotterdam from Metabolic, Glade et al. (2018) studied the healthcare sector as one of their focus points and looked at the opportunities for job creation when going circular. They mention that robotization, needed for circularity on healthcare, has a negative effect on employment, but on the other hand it creates jobs in automation, production design and maintenance of those robots.

2.3.4. Monetizing impact

In circular healthcare literature, there have also been a few who recognize the potential benefit of monetizing impact, by using full-cost accounting. Incorporating environmental and social externalities as costs (by monetizing them) into the traditional financial costs and then weigh these costs against patient and population outcomes will help healthcare decision making to steer towards value-based healthcare (Macneill et al., 2020; Sherman et al., 2020).

2.3.5. Product design and business models for circular medical devices

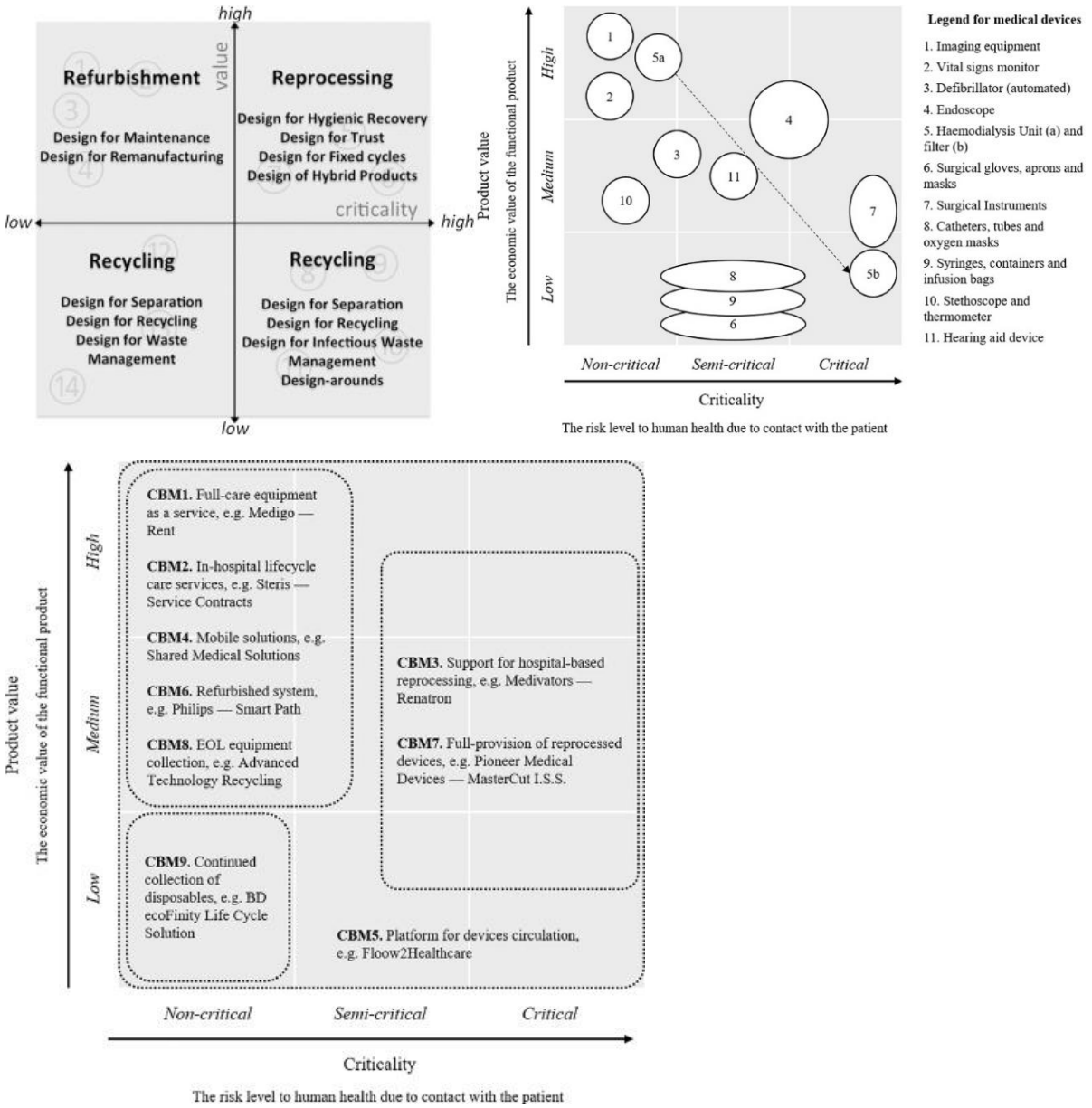
Kane et al. (2018) researched different design strategies for circular MDs. By performing a literature review, they identified different types of obsolescence in the MD industry, and the value retention strategies that prevent these types of obsolescence from becoming waste. The identified strategies were all similar to one of the 10R value retention strategies of Reike et al. (2018), but also included one extra value retention strategy following a type of obsolescence that is specific for the healthcare industry. 'Hygienic obsolescence' happens when MDs become unhygienic after clinical use and through 'reprocessing' they can be used again. The researchers identified two main factors that influenced the value retention strategy and product design for MDs the most; how easily MDs can be recovered after clinical use (criticality) and how much value can be retrieved from value retention (product value). Criticality is measured on the 'Spaulding scale' (McDonnell & Burke, 2011), defining how thoroughly a certain MD needs to be sterilized or disinfected. 'Critical products' are all MDs that enter tissue or the vascular system and after removing all organic materials, require sterilization with high-pressure steam or, when the MDs are sensitive to heat, a gas plasma. 'Semi-critical products' are MDs that contact mucus membranes or non-intact skin and must be disinfected on a high level, for example by full immersion in a chemical. 'Non-critical products' are all MDs that have only touched intact skin and therefore light disinfection with alcohol is sufficient. After placing the identified MDs on a scale with these two identified main factors criticality and product value on the axis, they coupled this with the identified value retention strategies and design strategies, as presented in figure 2, top left.

Guzzo et al. (2020) build forth on the work of Kane et al. (2018), first by improving the product value vs criticality matrix from just 'low and high' to 'low, medium, high' for product value and 'non-critical, semi-critical and critical' for criticality, as presented in figure 2, top right. Moreover, it is important to notice that they placed the Haemodialysis unit (5a) and filter (5b) in two different places, because these different subparts of the MD have different value and criticality and thus need to have different retention strategies. Such MDs are called modular (MOD) MDs in this study. The researchers continued by identifying circular business models for the MD industry and placing them in the same matrix, as presented in figure 2, bottom. The circular business models they identified consist of combinations of products and services that enable

one or multiple technical cycles and have positive economic, environmental and/or social impact compared to business as usual. The technical cycles are repair and maintenance, reuse and redistribution, refurbishment and remanufacturing, and recycling.

Figure 2

Top left: design strategies for circular MDs (Kane et al., 2018). *Top right: MDs inside 'product value vs criticality' matrix* (Guzzo et al., 2020). *Bottom: Circular Business Models for MDs inside 'product value vs criticality' matrix* (Guzzo et al., 2020).



CBM1, full-care equipment as a service, describes a business model where the product is delivered as a service and with that the supplier is responsible for the continuous availability of the equipment including the maintenance and repair. Fargnoli et al. (2018) proposed a methodology for creating and evaluating product-service systems. This methodology starts with identifying the markets demand and customers need, followed by identifying scenarios with improved economic and environmental impacts using LCA and LCC. The researchers applied their methodology to a case of MDs showing that servicing can be economically and environmentally beneficial.

CBM2, in-hospital lifecycle care services, describes a maintenance contract including predictive and corrective maintenance aiming to achieve the agreed service level. The hospital is now owner of the equipment, only has a repair and maintenance contract on top of it, compared to CBM1 where the supplier remained owner.

CBM3, support for hospital-based reprocessing, is a business model where equipment supporting in-house sterilization and disinfection processes are provided, including consultancy on improvement of those processes. In-house sterilization is viable for hospitals that have enough demand, space, and personnel to make reprocessing a cost attractive option. Bang et al. (2019) found that reprocessing duodenoscopes is economically more attractive than using SU ones, except for hospitals that don't have enough volume to do that. Viani, Vaccari & Tudor (2016) found that hospitals that have their own adequately sized inhouse sterilization unit, perceived SU MDs as more costly. If hospitals do not have enough demand, space, and personnel to do inhouse reprocessing, another option might be for hospitals in a network to bundle their sterilization in a central service which was studied by Tlahig et al. (2013).

CBM4, mobile solutions, is a business model where large and expensive equipment are offered as services in trucks or temporary buildings on a short-term contract. This is especially interesting for hospitals deal with fluctuating demand.

CBM5, platform for MD circulation, is a solution for increasing the use rate of MDs. It consists of third-party platforms that either facilitate sharing, renting or selling of MDs among departments or different hospitals.

CBM6, refurbished systems, describes a business model that delivers high value MDs with a same-as-new warranty. Providers of this business model often include MD selection, de-installation and trade-in schemes of the old MDs, part replacement, software upgrades, cosmetic changes and performance checks.

CBM7, full-provision of reprocessed MDs, is a business model where reprocessing of SU MDs is being taken over as a service. To explain this, an important distinction between reprocessing RER MDs and SU MDs needs to be made. Whether or not a MD is labeled as SU or RER is up to the manufacturer. RER MDs are designed for reuse and come with instructions on how to do the reprocessing. A SU MD might also be reprocessed, but the reprocessor will take over the full responsibility of the reprocessed MD from the OEM. According to the MDR, the reprocessed SU MD should, just like every 'normal' MD that is placed on the market, get a CE-certification, before they can be placed on the used. This CE-certification can be received through an independent organization that checks whether the MD complies with all regulations (European Commission, 2023). Because this is a risk and a hassle for hospitals, this business model is created. This business model often relies on initial disinfection and proper sorting in the right containers first by hospital employees. The supplier or service provider then collects the MDs, reprocesses and inspects them according to the local regulations, thus carrying the burden should something go wrong, and provides them back at the hospital as reprocessed. Price mechanisms used are either discounts, rebate checks or a pay-per-use service model. The CE-certified surgical shaver of *Pioneer Medical Devices AG* is a textbook example of such a MD and business model. This MD makes use of two design strategies from Kane et al. (2018), who also suggest those two design strategies are best performed in combination with a servicing business model. The first design strategy that is used in this MD is to 'design for a fixed number of cycles', instead of a certifying a MD either as SU, with only one use, or as RER, with infinite uses, which is never really the case as MDs can always get mechanically or chemically damaged though reprocessing. The second design strategy is 'design for disassembly' where the product is designed so that all different elements are detachable, and those elements have different cycles. Again, such MDs are called MOD in this study. The surgical shaver consists of a critical shaver head and a non-critical control unit. The shaver head is designed to be sterilized at the fixed number of 10 times and is sold on pay-per-use model meaning *Pioneer*

*Medical Devices A*G takes back the shaver and is responsible for keeping track of the number of cycles per shaver head.

CBM8, EOL equipment collection, concerns the collection and proper handling (parts harvesting and recycling of non-valuable parts) of Waste Electrical Electronic Equipment (WEEE) by a recycling company certified to do so.

CBM9, continued collection of disposables, is the only business model identified specifically for low-value non-critical products, also known as SU MDs. In this business model, the MDs first need to be correctly sorted into separate bins by hospital employees, then a recycling company continuously collects them to be recycled. Even though this is a last resort solution, as recycling is one of the lower and therefore one of the least preferred value retention options (Reike et al., 2018), it is still important as it saves (plastic) waste from being incinerated. Waste incineration is the most harmful plastic disposal method, polluting air, soil and water which in turn has many negative health impacts, while this still happens with a significant amount of the waste created (Health Care Without Harm (HCWH) Europe, n.d.).

2.3.6. Waste management

In a circular economy waste does not exist and is designed out by intention (Ellen MacArthur Foundation, 2013a). However, in a hospital, hazardous waste streams will always exist. As mentioned in previous sub-section about waste management '2.2.2. Waste management', the world health organization waste (World Health Organization, 2014) found that only 15% of all waste is considered hazardous waste and that further segregation of the category residual or non-hazardous healthcare waste which is 85% is encouraged. The green deal sustainable healthcare 3.0 (Dutch Government & Healthcare sector, 2022) goal around waste is for hospitals to have 25% less residual hospital waste (Non-hazardous or general healthcare waste) in 2026 compared to 2018 and to have only 25% residual hospital waste in 2030. Thus, this 85% residual or non-hazardous healthcare waste (World Health Organization, 2014) should be reduced to only 25% in 2030. Lowering the residual or non-hazardous hospital waste stream will safe this stream from being incinerated, which will not only result in lower carbon footprint but also in lower financial savings as found by Rizan et al. (2021) and van Straten et al. (2021). Rizan et al. (2021) studied the environmental impact of different processing methods from waste streams from a UK hospital. They argue that healthcare waste policies should encourage processes with the lowest GWP such as recycling surgical instruments and surgical linens (21 kg CO2e/tonne waste), recycling batteries (65 kg CO2e/tonne waste) or low temperature incineration with energy from waste for dry mixed recyclable waste and domestic waste (172 kg CO2e/tonne waste) and for non-infectious offensive waste (249 kg CO2e/tonne waste). Infectious waste might be autoclaved followed by low temperature incineration with energy from waste (569 kg CO2e/tonne waste), rather than sending it for high temperature incineration (1,074 kg CO2e/tonne waste). Van Straten et al. (2021) performed a feasibility study to show if it was financially feasible to collect SS waste consisting of mostly surgical instruments from the Operating Rooms (OR) to repair or recycle it. The SS waste was collected during six months from three hospitals in the Netherlands and was first washed and autoclaved, then at *Van Straten Medical* (*VSM*) they saw if they could repair some of it and if that was not possible, recycle it into SS raw material. The results showed that of the 1380 kg, 237 kg was repaired to be reused saving 38,868 EUR for the hospitals, compared to if these MDs would be bought new. The other 1,143 kg was recycled into SS raw material worth 1,040 EUR, which was sufficient covering logistics and disinfection costs for *VSM*. Lastly, another savings for the hospitals was on waste handling costs and this was another 316 euros. Total hospital savings therefore resulted in 39,184 euros.

There are however multiple difficulties around waste management from MDs, that Moultrie et al. (2015) summarizes in three main problems. First, many MDs end up in hazardous waste streams while being uncontaminated and fit for recycling. Second, toxic or hazardous substances are present in MDs, like plastics and their plasticizers (especially PVC) and heavy metals in WEEE. Third, the dominance of SU

MDs in the industry, and once their packaging is opened everything inside needs to be discarded, regardless of whether it has been used or if safe reuse would be possible.

2.3.7. Material logistics infrastructure in a circular hospital

Research into how the material logistics infrastructure in a circular hospital looks like, and what solutions are required to support the shift from SU towards RER MDs is lacking and therefore has been mentioned as important area for future research by multiple authors.

Viani et al. (2016) found that hospitals had difficulties with disassembly and segregation, because of limited space. For some hospitals this was combined with having limited potential buyers of the recycled streams, resulting in difficulties with setting up profitable recycling streams. Kane et al. (2018) identify the most effective ways of encouraging waste segregation as future research area. The World Health Organisation (2014) state the importance for hospitals to obtain accurate data about their waste streams so they can identify locations where waste segregation is going well and where it can be improved. Moreover, the data should be used to determine recycling or waste minimization measures and to estimate quantities of hazardous waste streams as those require special handling. Next to this, the data can be used to specify waste collection and transport equipment, storage areas, treatment technology and disposal arrangements. In addition to this, Sherman et al. (2020) mention optimizing resource and waste management are necessary components, but alone not sufficient to reach a sustainable future. According to them metrics should encourage management decisions towards a better (circular) system. Macneill et al. (2020) mention the importance to look for opportunities for slowing and closing material and energy loops within a facility. To do this, hospitals should reorganize their infrastructure for reuse and for collecting recyclable materials for which reuse is not possible. For reuse this means creating reprocessing facilities for MDs. Moreover, if hospitals cannot find a reuse case for a MD within their own facility, then they should look for reuse opportunities across industries and organizing this again requires the right material logistics infrastructure.

In conclusion, when circularity becomes a core strategy of hospitals and MDs are handled in a circular way, the material logistics infrastructure inside hospitals will need to be adapted and solutions are required to do this, but research on what this entails is lacking. This study intends to fill this research gap by answering the following research question:

***RQ**: What are the implications on the material logistics infrastructure in a circular hospital?*

3. Methodology

This chapter describes all important aspect related to the methodology of this study, including the research objective, research questions, scope, research strategy and methods and data collection.

3.1. Research objective

The objective of this study was to design a list of alternative viable material logistics infrastructure solutions that can help to move away from SU MDs towards RER MDs, and other solutions that increase circularity, so that they can be implemented by Dutch academic hospital managers to improve environmental and health impact and save on costs. Both academic and management literature were combined with observations, expert knowledge and archival documentation of Dutch academic hospitals Erasmus Medisch Centrum (Erasmus MC) and Leids Universitair Medisch Centrum (LUMC) and expert knowledge from business offering a solution and experts by experience of a solution.

3.2. Research questions

To reach this research objective the following research question was answered:

***RQ**: What are the implications on the material logistics infrastructure in a circular hospital?*

Four sub questions were answered that support answering the research question. The main problem that this study intended to solve, as defined in chapter '2. Conceptual background', is that the current material logistics infrastructure around MDs is not designed for handling RER MDs, and is mostly linear, having a negative impact on the environment and global health. To understand how this problem exactly looks like, in SQ1 MDs are captured in a typology based on what material logistics infrastructure elements are required when switching from a SU towards a RER version and increase circularity.

***SQ1**: How can MDs be captured in a typology based on what material logistics infrastructure elements are required when switching to their RER version?*

In SQ2, the created typology of SQ1 was used to see how well the current material logistics infrastructure inside the two case hospitals Erasmus Medisch Centrum (Erasmus MC) and Leids Universitair Medisch Centrum (LUMC) can handle RER MDs and is circular, and what problems can be observed that hinder moving towards more RER MDs and increase circularity.

***SQ2:** To what extent have the two case hospitals implemented circularity based on the typology and what problems can be observed?*

In SQ3, requirements for design solutions, or design criteria, were created to make sure that the solutions that were designed when answering SQ4 were according to the right requirements.

***SQ3:** What are requirements for design solutions in a circular hospital?*

Lastly, in SQ4, alternative design solutions for the observed problems for SQ3 were presented. When implemented, these solutions create a material logistics infrastructure that is required in a circular hospital.

***SQ4**: What are the alternative design solutions for the observed problems to create a material logistics infrastructure that is required in a circular hospital?*

3.3. Scope

This study aimed to design solutions for Dutch academic hospitals, however this does not mean that the solutions that were designed would not work in non-academic or non-Dutch hospitals. The external validity of this study will be discussed further in subsection '7.4. Limitations'. The choice to study Dutch academic

hospitals was made because of their size and willingness to cooperate and innovate. To answer SQ1, a selection of MDs had to made in order to capture them in a typology, because not all MDs could be analysed as there are over 500,000 different MDs on the EU market (European Commission, n.d.). The scope for this selection was all MDs that are used in a hospital (not only Dutch or academic) that have an LCA (and LCC) study, because these MDs already have a working RER versions and can give an indication on what the environmental and/or cost savings would be when switching from one version to another, as LCA and LCC are approaches to measure environmental impact and costs respectively, like mentioned in the conceptual background sub-section '2.1.6. How to measure these benefits – or impact'.

3.4. Research strategy

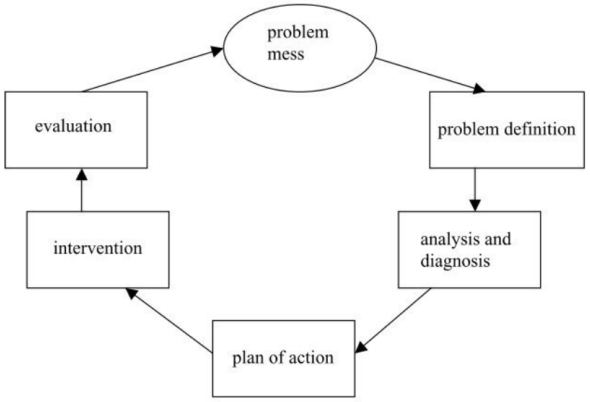
To reach the research objective, the research strategy that was used was design science research, which can be described as research based on the approach of design sciences, that is, research that develops valid general (prescriptive) knowledge to solve field problems (van Aken & Romme, 2009). This strategy was chosen to reach the research objective, because this study aimed at finding solutions for the field problem that the current material logistics infrastructure around MDs is mostly linear and therefore having a negative impact on the environmental and global health. This study was not a quest for truth, for example measuring these negative impacts. Instead, it was a quest to improve this field problem by finding material logistics infrastructure solutions that can be implemented to increase circularity. This study not only aimed at creating descriptive knowledge about how the material logistics infrastructure of Dutch academic hospitals currently is designed and why, but also prescriptive knowledge on how the material logistics infrastructure of Dutch academic hospitals should be designed to move towards a material logistics infrastructure that is able to handle RER MDs and increase circularity – solving the problem.

3.5. Methods and data collection

The problem-solving cycle (van Aken et al., 2007), which is a known method in design science research, was used to structure this study, except for the last step 'evaluation' as presented in figure 3. Design science research can use all methods for data gathering and analysis (van Aken & Romme, 2009). As mentioned in the research objective, data collected in this study comes from academic and management literature combined with observations, expert knowledge and archival documentation of two Dutch academic case hospitals Erasmus MC and LUMC and expert knowledge from business offering a solution and experts by experience of a solution. During each phase of this problem-solving cycle, different combinations of these collected data were used to answer the research questions, and this will be explained further in the sub-sections below that discuss the different phases of the problem-solving cycle.

Figure 3

Problem-solving cycle (van Aken et al., 2007).



Note. In this study the 'plan of action' and 'intervention' steps were combined in a step called 'solution design'. The 'evaluation' step was not performed.

Moreover, during the full length of this study, an interdisciplinary thesis-lab called 'sustainable hospitals' was joined, which held bi-weekly lectures, workshops, and visits for a group of master students from Leiden, Delft and Erasmus University on topics around sustainability in hospitals (Centre for Sustainability Leiden-Delft-Erasmus Universities, n.d.). Also, the Nevi healthcare conference 2023 was joined with sessions around innovation and sustainability in healthcare (Nevi, 2023). Joining the thesis lab and the Nevi healthcare conference not only helped to get more diverse insights to answer the research questions from the sessions itself, but also helped to get access to the literature, expert knowledge and archival documents needed, because it led to an increased network of (sustainable) hospital professionals.

3.5.1. Problem definition

In this phase, SQ1 was answered focussing on defining the problem by creating a typology. To answer SQ1, mostly process-based, bottom-up LCA (and LCC) studies that compare a SU with a RER version of MDs (dental MDs excluded, because they are not used within a hospital) inside the *HealthcareLCA database* (Drew et al., 2022) were analysed. Besides these LCA (and LCC) studies some other management and academic literature from the conceptual background and insights from the consultations with respondents were also used to support creating the typology.

3.5.2. Analysis and diagnosis

This chapter starts with a short introduction of the two case hospitals, Erasmus MC and LUMC, that was based on management literature (their annual and sustainability reports) and an introduction about the roles of the different internal stakeholders that were used as respondents. Then SQ2 was answered by performing an empirical analysis of the two case hospitals to see how well they have already implemented circularity based on the created typology and what are problems can be observed. The empirical analysis consists of expert knowledge, archival documentation, and observations gained through consultations with respondents from the two case hospitals and some expert knowledge gained through consultations with respondents from business offering a solution and experts by experience of a solution. Moreover, sometimes this phase refers back to LCA (and LCC) studies from the problem definition phase, as the analysis and diagnosis phase builds forth on the problem definition phase.

To start the empirical analysis of how the material logistics is currently designed at the two case hospitals, a visit at their logistics centre was performed. During this visit, the logistics manager was consulted, and observations were made. From here a snowballing technique was used to see what other respondents should be contacted to get the full picture of how the material logistics is currently designed at the two case hospitals from all aspects from the typology. Some respondents were consulted by an online meeting and others were consulted at the hospitals so that also observations could be made during those visits. Before every consultation with a respondent, PowerPoint slides were prepared with specific questions for those respondents around the typology to bring some structure to the consultations. Some respondents were also consulted during sessions of the interdisciplinary thesis-lab 'sustainable hospitals'. After every consultation the most important findings from observations and conversations were recorded in a diary.

Eventually, by using the snowballing technique and the thesis lab, seventeen different consultations (some online, some with observations in the hospital) with respondents from Erasmus MC and seven with LUMC were performed. The archival documentation that was used consist of an overview of collected waste streams and procurement data from their SKUs of 2022 from both hospitals. This archival documentation was received by asking for it during the consultations. All consultations with respondents were coded to be able to refer to them. Respondents from Erasmus MC were coded (E1) till (E17), respondents from LUMC were coded (L1) till (L7). Besides these respondents from the two case hospitals there were six consultations with respondents from business offering a solution and experts by experience of a solution, that were

mostly used in the solution design (plan of action & intervention) phase these were coded (S1) till (S6). Expert knowledge and archival documentation that was shared during or shortly after the consultations, and observations made during the consultations were referred to with the same code. An overview of all consultations with respondents can be found in Appendix A.

During the analysis and diagnosis phase, a total of 70 problems at either one or both case hospitals where observed. These problems are coded [P1] to [P70] and are presented in Appendix B.

3.5.3. Solution design (plan of action & intervention)

This chapter starts with answering SQ3, the requirements for design solutions. These requirements were answered based on expert knowledge and observations during the same consultations mentioned previously, at the two case hospitals. Then a first version of answering the research question is presented, alternative design solutions for the material logistics infrastructure in a circular hospital. These design solutions were answered based mostly on a combination of on the one hand what is already happening at one the two case hospitals and thus again expert knowledge or observations from consultations at the two case hospitals, and on the other hand expert knowledge from consultations with business offering a solution and experts by experience of a solution. These business offering solutions and experts by experience for some of the solutions were either mentioned during conversations with the two case hospitals or through the thesis lab and the Nevi Healthcare conference and then contacted to ask for a consultation. As mentioned above, an overview of all consultations with respondents is presented in Appendix A. Besides information from these consultations also some management and academic literature was used to give more context to the solutions.

4. Problem definition

This chapter focusses on answering SQ1, by creating a typology that further defines the main problem this study intends to solve, that is that the current material logistics infrastructure around MDs is not designed for handling RER MDs, and is mostly linear, having a negative impact on the environment and global health.

***SQ1**: How can MDs be captured in a typology based on what material logistics infrastructure elements are required when switching to their RER version?*

As mentioned in previous chapter, LCA (and LCC) studies that compare a SU with a RER version of MDs (dental MDs excluded, because they are not used within a hospital) inside the *HealthcareLCA database* (Drew et al., 2022) are analysed. In these LCA (and LCC) studies, RER versions are enabled by different technical cycles that are similar to the technical cycles of Guzzo et al. (2020); repair and maintenance, reuse and redistribution, refurbishment and remanufacturing, and recycling. RER versions were always enabled by some type of reprocessing, and in this study 'reuse and redistribution' and 'refurbishment and remanufacturing' are both called types of reprocessing. In a single scenario from a study no reprocessing takes place, but simply wait and reuse. 'Repair and maintenance' is called repair in this study and is not included as a different type of reprocessing, but for MDs from some types of reprocessing repair might be required and for others not. Lastly, switching from a SU to a RER version of a MD is only a level of circularity and not the only circular solution option. Making a MD RER might result in lower environmental impact and costs and is one of the targets of the green deal sustainable healthcare 3.0 (moving to 20% RERs) (Dutch Government & Healthcare sector, 2022), but what happens at its EOL should also critically be assessed, because both versions will still have waste at its EOL and reducing this waste is another target of the green deal sustainable healthcare 3.0 (moving to only 25% residual waste in 2030) (Dutch Government & Healthcare sector, 2022). Therefore, the technical cycle of 'recycling', is important to consider for both the SU as the RER versions. Some LCA (and LCC) studies have included recycling as specific EOL scenario next to EOL scenarios landfilling and incineration, in both the SU and RER versions. When looking for solutions, waste separation and collection should not only be assessed for all MDs that will be identified in this chapter, but also for all other MDs in the hospital, because for some SU MDs (non-critical & low-value) moving to a RER version might not be the best option, as explained in a circular business models of Guzzo et al., (2020) CBM9 "continued collection of disposables".

By analyzing the LCA (and LCC) studies, two criteria are identified to capture the MDs from the analysed studies in a typology based on their differences in the requirements when switching to a RER version on six material logistics infrastructure elements, that are also are identified. The six material logistics infrastructure elements that are identified include 'Transport', 'Tracking and tracing', 'Storage space', 'Reprocessing', 'Repair', and 'Point of collection space'. 'Transport' describes how the MDs (and their packaging) are transported between every step and this is shown by how they flow through the hospital in figures 4 till 9. Inside these figures a round indicates a step outside the hospital, a square indicates a step inside the hospital, a black arrow indicates transport of a MD (and its packaging), and a red arrow indicates transport of waste. 'Tracking and tracing' describes what data about a MD (and its packaging) is being tracked and traced by the hospital to enable the material logistics. 'Storage space' describes space requirements to store MDs (and its packaging) and materials for reprocessing and repair. 'Reprocessing' and 'Repair' both describe what materials, machines and employees are required to enable these elements that are only present in RER versions. 'Point of collection space' describes space requirements for waste to be picked up for either recycling, incineration or landfill or space requirements for MD to be picked up for external reprocessing or repair. The first criterium to capture the MDs from the analysed studies in a typology is the type of reprocessing, as these influence what is required for 'Reprocessing' and 'Repair'. The second criterium is whether this reprocessing happens internal (inside the hospital) or external (outside the

hospital), as this not only impacts what is required for 'Reprocessing' an 'Repair' itself, but also all other elements of the material logistics infrastructure, including 'Transport', 'Tracking and tracing', 'Storage space' and 'Point of collection space'.

Based on the first criterium, there are seven types of reprocessing identified. As mentioned in the conceptual background sub-section '2.3.5. Product design and business models for circular medical devices', Kane et al. (2018) explained that reprocessing is a value retention strategy specific for the healthcare sector and it enables reuse of a MD that has become unhygienic after clinical use. Moreover, this subsection introduced the 'Spaulding scale' (McDonnell & Burke, 2011) that defines how thoroughly a certain MD needs to be sterilized or disinfected in order to be reused again. This scale includes 'non-critical items' where light disinfection is enough, 'semi-critical items' which require high level disinfection, and 'critical items' that need to be sterilized. These three levels on the 'Spaulding scale' were used as a starting point to create the types of reprocessing. 'Critical items' where split in two by their way of sterilizing, as some the most common type of sterilization might damage the MD. The two different types of sterilization identified are steam sterilization (autoclave) and hydrogen peroxide gas plasma sterilization. Now there are four types of reprocessing. Then two more reprocessing types were created for MDs that are reprocessed in their own unique way. The fifth category is reprocessing endoscopes, as they are washed, dried and sometimes also sterilized in machines designed specifically for endoscopes, even though they could otherwise be categorized in high-level disinfection or gas plasma sterilization, depending on the endoscope. The sixth category is for medical textiles as these are washed and sometimes also sterilized at an external laundry service. Lastly, there is a reprocessing type for reprocessing of SU MDs. As also explained in the conceptual background sub-section '2.3.5. Product design and business models for circular medical devices' under CBM7 (Guzzo et al., 2020), SU MDs might also be reprocessed, but then the reprocessor takes on full responsibility thus this will be performed at an external supplier or service provider who is willing to take on this risk. In conclusion, the seven types of reprocessing that are identified are light disinfection, high-level disinfection, steam sterilization, hydrogen peroxide gas plasma sterilization, reprocessing endoscopes, reprocessing medical textiles, and reprocessing SU MDs.

Then, based on the second criterium, four types of reprocessing are split in two, because for those types reprocessing can happen either internally or externally. This is the case for high-level disinfection, steam sterilization, hydrogen peroxide gas plasma sterilization, reprocessing endoscopes. This creates eleven types of MDs that have different material logistics infrastructure requirements across six material logistics infrastructure elements: light disinfection (T1), high-level disinfection (T2 & T3), steam sterilization (T4 & T5), hydrogen peroxide gas plasma sterilization (T6 & T7), reprocessing endoscopes (T8 & T9), reprocessing medical textiles (T10), reprocessing SU MDs (T11). To be able to present the differences from the SU and the RER versions of all types (T1-11), T0 is created that describes the requirements on material logistics infrastructure elements for the SU version, and those are similar across all types (T1-11). This will be explained in section '4.1. SU MDs (T0)' and this will become the first row of the typology presented in **table 2**. Inside this first row of the typology, when a material logistics infrastructure element has no requirement for the SU version, this will be presented with -.

Sections '4.2. Light disinfection (T1)' till '4.8 Reprocessing SU MDs (T11)', the LCA (and LCC) studies will be discussed based on the seven reprocessing types and explain two things. First, these sections explain additional requirements of the material logistics infrastructure elements compared to T0 of each types of MDs (T1-T11) and each type of MD will become a different row in the typology and this is visualized in tables 3, 5, 7, 9, 10, 12 and 14. Inside these rows of the typology, additional requirements are explained with text, where text in brackets indicates that the additional requirement might be needed. Expected changes in 'Storage space' and 'Point of collection space' requirements are indicated with arrows (↓) and (↑), where more arrows indicate more space required, and the reason for the change is mentioned in text. When an element has no additional requirement, this is presented with -. Second, these sections present a summary

of the results of the analysed LCA (and LCC) studies in tables 4, 6, 8, 11, 13 and 15 and discusses these results in the text. The goal of these tables is to create an overview of all MDs that have an LCA (and LCC) study comparing a SU with a RER version, so that hospital employees can look a specific MD up to know what version has lower environmental impact and/or costs. Most of the time the RER version of the MD had lower environmental impact and costs, but sometimes the opposite was true. This is an interesting finding, because this implies that not all MDs that can be made RER also should be made RER. Only RER MDs that have lower environmental impact should be preferred over their SU version and some specific SU MDs that have lower environmental impact should be preferred over their RER versions. Switching from a RER version to the specific SU version will enable that the material logistics infrastructure requirements (later specified in the typology) that were previously used for that RER MD can now be used for switching from a SU to RER versions of other MDs were the RER version have lower environmental impact. Considering switching from a RER to a SU version, however, should be done with extreme care because almost all LCA (and LCC) studies that found a SU version to have lower environmental impact studied a specific version of that MD, and mentioned this versions name and its OEM. This has two implications. First, results might only be valid for that specific SU version and not for all SU versions of that specific type of MD. Second, independency of the authors could be questioned, however, all authors declared to have no conflict of interest. One additional goal for these tables is for when hospitals know their use patterns of the MDs in the tables, they can calculate what the potential environmental and/or cost savings would be when they switch to the version with the lower environmental impact and/or cost. How this would exactly work will be further discussed in section '6.2. Solutions', and the limitations related to interpreting LCA (and LCC) study results will be further discussed in section '7.4. Limitations'.

Each LCA (and LCC) study results table results consists of six columns. The first column in each table is the healthcare disciplines in which the MD is used and includes, 'anesthesia', 'cardiology', 'gastroenterology', 'general healthcare', 'general surgery', 'infectious disease', 'neurosurgery', 'obstetrics and gynecology', 'respiratory medicine' and 'urology'. The second column defines the specific type of the MD. There can be multiple studies who studied the same specific type of MD, and this way they will be presented close below each other. The third column mentions the source of the different studies. The fourth column describes more precise what versions of the specific type of MD are studied. If the name of the specific version of MD or its OEM was mentioned in the study this will be mentioned here. Information on the material composition might also be presented as this might also be used to identify the version of a specific type. Versions of MDs are either SU, RER or MOD which means it consist of different subparts that can be RER or SU, just like the 'design for disassembly' strategy of Kane et al. (2018) that was mentioned in chapter '2. Conceptual background'. The fifth column describes different scenarios and their FU. It is possible that within the specific version of a MD that is studied, multiple scenarios are studied, for example based on how often they are reused or what happens with the materials at their EOL. How many cycles a MD is reused in a RER scenario is presented as a number with a hashtag in front of it. This number can either be the predefined number of cycles or a hypothetical or worst-case scenario of what will happen when a device is reused that number of times (#…). Also, in some studies only the number of years is presented which be specified after the hashtag (#… years). When the reprocessing type in a scenario differs from the usual reprocessing type of that type of MD, this will also be presented in front of the hashtag (… #…), for example in the 'reprocessing medical textiles' type of MD, face masks are sometimes reprocessed SU versions instead of washed RER versions. Besides the number of cycles, some studies also included after how many cycles the MD is repaired and this will then be specified with another hashtag and number (repair #…). Where possible, the FU in which the environmental impact and costs are presented in column 6 and 7 respectively, has been converted to one use of the MD. To do this the environmental impact and costs were divided by the 'real FU' that was used in the study. For example, if the study compared a RER version with 5,000 reuses with 5,000 SU versions and presented the environmental impact as 5,000 uses, this environmental impact was divided by 5,000 to present the 'new FU' of one use. This has been done to

increase comparability. When this is done, the FU is indicated with a * in front of the scenario/FU. Column 6 presents the global warming potential (GWP) per FU which is measured in CO2e. Even though one environmental impact category is not more important than the other, GWP is the most used and commonly understood environmental impact category and therefore has been chosen to be included in the table. Some studies also calculated other impact categories, but because of limited space available in the tables, only GWP is presented. If more impact categories than GWP studied, this is indicated with a * in front of the GWP. Column 7 presents the LCC per FU. Because studies were performed in the UK, the US, Australia or in the EU, the LCC are presented with their valuta GBP, USD, AUD and EUR respectively. When the GWP was not presented in absolute values, this sometimes had to be read from graphs. When this was also not possible, Column 6 states N/A. Column 7 states N/A when the study did not include an LCC.

Finally, in section '4.9 Typology' all rows of the typology that were explained in the previous sections of this chapter are presented below each other to present the full overview of the typology in **table 16.**

4.1. Single use medical devices (T0)

Material logistics infrastructure around SU versions is similar in all reprocessing types as they all follow a simple linear route. Suppliers deliver MDs at the central warehouse, just like explained in the conceptual background, this is the first of the three cycles from the study of Castro et al. (2020). From the central warehouse, MDs are delivered to the decentral storage locations at different departments, which is the second cycle. Both the central warehouse as the decentral storage locations consists of a sterile and unsterile section. In the third cycle, MDs are picked from the decentral storage locations to be brought to the patient care location where the MD is used. The fourth cycle, as suggested by Božić et al. (2022) is waste management and this includes collecting, sorting and removing waste from the place of origin to the point of collection, from where a waste handler picks up the different streams to further handle it. As explained, both SU as RER versions will still have waste, with which different things can happen at its EOL. In some LCA (and LCC) studies these different EOL scenarios were modelled as incineration, landfill or recycling and this is performed by the waste handler. The red arrows in figure 4 represent this fourth cycle. The arrow from the central warehouse represents packaging waste, such as shipping boxes, and packaging that holds multiple boxes with MDs, that are removed before MDs are picked from the racks. The arrow from the decentral storage location represents the last packaging waste that is removed before the MD can be used at the patient location. The arrow from the patient care location represents the SU MD itself that is seen as waste after it has been used. Table 2 summarizes the material logistics infrastructure elements that are required for SU MDs (T0). 'Transport' happens between all stages from central warehouse to point of collection and is likely to be performed by logistics employees. Only the third cycle, picking MDs from the decentral storage location and transporting it to the patient care location is most likely to be performed by a healthcare employee, instead of a logistics employee. 'Tracking and tracing' requirements include inventory levels to ensure MDs are always available for hospital employees to use, the current location of MDs to know where MDs are in case MDs from a bad production batch must be recalled or a when MDs with the shortest expiration date need to be picked, and the amount of waste generated for separate streams. 'Storage space' required are a central warehouse and decentral storage locations. 'Point of collection space' required is a waste department where all separate streams come together to be picked-up by the waste handler.

Figure 4

Simplified flow diagram SU MDs (and their packaging).

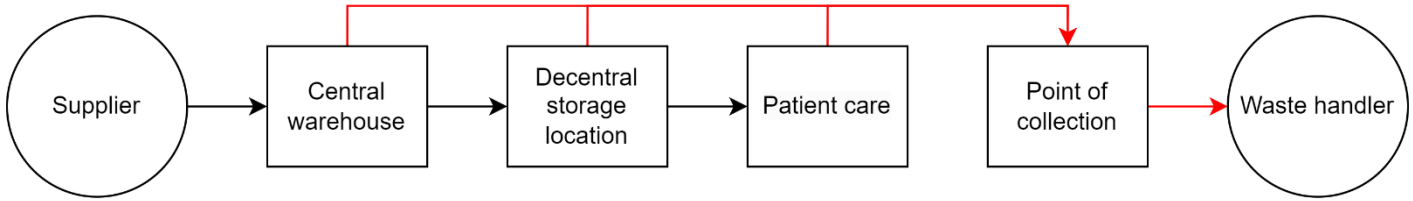


Table 2

Typology for single use medical devices (T0).

Types of MDs			Material logistics infrastructure elements and their requirements					
	Reprocessing type	**Internal/ external**	**Transport**	**Tracking and tracing**	**Reprocessing**	**Repair**	**Storage space**	**Point of collection space**
T0	Single use medical devices (no reprocessing)	-	Figure 4	Inventory levels, current location of unique MDs, waste generated for separate streams	-	-	Central warehouse, decentral storage locations	Waste department for separate streams

4.2. Light disinfection (T1)

Light disinfection (or low-level disinfection) is performed for MDs that come into contact with intact skin (McDonnell & Burke, 2011). MDs that can be light disinfected that have an LCA (and LCC) study are a blood pressure cuff and laryngoscope handle. Their results are summarized in table 4. The material logistics infrastructure required for RER versions of this type is the least difficult because reprocessing happens internally at the patient care location, as presented in figure 5, and no 'Transport' is therefore required to another place for reprocessing, like is required in other RER types. Moreover, this type has no additional 'Track and tracing' or 'Repair' requirements. Even though using only disinfection wipes would be enough according to the Spaulding scale, the manufacturer of blood-pressure cuffs recommended cleaning them in an enzyme bath ones every 5 days, so this was included in the research of Sanchez et al. (2020). Therefore, 'Reprocessing' requirements are disinfection wipes (with alcohol) to disinfect MDs so that they can be reused again, maybe also an enzyme bath, and employees whose time is required to clean the devices. Because the use phase of the MDs is prolonged, inventory levels can be lower and thus less 'Storage space' is required for the MDs (and their packaging) and moreover less 'Point of collection space' will be required because less waste from MDs (and their packaging). A bit additional 'Storage space' 'Point of collection space' for reprocessing equipment will be required, but this will probably not outweigh the lower requirements for the prolonged use phase. Therefore, prolonged use is indicated with (↓↓) and reprocessing equipment with (↑) in table 3.

Table 4 shows, that RER versions can result in lower GWP and costs compared to SU versions. In the study of Sanchez et al. (2020) the SU version of blood pressure cuffs is dedicated to one patient and then discarded. The RER version is cleaned after each encounter or daily for patient dedicated MDs, such as in the IC scenario. Therefore, with patient dedicated MDs the GWP of the RER version is way lower than when MDs are shared as this required more cleaning. In all scenarios the RER version did not only have lower GWP, but also lower life cycle costs compared to the SU version. Laryngoscopy handles sometimes classified to be light disinfected, but also sometimes to be high-level disinfected, therefore Sherman et al. (2018) considered both scenarios, and the RER scenario of light disinfection is included in this table 4 in this section, and the RER scenario of high-level disinfection is included in table 6 in the next section '4.3. High-level disinfection'. When looking at all scenarios from the study of Sherman et al. (2018), RER with high-level disinfection has the lowest GWP and RER with light disinfection has the lowest costs. In a hospital where light disinfection and high-level disinfection are both allowed, monetization of impact can be used here to compare what version is better.

Figure 5

Simplified flow diagram of RER MDs (and their packaging) reprocessed by light disinfection.

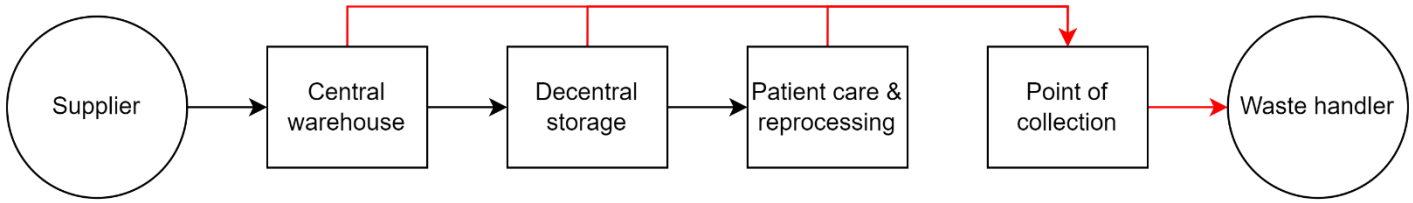


Table 3

Typology for light disinfection (T1).

Types of MDs			Material logistics infrastructure elements and their requirements					
	Reprocessing type	**Internal/ external**	**Transport**	**Tracking and tracing**	**Reprocessing**	**Repair**	**Storage space**	**Point of collection space**
T1	Light disinfection	Internal	Figure 5	-	Disinfection wipes, (enzyme bath), employees	-	Prolonged use (↓↓), reprocessing equipment (↑)	Prolonged use (↓↓), reprocessing equipment (↑)

Table 4

LCA (and LCC) study results for light disinfection.

Light disinfection						
Healthcare discipline	**Specific type**	**Source**	**Version**	**Scenario/FU**	**GWP**	**LCC**
Anesthesia	Laryngoscopic handle	(Sherman et al., 2018)	RER: SS, powered by 2 alkaline C batteries	One use (#400, batteries #40)	0.080	0.58 USD
			SU1: plastic, powered by 3 embedded button-sized lithium ion batteries	One use	1.410	10.66 USD

Anesthesia	Laryngoscopic handle	(Sherman et al., 2018)	SU2: steel, powered by 2 alkaline C batteries	One use (batteries #40)	1.600	10.66 USD
General healthcare	Blood pressure cuff	(Sanchez et al., 2020)	RER: *WelchAllyn Flexiport Reusable Blood Pressure Cuff (Adult size 11)*	One day (20 patient encounters) in an outpatient office/clinic setting (#3 years), incineration	*0.23	4.47 USD
				One day (20 patient encounters) in an outpatient office/clinic setting (#3 years), landfill	*0.18	
				One day (20 patient encounters) in an in-patient setting/general ward with shared MDs (#3 years), incineration	*0.9	17.25 USD
				One day (20 patient encounters) in an in-patient setting/general ward with shared MDs (#3 years), landfill	*0.71	
				One day (20 patient encounters) in an IC with patient dedicated MDs (#3 years), incineration	*0.06	5.15 USD
				One day (20 patient encounters) in an IC with patient dedicated MDs (#3 years), landfill	*0.05	
			SU: *WelchAllyn Flexiport Disposable Blood Pressure Cuff (Adult size 11)*	One day (20 patient encounters) in an outpatient office/clinic setting (#3 years), incineration	*9.78	40.36 USD
				One day (20 patient encounters) in an outpatient office/clinic setting (#3 years) landfill	*7.2	
				One day (20 patient encounters) in an in-patient setting/general ward with shared MDs (#3 years), incineration	*1.96	20.18 USD

				One day (20 patient encounters) in an in-patient setting/general ward with shared MDs (#3 years), landfill	*1.44	
General healthcare	Blood pressure cuff	(Sanchez et al., 2020)	SU: *WelchAllyn Flexiport Disposable Blood Pressure Cuff (Adult size 11)*	One day (20 patient encounters) in an IC with patient dedicated MDs (#3 years), incineration	*1.96	8.07 USD
				One day (20 patient encounters) in an IC with patient dedicated MDs (#3 years), landfill	*1.44	

4.3. High-level disinfection (T2 & T3)

High-level disinfection is performed for MDs that come into contact with mucous membranes or non-intact skin (McDonnell & Burke, 2011). MDs that can be high-level disinfected that have an LCA (and LCC) study are an anesthetic drug dray, laryngoscope blade, laryngoscope handle, bedpan, sharps container and suction receptacle. Their results are summarized in table 6. MDs of this reprocessing type are washed in normal washing machines, that are also used for all MDs that need to be sterilized. Because of the washing step, the material logistics infrastructure required for RER versions of this category is more extensive than light disinfection. Even though sterilization is not required for these MDs, they still need to be brought to the place of reprocessing to be washed and disinfected. This point of retention can be either internally at the central sterile services department (CSSD) of the hospital or externally (for sharps containers it is always externally). Here MDs are put in a washing machine and washed with hot water which is called 'thermal disinfection' (McGain et al., 2010; Sørensen & Wenzel, 2014). The material logistics requirements for RER versions are dependent on whether reprocessing happens internally, as presented in figure 6, T2, or externally, as presented in figure 7, T3. There is one exception MD where reprocessing by high-level disinfection always happens externally, but that moving to that RER version has no impact on the material logistics requirements. This is the case for sharps containers that are used to collect sharps waste. Because both the SU and RER version are picked up at the point of collection, and reprocessing happens externally there are no different material logistics requirements for the hospital.

When reprocessing happens internally, as presented in figure 6, T2, MDs need to be brought to the CSSD and then back to decentral storage from where they can be picked to be used again. This 'Transport' from and to the CSSD is additional transport, but transport from suppliers to the central warehouse, from the central warehouse to the decentral storage location and from the patient care location to the point of collection will be less. Because 'Transport' is more complex with MDs going in multiple use cycles, there is an additional requirement for 'Tracking and tracing' the history of unique MDs. This includes the location of the MD during all phases, so that when something breaks prematurely or goes missing it can be identified where this happens and why. Moreover, the number of cycles a unique MD has been reused should be tracked and traced by the CSSD where the device is reprocessed. When a MD is MOD, then its RER subparts need to be tracked and traced. 'Reprocessing' requirements are washing machines, PPE, packaging (to repack the MD after reprocessing) and employees at the CSSD. 'Repair' is still not required for this type of reprocessing. There are multiple implications on the 'Storage space' and 'Point of collection space' required. First, more 'Storage space' is required because during the time that a MD is being reprocessed, it cannot be used. This is indicated with reprocessing time (↑↑). Second, there will be a bit additional 'Storage space' required for reprocessing packaging that is used after reprocessing to enable storing MDs back at their decentral storage location (↑) and other reprocessing, mostly PPE in this case (↑). 'Point of collection space' required will be less because MDs go into more use cycles and with each cycle less waste from that MD itself is created (↓↓). MDs can either be discarded after reaching their maximum number of cycles and will then flow, just like waste from reprocessing, from the CSSD to the point of collection, or can be discarded when a user decides it cannot be used and will then flow, just like the SU versions, from the patient care location to the point of collection. Therefore, the red arrow from reprocessing to point of collection in figure 6, includes MDs that have reached their maximum number of cycles and reprocessing equipment, being mostly PPE. Packaging waste will be similar as the with the SU versions, because the RER versions are packaged again as explained above and therefore while packaging has an implication on 'Storage space' required, it has no implication on 'Point on collection space' required.

When reprocessing happens externally, as presented in figure 7, T3, MDs are brought to a point-of-collection, which is represented with the black arrow from patient care to point of collection. From this point of collection, an external reprocessor will pick up the MDs and deliver them back at the central storage, just like a supplier of a SU MD would do. 'Transport' from the patient care to the point of collection

is an additional transport, but this transport would otherwise need to happen in the form of waste transport from the patient care to the point of collection. The required 'Point of collection space' will be lower for waste from the MDs itself, but higher for these same MDs that are now collected separately to be picked up by the reprocessor. Again, there is no difference in packaging waste and this time also no additional waste from reprocessing equipment, as reprocessing happens externally. Thus overall, the same amount of 'Point of collection space' is required, but it will consist of more separate streams. Lastly, because reprocessing happens externally there is no additional 'Reprocessing' requirement, and 'Tracking and tracing' the number of reprocessing cycles will now need to be done by the external reprocessor.

Table 6 shows that all RER versions of these MD were found to have a lower environmental impact than the SU version, except for bedpans. Bedpans are used when patients are not able to leave their bed for toilet visits (Sørensen & Wenzel, 2014). After using the RER bedpan, the excreta are flushed and the bedpan itself is washed in the normal washing machine. The SU version, that was found to have the lowest environmental impact, is made an inflatable PE bedpan with a cellulose and SAP inlay. Sharps containers are used to collect sharps waste. SU containers are discarded as a whole including its content. The sharps containers will be picked up by a waste processor who either incinerated or autoclaves it before landfilling. An alternative to this are RER sharps containers, used in a system in the UK and the US. These RER sharps containers are just like the SU sharps containers collected by a waste processor only its content will be autoclaved or incinerated before being landfilled. To reach the content the container is robotically opened and decanted after which the container itself is robotically cleaned and decontaminated to be reused a certified maximum of 500 times (Grimmond & Reiner, 2012). When a RER container reached this EOL, 80% of its materials are being recycled (Grimmond et al., 2021). The RER containers are barcoded to be able to track when they have reached 500 cycles. Grimmond et al. (2021) argue that on average they are reused of 7.4 times/year, giving a theoretical EOL lifespan of 68.5 years. However, they used the 'worst case scenario' of 18 years which is the average years of RER sharps containers in use in the UK in 2021. For McPherson et al. (2019) the oldest RER container still in the US in 2019 was 19 years and this had been used 360 times, giving it a "worst-case" lifespan of 26.4 years. The suction receptacle is used to collect bodily fluids that are sucked up during surgery. It consists of a cannister and a lid, and the RER version also has an "O" ring as a seal between the cannister and the lid. At the CSSD the bodily fluids are flushed in the sewer before the suction receptacle itself is reprocessed. Studies that also included LCC all found the RER versions to have lower costs.

Figure 6

Simplified flow diagram of RER MDs (and their packaging) internally reprocessed.

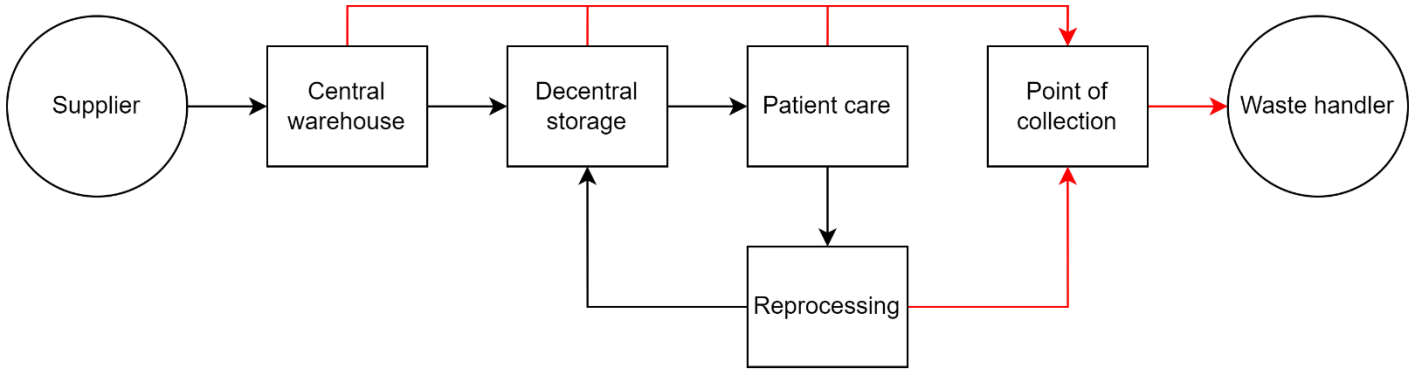


Figure 7

Simplified flow diagram of RER MDs (and their packaging) externally reprocessed.

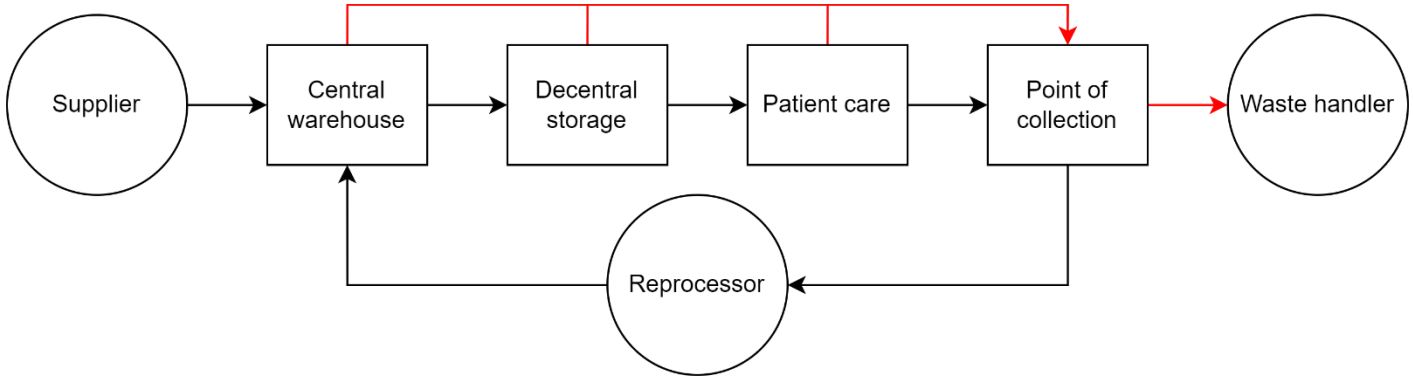


Table 5

Typology for high-level disinfection internal (T2) and external (T3).

Types of MDs			Material logistics infrastructure elements and their requirements					
	Reprocessing type	**Internal/ external**	**Transport**	**Tracking and tracing**	**Reprocessing**	**Repair**	**Storage space**	**Point of collection space**
T2	High-level disinfection	Internal	Figure 6	Unique MD (and RER subparts) history: locations, #cycles	CSSD, washing machine, PPE, packaging, employees	-	Reprocessing time (↑↑), reprocessing packaging (↑), other reprocessing equipment (↑)	More use cycles (↓↓), reprocessing equipment (↑)
T3		External	Figure 7	Unique MD (and RER subparts) history: locations	-	-	Reprocessing time (↑↑↑)	More separate streams

Table 6

LCA (and LCC) study results for high-level disinfection.

High level disinfection						
Healthcare discipline	**Specific type**	**Source**	**Version**	**Scenario/FU**	**GWP**	**LCC**
Anesthesia	Anesthetic drug tray	(McGain et al., 2010)	RER: PA	One use (#300)	*0.110	0.23 AUD
			SU: PE	One use	*0.126	0.47 AUD
	Laryngoscope blade	(Sherman et al., 2018)	RER: SS	One use (#4,000)	0.060	0.98 USD
			SU1: plastic	One use	0.380	10.66 USD
			SU2: steel	One use	0.440	
	Laryngoscope handle	(Sherman et al., 2018)	RER: SS, powered by 2 alkaline C batteries	One use (#400, batteries #40)	0.06	0.98 USD
			SU1: plastic, powered by 3 embedded button-sized lithium ion batteries	One use	1.41	10.66 USD

Anesthesia	Laryngoscope handle	(Sherman et al., 2018)	SU2: steel, powered by 2 alkaline C batteries	One use (batteries #40)	1.60	10.66 USD
General healthcare	Bedpan	(Sørensen & Wenzel, 2014)	RER1: SS (#1000)	One use (#1,000)	0.275	N/A
			RER2: PE (#1000)	One use (#1,000)	0.275	
			MOD: SU cardboard inner bedpan, SU cellulose and SAP liquid absorbing inlay, RER PE back support	One use (back support #1,000)	0.18	
			SU: inflatable PE bedpan, cellulose and SAP inlay	One use	0.14	
	Sharps container	(Grimmond et al., 2021)	RER: ABS polymer *Sharpsmart UK*	Use for 1,000 fill line liter sharps waste (#500 reuses, 18 years lifespan worst case scenario)	50.7	N/A
			SU: PP	Use for 1,000 fill line liter sharps waste	313	
		(McPherson et al., 2019)	RER: ABS polymer	Use for 10,000 APD (adjusted patient days) (#500, 26.4 years lifespan worst case scenario)	2,900	N/A
			SU: PP	Use for 10,000 APD (adjusted patient days)	8,370	
		(Grimmond & Reiner, 2012)	RER: ABS Polymer *Daniels Sharpsmart Inc., Chicago, IL, USA*	Use for 100 occupied hospital beds for one year (#500)	4,000	N/A
			SU: PP *BD, Franklin Lakes, NJ, USA*	Use for 100 occupied hospital beds for one year	24,200	
General surgery	Suction receptacle	(Ison & Miller, 2000)	RER: The canister and the lid, and an "O" ring that acts as a seal between the canister and lid.	One KG of bodily fluid collected during elective surgery at Horton General NHS Trust (GWP) & a year of using the RER version at Horton General NHS Trust (LCC)	4000	195 GBP
				One KG of bodily fluid collected during elective surgery at Horton General NHS Trust (GWP) & a year of using the RER version at Horton General NHS Trust (LCC)	*450	650 GBP

General surgery	Suction receptacle	(Ison & Miller, 2000)	SU: The canister and the lid,	One KG of bodily fluid collected during elective surgery at Horton General NHS Trust (GWP) & a year of using the RER version at Horton General NHS Trust (LCC)	*9,000	18,125 GBP
				One KG of bodily fluid collected during elective surgery at Horton General NHS Trust (GWP) & a year of using the RER version at Horton General NHS Trust (LCC)	*12,500	11,000 GBP

4.4. Steam sterilization (T4 & T5)

MDs that enter tissue or the vascular system and are not heat sensitive should be steam sterilized, after removing all organic materials (McDonnell & Burke, 2011). MDs that can be reprocessed by steam sterilization that have an LCA (and LCC) study are a central venous catheter insertion kit, laryngeal mask airway (LMA), laryngoscope blade, surgical scissors, laparoscopic trocar/port, laparascopic clip applier and cartridge, laparascopic scissors, lumbar fusion set (for implanting 4 scews and two rods) and vaginal sepeculum. Sterile packaging used for steam sterilization is also included in this reprocessing type. Their results are summarized in table 8. One MD that can be reprocessed by steam sterilization that is not included in table 8 is a breathing circuit. This MD comes from the LCA (and LCC) study of McGain et al. (2017) who studied anesthetic MDs including laryngoscope handles that were high-level disinfected, breathing circuit, LMA and laryngoscope blades that were steam sterilized, and videolaryngoscopes that were sterilized by hydrogen peroxide gas plasma. However, their results could not be presented in the tables for high-level disinfection, steam sterilization or hydrogen peroxide gas plasma sterilization, because their scenario/FU was not on a specific MD level, but on a hospital level, measuring the use of a combination of all anesthetic MDs over a year. MDs that are steam sterilized are mostly used at the OR, either for surgery itself or for anaesthesia. Many of these MDs are made from stainless steel (SS) as SS is not heat sensitive. Some of them are sterilized as individual MDs, but most of them are part of a net (also called a tray or a set) that is sterilized. The material logistics requirements for RER versions of this reprocessing type are again dependent on whether reprocessing happens internally, as presented in figure 8, T4, or externally, as presented in figure 9, T5, and are quite similar to high-level disinfection but with some additional changes compared to SU versions.

When reprocessing/repair happens internally as presented in figure 8, T4, 'Reprocessing' requirements at the CSSD are enough washing machines, steam sterilizers that are also called autoclaves, sterile packaging and employees. Washing is a necessary step before sterilization. After washing and before going into the autoclaves, the MDs are packaged with special sterile packaging. This sterile packaging are SU flexible pouches that can be thermally sealed for individual MDs and SU blue wrap or RER rigid sterilization containers for MDs in nets (Rizan et al., 2021). The choice for what sterile packaging for sets is used has significant impact on the 'Storage space' required at the CSSD and also some impact on 'Point of collection space' required. When blue wrap (also called tray wrap) is used, 'Storage space' required for sterile packaging will be a bit more, compared to SU MDs (↑) and the same 'Point of collection space' will be required, compared to SU, because there will still be the same packaging per net or individual MDs used. This is like the high-level disinfection reprocessing internally type (T2). However, when rigid sterilization containers are used, even more 'Storage space' is required for sterile packaging (↑↑), because these containers are rigid and therefore not only take up much more space than blue wrap when no net is inside, but also when a net is inside after being reprocessed, as the container itself is bigger compared to a net packaged in blue wrap because the net needs to be placed inside the container). 'Point of collection space' required will less for rigid sterilization containers (↓), because less packaging waste will be generated, as the packaging itself is now RER. Besides the differences for reprocessing compared to high-level disinfection, MD of this reprocessing type might also be repaired to enable more use cycles and with that increase the MDs lifetime, like shown in the studies on surgical scissors (Ibbotson et al., 2013; Rizan et al., 2022). The study of Rizan et al (2022) analysed three scenarios for RER surgical scissors, and two of which the RER scissors were repaired either on-site or off-site. They showed that the time that the MD cannot be used because it is in repair, which they called turnaround time, was 31.6 days for off-site repair and 3.6 days for on-site repairs. This supports the argument that the 'Storage space' required is a more for internal/on-site repair/reprocessing, because of the reprocessing/turnaround time (↑↑) and more for external/off-site repair/reprocessing, because the MD cannot be used while being away. Rizan et al. (2022) also analysed what other MDs are repaired on-site versus off-site. On-site repair might happen for general surgical scissors, osteotomes, needle holders, retractors, and clamps. Off-site repairs might be more feasible for

more complex equipment, such as endoscopes. Internal repair would happen in another place then reprocessing at the CSSD and is therefore visualised with a different square in figure 8, and 'Transport' will therefore also need to go to this other place of repair. 'Repair' requirements are repair equipment and employees trained to do the repairs. An additional 'Tracking and tracing' requirement for the unique MD (and RER subparts) history is the number of repairs.

When reprocessing/repair happens externally, as presented in figure 9, T5, the requirements for different material logistics elements for the hospital are similar like when high-level disinfection happens externally, as presented in figure 7, T3, because repair cycles should be added by the external repairer, just like with the number of cycles. Despite similar requirements for different material logistics elements, the reprocessing type is still different and therefore it is mentioned as a separate type in the typology, so that it will be analysed separately in the next chapters '5. Analysis and diagnosis' and '6. Solution design (plan of action & intervention)'.

Table 8 shows that RER or MOD versions are found to have lower GWP except for the lumbar fusion set and in one of the two studies for central venous insertion kit and one of the two studies for sterile packaging. In the study of sterile packaging, Rizan et al. (2022) found SU blue wrap (which they call tray wrap) to be better for the environment compared to RER rigid sterilization containers, while they found those same containers to be lower cost. The study of Friedericy (2022) found rigid sterilization containers to have lower environmental impact even when blue wrap was upcycled with closed-loop recycling. These different results might be explained because of the different materials they chose for blue wrap. In the study of the central venous catheter insertion kit of McGain et al. (2012), they compared Australia's brown coal sourced energy and Europe's energy grid and the impact presented in table 8 is the one from Europe as this is more relevant for this study. In a more recent study about the central venous insertion kit, Hemberg et al. (2023), did have Europe in their initial system boundary and included medical textiles from the central venous insertion kit, that were washed at an external laundry as well. They found a MOD version to have the lowest environmental impact a RER version to have the lowest costs. That the GWP results differ depending on the location was also found in the study of McGain et al. (2017), that was not included in table 8. In their analyses they found that switching from SU to RER anesthetic equipment in Australia would increase their GWP by almost 10%, while in the UK/Europe and in the USA this would reduce their GWP by 85% and 50% respectively. They also mention that this is a result of the differences in energy sources in the different countries of which the sterilization process makes use of. In many other studies the RER versions where also found to have lower life cycle costs. The LCC and environmental impact are again also dependent on the number of cycles that the RER MD is reused. A great example is the study of (Eckelman et al., 2013) who found the SU LMA unit costs to 8.76 EUR, compared to 7.33 EUR per unit for the RER LMA if reused 40 times. However, if the RER LMA is discarded prematurely after 20 uses, the unit costs increase to 11.90 EUR, and when the lifetime can be extended to 80 uses, the unit costs decrease to 5.03 EUR. Therefore, they also pointed out that facilities that select RER MDs should implement inventory and operating procedures that ensure that MDs are reused to the greatest possible extent. This supports the importance of tracking and tracing the unique MD history, so that when a MD needs to be discarded prematurely or goes missing, it can be identified where this has happened and why and take action to eliminate the identified root cause.

Figure 8

Simplified flow diagram of RER MDs (and their packaging) internally reprocessed or repaired.

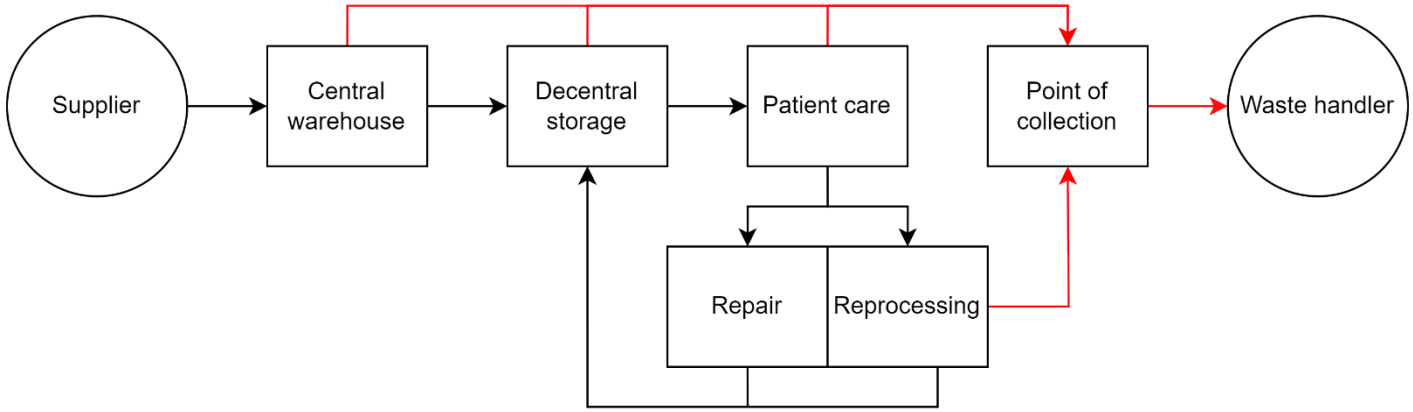


Figure 9

Simplified flow diagram of RER MDs (and their packaging) externally reprocessed or repaired.

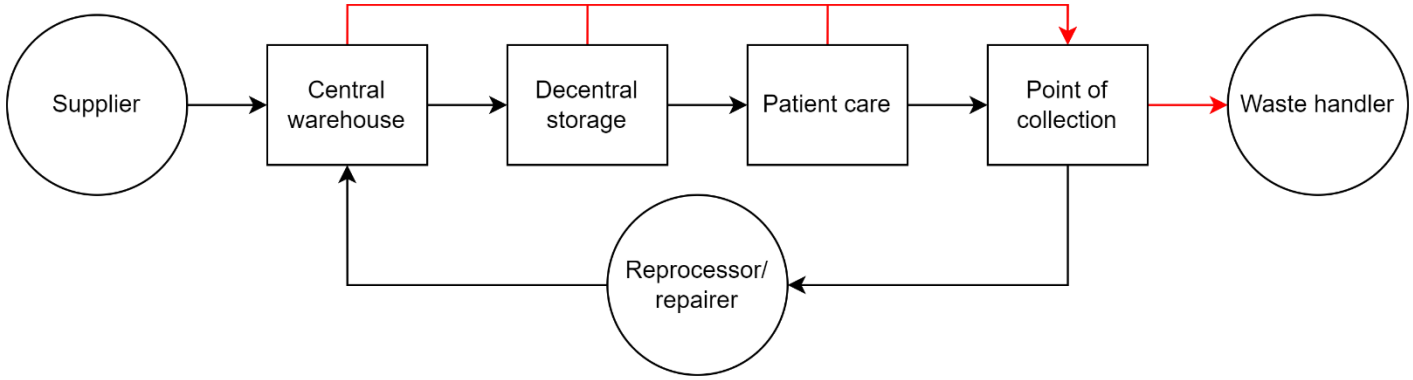


Table 7

Typology for steam sterilization internal (T4) and external (T5).

Types of MDs			Material logistics infrastructure elements and their requirements					
	Reprocessing type	**Internal/ external**	**Transport**	**Tracking and tracing**	**Reprocessing**	**Repair**	**Storage space**	**Point of collection space**
T4	Steam sterilization	Internal	Figure 8	Unique MD (and RER subparts) history: locations, #cycles, #repairs	CSSD, washing machine, autoclave, sterile packaging, PPE, employees	Repair equipment, employees	Reprocessing time (↑↑), sterile packaging: blue wrap (↑) or sterile packaging: rigid sterilization containers (↑↑), other reprocessing equipment (↑)	More use cycles (↓↓), sterile packaging: rigid sterilization containers (↓)
T5		External	Figure 9	Unique MD (and RER subparts) history: locations	-	-	Reprocessing time (↑↑↑)	More separate streams

Table 8

LCA (and LCC) study results for steam sterilization.

Steam sterilization						
Healthcare discipline	**Specific type**	**Source**	**Version**	**Scenario/FU**	**GWP**	**LCC**
Anesthesia	Central venous catheter insertion kit	(McGain et al., 2012)	MOD: three RER SS MDs, SU nylon plastic kidney dish, two RER galley pots	One use (MDs and galley pot #300, sharpening of MDs #100), reprocessed on the European energy grid	0.572	6.35 AUD
			SU: two SS MDs, PP kidney dish, two galley pots	One use	0.407	8.65 AUD

Anesthesia	Central venous catheter insertion kit	(Hemberg et al., 2023)	RER: metal MDs (bowl, scissors, haemostatic forceps, and needle holder), medical textiles (gown and drape)	One use (MDs #300 and medical textiles #70)	*0.24	5.70 EUR
			MOD: RER metal MDs (bowl, scissors, haemostatic forceps, and needle holder), SU medical textiles (gown and drape)	One use (MDs #300)	*1.7	9.10 EUR
			SU: metal (scissors and needle holder) and plastic (bowl and haemostatic forceps) MDs, medical textiles (gown and drape)	One use	*2.3	9.20 EUR
	Laryngeal mask (airway)	(Liang, 2019)	RER: *Ambu® Aura40*	One use (#40)	*N/A	N/A
			SU: *Ambu® AuraStraight*	One use		
		(Eckelman et al., 2013)	RER: *Classic™*	One use (#40)	7.7	8 USD
			SU: *Unique™*	One use	11.3	9.60 USD
	Laryngoscope blade	(Sherman et al., 2018)	RER: SS	One use (#4,000)	0.22	1.95 EUR
			SU1: plastic	One use	0.38	9.91 EUR
			SU2: steel	One use	0.44	
General healthcare	Sterile packaging	(Friedericy et al., 2022)	RER: rigid sterilization container *B.Braun Medical B.V.* bottom *JK441 (59.2 × 27.4 × 12.0 cm),* lid *JP489*	*One use of a standard format MD net (*European Standard DIN: 480 × 250 × 60 mm*) (#5,000), landfill	0.057	N/A
				*One use of a standard format MD net (*European Standard DIN: 480 × 250 × 60 mm*) (#5,000), recycling	0.054	
			SU: blue wrap *three layered SMS one-step non-woven Quick Check Sterilization Wrap (101 x 101 cm*), landfill	*One use of a standard format MD net (*European Standard DIN: 480 × 250 × 60 mm*), landfill	0.374	
				*One use of a standard format MD net (*European Standard DIN: 480 × 250 × 60 mm*), recycling	0.1766	

General healthcare	Sterile packaging	(Rizan et al., 2022)	RER: aluminum container (2996.54 g), SS basket (1053.09 g)	*One MD reprocessed in a net of 29 MDs in RER (#1,000, basket #116)	0.077	1.05 EUR
			SU1: tray wrap (inner wrap PP, outer wrap paper, indicator tape)	One MD reprocessed in a net of 29 MDs in SU1 (basket #116)	0.066	1.07 EUR
			SU2: Flexible pouch, outer pouch; paper (4.10 g), general PE (5.96 g), inner pouch; paper (3.68 g), general PE (4.83 g)	One MD reprocessed individually with SU2	0.189	7.35 EUR
General surgery	Surgical scissors	(Rizan et al., 2022)	RER: *Straight Mayo*	One use (#400, on-site repair #40)	*0.0563	0.97 GBP
				One use (#400, off-site repair #40)	*0.057	0.97 GBP
				One use (#40, because no repair)	*0.0703	1.43 GBP
		(Ibbotson et al., 2013)	RER: SS	One use (#4,500, repair #750)	*0.067	1.74 EUR
			SU1: SS	One use	*0.267	2.75 EUR
			SU2: plastic	One use	*0.667	3.13 EUR

General surgery	Laparoscopic trocar/port	(Rizan & Bhutta, 2022)	MOD: 5 mm: RER canulla; *Surgical innovations (YC0509511 YelloPort + PLUS™ 5.5 mm × 95 mm Cannula Threaded + Luer)*, RER trocar; *Surgical innovations (YT0509503 YelloPort + PLUS™ 5.5 mm × 95 mm Pencil Point Trocar)*, SU duckbill valve; *Surgical innovations (YA05VSS02 YelloPort + PLUS™ 5 mm Valve S-Use (Tube 2/50 seals))* & 10 mm: RER canulla; *Surgical innovations (YA05VSS02 YelloPort + PLUS™ 5 mm Valve S-Use (Tube 2/50 seals))*, RER trocar; *Surgical Innovations (ET1010503 YelloPort Elite™ 10 mm × 105 mm Pencil Point Trocar)*, SU duckbill valve; *Surgical innovations (EA512US YelloPort Elite™ 5–12 mm Universal Seal)*	One procedure (two 5mm and two 10 mm)	*0.933	59 GBP
			SU: 5 mm, PC (37.68 g), PP (5.66 g), Si (2.18 g), PO (0.71 g) & 11 mm, PC (58.84 g), PP (6.29 g), Si (3.86 g), SS (1.29 g), PO (1.6 g)	One procedure (two 5mm and two 11 mm)	*2.56	102 GBP
		(Boberg et al., 2022)	RER: 5 mm trocar with stopcock, 5 mm cannula without stopcock, 12 mm trocar	One procedure, two small and two big trocars (5 mm trocar and cannula #100, 12 mm trocar #500)	*0.236	34.72 EUR
			MOD: 5 mm RER trocar, 10 mm RER trocar, 5-12 mm SU trocar	One procedure, two small and two big trocars (5 mm #100, 10 mm #500)	*1.014	37.12 EUR
			SU: 5 mm and 5-12 mm trocar	One procedure, two small and two big trocars	*1.13	75.14 EUR
General surgery		(Rizan & Bhutta, 2022)	MOD: RER clip applier *Microline surgical (1002 Reusable multi-fire clip applier 10 mm)*,	One use (clip applier #500)	*0.445	52 GBP

	Laparoscopic clip applier and cartridge		SU clip cartridge *Microline Surgical (1122 Disp. 10clips M/L Titanium K2 cartridge)*			
			SU: SS (64.13 g), PP (24.91 g), PC (19.83 g), PVC (6.71 g), PA (0.40 g), Ti (0.08 g)	One use	*2.56	156 GBP
	Laparoscopic scissors	(Rizan & Bhutta, 2022)	MOD: RER handle *Surgical innovations (101–43,000 Logic™ Vertical Handle without ratchet)*, SU scissor shaft and blade *Surgical innovations (120–7000 LogiCut™ Metzenbaum Scissors disposable)*	One use (handle #500)	*0.378	20 GBP
			SU: SS (27.23 g), PC (26.68 g), Si (5.53 g), PL (0.54 g), Cu (0.3 g), Zn (0.3 g), Ni (0.3 g)	One use	*1.14	24 GBP
Neurosurgery	Lumbar fusion set (for implanting four screws and two rods)	(Leiden et al., 2020)	RER:*Viper 2 from DePuy Synthes*	One use (#300 or #500)	N/A	N/A
			SU: *Neo Pedicle Screw System from Neo Medical SA*	One use		
Obstetrics and gynecology	Vaginal speculum	(Rodriguez Morris & Hicks, 2022)	RER: SS (moving screws replaced if needed)	One use (#50), landfilled	*0.0886	N/A
				One use (#150), landfilled	*0.0692	
				*One use (#250), landfilled	*0.0652	
				*One use (#500), landfilled	*0.0624	
				*One use (#750), landfilled	*0.0614	
				*One use (#50), incinerated	*0.1006	
				*One use (#150), incinerated	*0.0828	
				*One use (#250), incinerated	*0.0792	
				*One use (#500), incinerated	*0.0764	
				*One use (#750), incinerated	*0.0756	
				*One use (#50), recycled	*0.0764	
				*One use (#150), recycled	*0.0538	

Obstetrics and gynecology	Vaginal speculum	(Rodriguez Morris & Hicks, 2022)	RER: SS (moving screws replaced if needed)	*One use (#250), recycled	*0.0524	N/A
				*One use (#500), recycled	*0.052	
				*One use (#750), recycled	*0.052	
			SU: acrylic	*One use, landfilled	*0.444	
				*One use, incinerated	*0.588	
				*One use, recycled	*0.304	
		(Donahue et al., 2020)	RER: *Sklar Merit stainless steel grade 304, Graves and Pederson*	One use (#500)	0.202	N/A
			RER2: surgical SS (grade 316)	One use (#500)	0.216	
			SU: *Welch Allyn KleenSpec, acrylic*	One use	0.878	

4.5. Hydrogen peroxide gas plasma sterilization (T6 & T7)

MDs that enter tissue or the vascular system but are sensitive to heat should be sterilized by hydrogen peroxide gas plasma after removing all organic materials (McDonnell & Burke, 2011). There are no MDs that can be reprocessed by hydrogen peroxide gas plasma sterilization that have an LCA (and LCC) study. Only the study of McGain et al. (2017) of anesthetic MDs includes a videolaryngoscope that requires to be sterilized by hydrogen peroxide gas plasma, after being reprocessed in washer disinfectors for endoscopes. But as mentioned in the previous section, this research did not include impacts on an individual MD level and therefore could not be presented in a table. Thus, reprocessing by hydrogen gas plasma sterilization does not have a table with results from LCA (and LCC) studies. The material logistics requirements for RER versions of this reprocessing type is similar to steam sterilization and follow the same flow throughout the hospital for internal reprocessing/repair, as presented in figure 8, or external reprocessing/repair, as presented in figure 9. The only differences are that MDs will not be sterilized by autoclaves, but by machines that use hydrogen peroxide gas plasma and that this will always happen with individual MDs in pouches instead of also in nets as with steam sterilization. Therefore, when reprocessing happens internally, the 'Reprocessing' requirement are not autoclaves, but hydrogen peroxide gas plasma sterilizers and 'Storage space' and 'Point of collection space' implications for when nets are sterilized in rigid sterilization containers do not apply here.

Table 9

Typology for hydrogen peroxide gas plasma sterilization internal (T4) and external (T5).

Types of MDs			Material logistics infrastructure elements and their requirements					
	Reprocessing type	**Internal/ external**	**Transport**	**Tracking and tracing**	**Reprocessing**	**Repair**	**Storage space**	**Point of collection space**
T6	Hydrogen peroxide sterilization	Internal	Figure 8	Unique MD (and RER subparts) history: locations, #cycles, #repairs	CSSD, washing machine, hydrogen peroxide gas plasma sterilizer, sterile packaging, PPE, employees	Repair equipment, employees	Reprocessing time (↑↑), sterile packaging (↑), other reprocessing equipment (↑)	More use cycles (↓↓)
T7		External	Figure 9	Unique MD history: locations	-	-	Reprocessing time (↑↑↑)	More separate streams

4.6. Reprocessing endoscopes (T8 & T9)

Endoscopes got their own type of reprocessing because they are reprocessed (washing and sometimes also sterilization) and dried by machines that are designed for endoscopes. Endoscopes would otherwise fall under high-level disinfection or hydrogen peroxide gas plasma sterilization because they are sensitive to heat. Endoscopes that can be reprocessed that have an LCA (and LCC) study are a duodenoscope, bronchoscope, flexible cystoscope and flexible utereoscope. Their results are summarized in table 11. Another endoscope that might be reprocessed but was not included in table 11 is a videolaryngoscope, that like explained in the previous section requires sterilization by hydrogen peroxide gas plasma, after being reprocessed in endoscope reprocessing machines. The material logistics infrastructure required for RER versions of this reprocessing type is again similar to steam sterilization and dependent on whether reprocessing/repair happens internally, as presented in figure 8, T8, or externally, as presented in figure 9, T9, but with a couple differences. The biggest difference is again the different machines required for endoscope 'Reprocessing'. These machines include endoscope reprocessing machines that are used to wash and disinfect and sometimes also sterilize the endoscope. These machines can use different types of detergents, most commonly peracetic acid (Baboudjian et al., 2022), which can significantly change the results of the environmental footprint, just like shown in the bronchoscope study of Lilholt Sørensen (2018), where different detergent and PPE use impacted the results. In the flexible cystacope study of Kemble et al. (2023) two different endoscope reprocessing machines that perform washing and sterilization where modelled; "*ASP Evotech® ECR*" and "*Medivators Advantage Plus™ Endoscope Reprocessing System*". Next to endoscope reprocessing machines, endoscopes also need to be dried in special machines dedicated to do that, mostly done in special drying closets. Then, some special cases, like the videolaryngoscope, might require sterilization by hydrogen peroxide gas plasma, after being reprocessed in endoscope reprocessing machines. Thus, when reprocessing happens internally, 'Reprocessing' requirements are an endoscope reprocessing machine, endoscope drying machine, maybe a hydrogen peroxide gas plasma sterilizer and (sterile) packaging, which are again flexible pouches and not MDs in nets. A second difference compared to steam sterilization is when reprocessing internally, 'Transport' distance to the place of reprocessing might be a bit shorter, endoscope reprocessing can be located at the CSSD, but also closer to the patient care location. Therefore the 'Reprocessing' requirement of the CSSD might not be required. 'Repair' might also be required for endoscopes just like modelled in some of the studies (Davis et al., 2018; Kemble et al., 2023). Like mentioned in section '4.4. Steam sterilization (T4 & T5)', the study of Rizan et al. (2022) found that off-site/external repairs might be more feasible for more complex equipment, such as endoscopes.

Table 11 shows that there are mixed results whether SU or RER versions of endoscopes are better. Studies that found SU versions to have a lower environmental impact all studied a specific version of the endoscope and mentioned the name of this specific version and its OEM. As explained in the beginning of this chapter, this implies that the results might only be valid for that specific SU version and not for all SU versions, and that the independency of the authors could be questioned. There is one study that included a MOD version of an endoscope. Le et al. (2022) analysed two RER versions: one without and one with a SU endcap for infection prevention purposes. Unlike other researchers, they also included the risk of infection prevention in their modelling, which was lower for endoscopes with a SU endcap. Remarkable, is that two of the studies compared the same SU and RER version of flexible cystacope but with different results. This could be explained by the endoscope reprocessing machine used and the number of cycles. Kemble et al. (2023) modelled sterilization with "*ASP Evotech® ECR*" and "*Medivators Advantage Plus™ Endoscope Reprocessing System*" and modelled 3,920 reuse cycles with repairs after every 207 cycles. Hogan et al. (2022) modelled a preclean immediately after cystoscopy, followed by sterilization with "*EndoThermo Disinfectors (ETD) endoscopic reprocessing machine*" and modelled only 1120 reuses. In conclusion, there are many factors that could change the outcome of what version has lower GWP including the reprocessing machine and its detergent used, PPE use, number of cycles and different use cases.

Table 10

Typology for reprocessing endoscopes internal (T8) and external (T9).

Types of MDs			Material logistics infrastructure elements and their requirements					
	Reprocessing type	**Internal/ external**	**Transport**	**Tracking and tracing**	**Reprocessing**	**Repair**	**Storage space**	**Point of collection space**
T8	Reprocessing endocopes	Internal	Figure 8	Unique MD (and RER subparts) history: locations, #cycles, #repairs	(CSSD), endoscope reprocessing machine, endoscope drying machine, (hydrogen peroxide gas plasma sterilizer), (sterile) packaging, PPE, employees	Repair equipment, employees	Reprocessing time (↑↑), (sterile) packaging (↑), other reprocessing equipment (↑)	More use cycles (↓↓)
T9		External	Figure 9	Unique MD history: locations	-	-	Reprocessing time (↑↑↑)	More separate streams

Table 11

LCA (and LCC) study results for reprocessing endoscopes.

Reprocessing endoscopes						
Healthcare discipline	**Specific type**	**Source**	**Version**	**Scenario/FU**	**GWP**	**LCC**
Gastroenterology	Duodenoscope	(Le et al., 2022)	RER1: *TJF-Q180V; Olympus, Center Valley, Penn, USA*	One use (#625)	1.54	N/A
			MOD: *TJF-Q190V; Olympus* (with SU endcap)	One use (all but the endcap #625)	1.53	

Gastroenterology	Duodenoscope	(Le et al., 2022)	SU: *Exalt Model D; Boston Scientific, Natick, Mass, USA*	One use	36.3-71.5	N/A
Anesthesia	Bronchoscope	(Sørensen, 2018)	RER: PPE and detergents used for reprocessing operation (materials and energy for production of the RER excluded)	One reprocessing operation after one use	2.9	N/A
			SU: *Ambu® aScope™ 4 broncho*	One use	1.6	
		(Bringier et al., 2023)	RER: *Pentax® FI 16RBS; Pentax France, Argenteuil, France*	*One use (#2,000)	3.9	225 EUR
			SU: *Ambu® aScope™ 4 regular; Ambu A/S, Ballerup, Denmark*	*One use	2.9	85 EUR
Urology	Flexible cystocope	(Baboudjian et al., 2022)	RER: PPE and detergents used for reprocessing operation (materials and energy for production of the RER excluded)	One reprocessing operation after one use	*3.08	N/A
			SU: *Ambu® aScope™ 4 Cysto*	One use	*2.06	
		(Kemble et al., 2023)	RER1: *Olympus® SD Flexible Cysto-Nephro videoscope (CYF-VA)*	One use (#3,920, repair #207), reprocessed with *ASP Evotech® ECR*	1.04	N/A
			RER2: *Olympus® SD Flexible Cysto-Nephro videoscope (CYF-VA)*	One use (#3,920, repair #207), reprocessed with *Medivators Advantage Plus™*	0.53	
			SU: Ambu® aScope™ 4 Cysto	One use	2.4	
		(Hogan et al., 2022)	RER: *Olympus® SD Flexible Cysto-Nephro videoscope (CYF-VA)*	One use (#1,120)	4.23	N/A
			SU: *Ambu® aScope™ 4 Cysto*	One use	2.41	
	Flexible ureteroscope	(Davis et al., 2018)	RER: *Olympus Flexible Video Ureteroscope (URV-F)*	One use (#180, repair #16)	4.43	N/A
			SU: *LithoVue™ (Boston Scientific) single-use digital flexible ureteroscope*	One use	4.47	

4.7. Reprocessing medical textiles (T10)

Medical textiles got their own reprocessing type because RER versions are washed and sometimes also sterilized at an external laundromat. Medical textiles that can be reprocessed that have an LCA (and LCC) study are scrub suit, surgical drape (and tape), surgical gown, surgical pack (surgical gown + huck towel), body coverall, isolation gown, face mask and incontinence underpad. Their results are summarized in table 13. Whether the MDs are sterilized or not, depends on how and where it is worn or used. For example, a scrub suit, is a two-piece garment worn by operating room (OR) employees in hospitals and is composed of tunic and pants. This scrub suit is worn under a sterile surgical gown and therefore the scrub suit itself doesn't need to be sterile (Burguburu et al., 2022). An external laundry facility often supplies a wide variety of medical textiles, just like the one from the study of Vozzola et al. (2020) who processed surgical gowns, drapes, linens, and others. Because reprocessing of medical textiles always happens externally and do not require repair, these MDs flow in a similar way as external high-level disinfection that was presented in figure 7. The material logistics requirements are similar to all other types of external reprocessing/repair, but has some additional differences compared to SU MDs. First, because the material of RER medical textiles is thicker than SU medical textiles, more 'Storage space' will be required, indicated with thicker material (↑) in table 12. Second, for some RER medical textiles the different material might lead to a prolonged use phase and therefore lower inventory levels might be needed, indicated with prolonged use phase (↓↓). This was the case in the incontinence underpad study of Griffing & Overcash (2023) where SU versions are replaced 2.12 times quicker. When the use phase can be prolonged, this also has an implication on 'Point of collection space' required, because MDs to be picked up for reprocessing and MD waste will be less.

Table 13 shows that all RER versions have lower GWP, except for the face mask study of Cornelio et al. (2022), but they only included material production and transport in their analyses and therefore did not include raw material extraction, use or disposal life stages. Materials chosen for the RER version are especially important to assess for medical textiles for multiple reasons. First, because the material logistics reasons mentioned above that a thicker material requires more storage space or when the use phase is prolonged maybe less storage space. Second, because different materials have different environmental impacts. Moreover, because most medical textiles are worn, user comfort and permeability should also be assessed. Different materials might be chosen for parts that should be for example more permeable, because they are more likely to get into contact with (bodily) fluids, just Vozzola et al. identified different materials for critical and non-critical zones in studies of surgical gowns (2020) and surgical drapes (2018b). For face masks, version with the lowest GWP are RER cloth versions that can be washed in normal washing machines (instead on manual as in some scenarios). Moreover, for face masks some scenarios where reprocessing SU medical masks (FFP2 or N95). This was possible because during COVID-19, there was a shortage of PPE including face masks and therefore their CE-certification requirement for placing them on the market got dropped (van Straten, Ligtelijn, og, Putman, Dankelman, Sperna Weiland, & Horeman, 2021). Reprocessing these SU versions were also found to have lower GWP and LCC. Because these face masks are medical textiles they are included in this category and not in the next of reprocessing of SU MDs. There was also a scenario that did not reprocess the mask but simply reused it (by waiting some time before reusing).

Table 12

Typology for reprocessing medical textiles (T10).

Types of MDs			Material logistics infrastructure elements and their requirements					
	Reprocessing type	**Internal/ external**	**Transport**	**Tracking and tracing**	**Reprocessing**	**Repair**	**Storage space**	**Point of collection space**
T10	Reprocessing medical textiles	External	Figure 7	Unique MD history: locations	-	-	Reprocessing time (↑↑↑), thicker material (↑), (prolongued use (↓↓))	More separate streams, (prolongued use (↓↓))

Table 13

LCA (and LCC) study results for reprocessing medical textiles.

Reprocessing medical textiles						
Healthcare discipline	**Specific type**	**Source**	**Version**	**Scenario/FU**	**GWP**	**LCC**
General surgery	Scrub suit	(Burguburu et al., 2022)	RER: PE (65%), CO (35%), *Elis*	*One use (#63.5)	*0.49149	N/A
			SU: PP	*One use	*0.71702	
		(Mikusinska, 2012)	RER: CO (69%), PE (30%), carbon yarn (1%)	One use (#100)	*0.368	N/A
			SU: nonwoven PP outer fabric, lining of 70% viscose and 30% PE	One use	*1.96	
	Surgical drape (and tape)	(Vozzola et al., 2018b)	RER: woven PET (noncritical zone) & knit PET and ePTFE (50%) knit PET and PU (50%) (critical zone)	*One use of medium-sized 4m2 drape, 60 cm tape (#60)	*0.67	N/A
			SU: SMS PP (non-critical zone) & PP film (critical zone)	*One use of medium-sized 4m2 drape, 60 cm tape	*1.07	

General surgery	Surgical gown	(Vozzola et al., 2020)	RER: woven PET (noncritical zone) & knit PET with ePTFE barriers (70%), knit PET with PU barriers (30%) (critical zone)	*One use (#60)	0.557	N/A
			SU: nonwoven PET (non-critical zone) & PP film (critical zone)	*One use	1.64	
	Surgical pack (Surgical gown + huck towel)	(Carre, 2008)	RER: surgical gown; CO (6%), PL (94%), huck towel; CO	One use of a surgical pack (#127)	*1	N/A
			SU: surgical gown; PP, huck towel; paper vibre	One use of a surgical pack	*5.1	
Infectious disease	Body coverall	(Snigdha et al., 2023)	RER: Poly-cotton (65% cotton, 35% PL), PU coating	*One use (#10-15)	*0.29668	N/A
			SU: SMS, PE lamination film	*One use	*1.505	
	Isolation gown	(Vozzola et al., 2018a)	RER: woven PET	*One use (#60)	0.218	N/A
			SU: SMS PP	*One use	0.31	
		(Jewell & Wentsel, 2014)	RER: PET	*One use (#49-98)	*0.168-0.435	N/A
			SU: PP	*One use	*0.655-1.63	
	Face mask	(van Straten et al., 2021)	RER: Reprocessed SU *Aura 1862+, 3M*	One use of 2 hours (steam sterilization, #6)	0.0277	1.40 EUR
			SU: *Aura 1862+, 3M*	One use of 2 hours	0.0655	1.55 EUR
		(Cornelio et al., 2022)	RER1: CO (9.5 g), PU (1.2 g)	One use (#50)	0.012	N/A
			RER2: CO (9.4g), PU (0.4 g)	One use (#50)	0.0098	
			SU1: surgical mask, PP (2.1 g), PU (0.3 g), PVC (0.1 g), Al (0.1 g)	One use	0.006	
			SU2: surgical mask, PP (3 g), PVC (0.1), Al (0.1 g)	One use	0.007	
			SU3: surgical mask, PP (2.2 g), PU (0.4 g), PVC (0.3)	One use	0.00575	

		(Tao & You, 2021)	RER: Reprocessed SU N95 respirator	*One use (vapor hydrogen peroxide #20)	0.0339	0.138 USD
				*One use (dry-heat method #5)	0.05	0.307 USD
			SU: N95 respirator	One use	0.1	0.09
Infectious disease	Face mask	(Bouchet et al., 2021)	RER1: CO (5 g)	*One use/day (#15), home made	0.00033	N/A
			RER2: CO (5 g)	*One use/day (#15), made in China, oceanic freight	0.00817	
			RER3: PL (6.17 g), EL (0.13 g)	*One use/day (#15), made in France, land freighted to Switserland	0.003	
			RER4: PL (6.17 g), EL (0.13 g)	*One use/day (#5), made in Switserland, land freighted within Switserland	0.008	
			RER5: Reprocessed SU surgical mask, PP (2.5 g), PA (0.5 g), Al (0.2 g)	*One use/day (hot drying #10), made in China, oceanic freighted to Switserland	0.00833	
			RER6: surgical mask, PP (2.5 g), PA (0.5 g), Al (0.2 g)	*One use/day (wait and reuse #10), made in China, oceanic freighted to Switserland	0.00167	
			SU1: surgical mask, PP (2.5 g), PA (0.5 g), Al (0.2 g)	*One use/day, made in China, oceanic freighted to Switserland	0.01467	
			SU2: surgical mask, PP (2.5 g), PA (0.5 g), Al (0.2 g)	*One use/day, made in China, air freighted to Switserland	0.046	
		(Allison et al., 2021)	RER: cloth mask	*One use/day (#30)	*0.49702	0.07 GBP
				*One use/day (manual wash #50)	*2.10126	
			MOD: RER cloth mask, SU filter	*One use/day (#30)	*1.16859	
				*One use/day (manual wash #50)	*3.25292	
			SU: surgical mask	*One use/day	*0.0594	0.26 GBP
General healthcare	Incontinence underpad	(Griffing & Overcash, 2023)	RER: knitted PET fiber (top layer), 25% rayon, 75% PET fiber (absorbent layer), PU or PVC (impermeable layer), bottom layer (PET, knit)	One use (#60-100)	0.34	N/A
			SU: nonwoven PP (top layer), 30% super absorbent polymer, 70% cellulose (absorbent layer), PE film, nonwoven PP (bottom layer)	2.12 uses (because SU are replaced 2.12 quicker compared to RER)	0.88	

4.8. Reprocessing single use medical devices (T11)

MDs that are designed for SU can be reprocessed externally to be reused as a MD that performs as least as good as the original MD. The external reprocessor will guarantee the safety and functionality of its reprocessed MDs and the MDs should be in full compliance with the Medical Device Regulations (MDR) thus need a CE-certification that is needed for all MDs. The only MD that is presented in table 15 that has an LCA study where a SU MD is compared with reprocessing that SU MD is the electrophysiology catheter. Other SU MDs that might be reprocessed but were not included in table 15 include face masks, arthroscopic shaver, pulse oximeter, deep vein thrombosis (DVT) compression device, *Ligasure*, endoscopic trocar, ultrasconic scalpel and scissor tip. SU face masks were not presented in table 15, because they were already presented in table 13 in the previous section about reprocessing medical textiles. The other MDs are from an LCA study of Unger & Landis (2016) that was not included because impact was not compared on an individual MD level, but on a hospital level, comparing the combined impact of using all these SU MDs during a year at a hospital called Abrazo Central Hospital with scenarios where these SU MDs are reprocessed at a reprocessor called *Stryker* for 1-5 times. They mentioned reprocessing SU MDs involves decontamination, testing, and repairing after which they are resold for a 50% discounted price compared to new SU MDs. When this external reprocessing of a SU MD happens to a bit more complex MD, such as a catheter, this is called remanufacturing, just like both studies about remanufactured *Vanguard AG* catheters that also both had a CE-certification (Meister et al., 2023; Schulte et al., 2021). The material logistics requirements are again similar to all other types of external reprocessing/repair, as presented in figure 9, but this time with one additional difference compared to SU MDs. This difference with other external reprocessing types is that with the other types reprocessing would mostly happen at the same reprocessor, for example the same laundry service for medical textiles. However, when reprocessing SU MDs will happen at a large scale with many different MDs, the collection and 'Transport' of these different MDs and eventually 'Point of collection space' required will consist of a lot more separate streams, because these MDs will be reprocessed at their own reprocessor who has the CE-certification to do so.

Table 15 shows that remanufacturing electrophysiology catheters will result in lower GWP than when not doing this and just using the SU version. Meister et al. (2023) argue that the electrophysiology catheter is well fit for remanufacturing on a large scale because they have the potential for significant financial savings, physician motivation is high, and remanufacturing is promising. In both studies a rejection rate is presented in the tables besides the number of cycles for RER, because these are SU MDs by design and therefore do not have a predefined number of cycles. Instead, they go to a reprocessor who performs strict controls before reprocessing because they must guarantee the safety and quality of the remanufactured MDs. Therefore, there is always a percentage of MDs that is rejected during this process, which is reflected in the rejection rate. Besides this rejection rate Meister et al. (2023) also included a maximum number of cycles of 5 in which de catheter will be discarded either way. The study of Unger & Landis (2016) that was not included in table 15 found the GWP to increase slightly with more reprocessing instances, but annual costs savings to with one reprocessing to be already 182,000 USD and with five instances even 520,000 USD (in terms of 2013 USD). This LCC includes lower procurement price of 50% that was set by the reprocessor *Stryker* and lower waste handling costs.

Table 14

Typology for reprocessing single use medical devices.

Types of MDs			Material logistics infrastructure elements and their requirements					
	Reprocessing type	**Internal/ external**	**Transport**	**Tracking and tracing**	**Reprocessing**	**Repair**	**Storage space**	**Point of collection space**
T11	Reprocessing single use medical devices	External	Figure 9	Unique MD history: locations	-	-	Reprocessing time (↑↑↑)	Lot more separate streams

Table 15

LCA (and LCC) study results for reprocessing SU MDs.

Reprocessing SU MDs						
Healthcare discipline	**Specific type**	**Source**	**Version**	**Scenario/FU**	**GWP**	**LCC**
Cardiology	Electrophysiology Catheter	(Meister et al., 2023)	RER: Remanufactured SU *Vanguard AG*	One use (#1-5, 15% rejection rate)	0.612	N/A
			SU: *Vanguard AG*	One use	1.53	
		(Schulte et al., 2021)	RER: Remanufactured SU *Vanguard AG*	One use (47,9% rejection rate)	*0.87	N/A
			SU: *Vanguard AG*	One use	*1.75	

4.9. Typology

This section consists of the full typology. The typology will be used in next chapters '5. Analysis and diagnosis' and '6. Solution design (plan of action & intervention)' to find problems, requirements, and solutions for the two case hospitals Erasmus MC and LUMC, that might also be used in other Dutch Academic hospitals. The practical and theoretical implications of the typology as one of the main deliveries from this study will be discussed in chapter '7. Conclusion & discussion'.

Table 16

Typology for all types of medical devices; all reprocessing types internal or external.

Types of MDs			Material logistics infrastructure elements and their requirements					
	Reprocessing type	**Internal/ external**	**Transport**	**Tracking and tracing**	**Reprocessing**	**Repair**	**Storage space**	**Point of collection space**
T0	Single use medical devices (no reprocessing)	-	Figure 4	Inventory levels, current location of unique MDs, waste generated for separate streams	-	-	Central warehouse, decentral storage locations	Waste department for separate streams
T1	Light disinfection	Internal	Figure 5	-	Disinfection wipes, (enzyme bath), employees	-	Prolonged use (↓↓), reprocessing equipment (↑)	Prolonged use (↓↓), reprocessing equipment (↑)
T2	High-level disinfection	Internal	Figure 6	Unique MD (and RER subparts) history: locations, #cycles	CSSD, washing machine, PPE, packaging, employees	-	Reprocessing time (↑↑), reprocessing packaging (↑), other reprocessing equipment (↑)	More use cycles (↓↓), reprocessing equipment (↑)
T3		External	Figure 7	Unique MD (and RER subparts) history: locations	-	-	Reprocessing time (↑↑↑)	More separate streams

T4	Steam sterilization	Internal	Figure 8	Unique MD (and RER subparts) history: locations, #cycles, #repairs	CSSD, washing machine, autoclave, sterile packaging, PPE, employees	Repair equipment, employees	Reprocessing time (↑↑), sterile packaging: blue wrap (↑) or sterile packaging: rigid sterilization containers (↑↑), other reprocessing equipment (↑)	More use cycles (↓↓), sterile packaging: rigid sterilization containers (↓)
T5		External	Figure 9	Unique MD (and RER subparts) history: locations	-	-	Reprocessing time (↑↑↑)	More separate streams
T6	Hydrogen peroxide sterilization	Internal	Figure 8	Unique MD (and RER subparts) history: locations, #cycles, #repairs	CSSD, washing machine, hydrogen peroxide gas plasma sterilizer, sterile packaging, PPE, employees	Repair equipment, employees	Reprocessing time (↑↑), sterile packaging (↑), other reprocessing equipment (↑)	More use cycles (↓↓)
T7		External	Figure 9	Unique MD history: locations	-	-	Reprocessing time (↑↑↑)	More separate streams

T8	Reprocessing endoscopes	Internal	Figure 8	Unique MD (and RER subparts) history: locations, #cycles, #repairs	(CSSD), endoscope reprocessing machine, endoscope drying machine, (hydrogen peroxide gas plasma sterilizer), (sterile) packaging, PPE, employees	Repair equipment, employees	Reprocessing time (↑↑), (sterile) packaging (↑), other reprocessing equipment (↑)	More use cycles (↓↓)
T9		External	Figure 9	Unique MD history: locations	-	-	Reprocessing time (↑↑↑)	More separate streams
T10	Reprocessing medical textiles	External	Figure 7	Unique MD history: locations	-	-	Reprocessing time (↑↑↑), thicker material (↑), prolongued use (↓↓)	More separate streams
T11	Reprocessing single use medical devices	External	Figure 7	Unique MD history: locations	-	-	Reprocessing time (↑↑↑)	Lot more separate streams

5. Analysis and diagnosis

This chapter describes the empirical analysis of the two case hospitals and consists of three sections. As explained in the methodology, data retrieved through respondents from Erasmus MC are referred to with (E1) till (E17), from LUMC (L1) till (L7), and from business offering a solution and experts by experience of a solution (S1) till (S6). The first section gives a short introduction into the two case hospitals and the roles of their internal stakeholders that were consulted as respondents. The second and third section describe how the material logistics infrastructure is designed in the two case hospitals based on the typology, going into the different material logistics infrastructure elements and reprocessing types respectively. During both these sections different problems are identified and thus the combination of both sections answers SQ2. In total 70 problems are identified and an overview, structured by the title of the sub-section they were discussed in, can be found in Appendix B. Moreover, during these two sections some solutions were also identified that are already implemented at the two case hospitals, that will be referred back to in the next chapter '6. Solution design'.

SQ2: *To what extent have the two case hospitals implemented circularity based on the typology and what problems can be observed?*

5.1. Introduction into two case hospitals and internal stakeholders

This section consists of a short introduction of the two case hospitals: Erasmus MC and LUMC and an introduction about the roles of the different internal stakeholders that were consulted as respondents in the analysis.

Erasmus MC

Erasmus MC is a Dutch academical hospital with in 2022, 14,671 full-time equivalents (FTE), 1,215 beds, 30,288 admissions with an average stay of 6.23 days, 659,317 visits to the polyclinics and a CO2 footprint, of 84,184 CO2 (Erasmus, 2023). Their CO2 footprint in 2021 was 84,839 tonne CO2, as presented in figure 10, left consisting of electricity (42,119), processing of waste and production of materials (12,367), natural gas and other fuels for buildings (9,427), procurement of heat and cold (6,291), commuting employees (6,106), travel patients (5,106), travel visitors (2,135), washing textiles (541 tonne CO2), diffuse greenhouse gas emissions (373), travel students (229) (Erasmus, 2021).

However, these CO2 footprints that are presented in the annual reports are mostly scope 1 and 2 emissions, which are the hospitals own direct and indirect emissions. Only a little fraction of scope 3 emissions, that are made at organizations a hospital buys it products and services from, are reported on. In a yet to be released report performed by *Metabolic*, the whole CO2 footprint of scope 1, 2 and 3 was calculated for Erasmus MC by using the EEIO, top-down approach that has been explained in the conceptual background. Then the CO2 footprint was around 210,000 tonne with around 70% coming from scope 3. Around 6.1% from 210,000 tonne comes from waste. From this waste percentage 17.6% is specific hospital waste and 72.1% is residual waste. Around 10% of the scope 3 emissions come from MDs and 7% of those are 'scan relevant' MDs, because these are more expensive MDs such as implants and the EEIO, top-down approach couples emissions with monetary spend as explained (E2).

In 2022, their recycling percentage of non-specific hospital waste was 19% (Erasmus, 2023), and these and other waste streams will be further analysed in sub-section '5.2.6. Point of collection space'.

LUMC

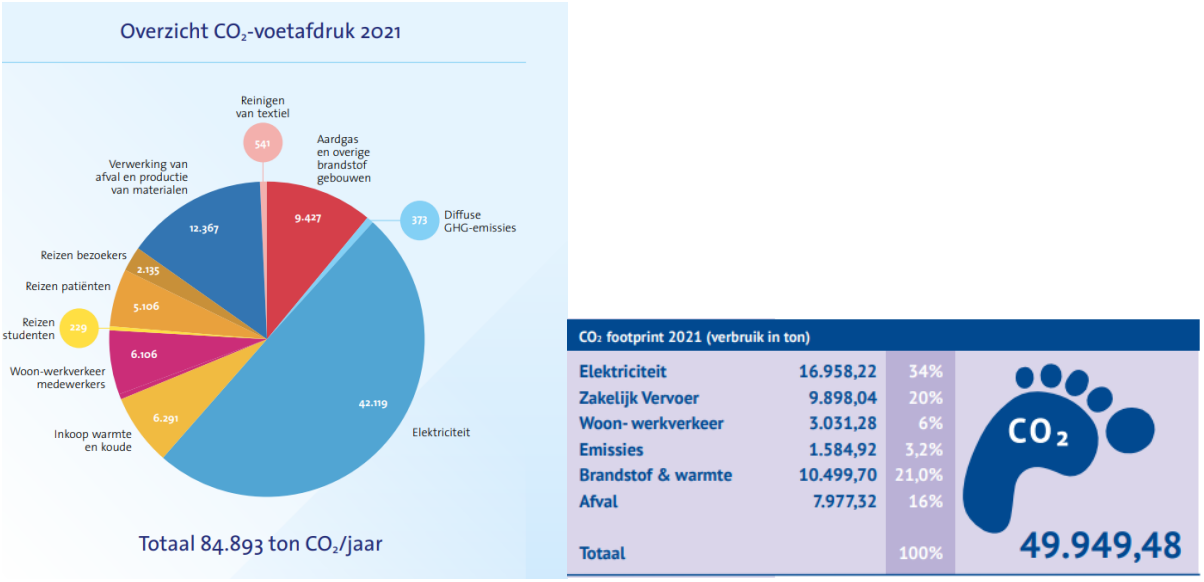
LUMC is a Dutch academical hospital with 7,195 FTE in 2022 (LUMC, 2022). In 2021, there were 21,609 admissions and their CO2 footprint (or GWP) was 49,949.48 tonne CO2 that also consists mostly of scope 1 and 2 as presented in figure 10, right including electricity (16,958.22), fuel & heat (10,499.70), business

travel (9,898.04), commuting (3,031.28), emissions (1,584.92), and waste (7,977.32) (LUMC, 2021). The number of beds, average stay per admission and number of polyclinic visits were not presented in their annual report or overview of fact and numbers.

In 2021, LUMC had a recycling percentage of non-specific hospital waste was 38% (LUMC, 2021), and just like the waste streams from Erasmus MC, the waste streams from LUMC will also be further analysed in sub-section '5.2.6. Point of collection space'.

Figure 10

Left: CO2 footprint Erasmus MC 2021 (mostly scope 1 and 2) (Erasmus, 2021). Right: *CO2 footprint LUMC 2021 (mostly scope 1 and 2)* (LUMC, 2021).



Internal stakeholders

Green teams are bottom-up teams from different departments created to implement sustainable improvements in the hospitals. In 2022, Erasmus MC had 30 green teams (Erasmus, 2023), and LUMC had 25 green teams (LUMC, 2022).

Infection prevention is responsible for microbiological safety for patients care. Employee care is not the main concern of infection prevention, however safe transport by employees is their concern because these employees can then indirectly also contaminate patients. They make policy on which the infection commission must give their approval. They also decide on how MDs should be reprocessed (E17).

When infection prevention decides something should be mechanically washed and/or sterilized, then **experts sterile medical devices** go see if that is also possible with the machines available (E17). Moreover, they write policy for the CSSD and are responsible for SU sterile MDs (E10). Experts sterile medical devices are part of **medical technology**, who are responsible for the medical safety of everything that gets sterilized (E8). At Erasmus MC medical technology also does repairs, while at LUMC they are more focused on developing new MDs or processes. At LUMC **instrument management** is responsible for all RER MDs that are reprocessed at the CSSD, from the moment they arrive in the hospital till they leave at their EOL (L6).

There are multiple **logistics teams** that are all responsible for a different part of logistics process inside a hospital. At Erasmus MC, there are four logistics teams including a team at the distribution center in Barendrecht (consisting of 18 employees (19 with their coordinator) and 17,9 FTE), a team for goods-reception and transport to decentral storage locations (consisting of 24 employees and 22,11 FTE), a

team for waste transport (consisting of 33 employees and 30,44 FTE) and a team that puts MDs in the closets at the decentral storage locations and performs so called 'scan rounds' there that will be explained in sub-section '5.1.2. Tracking and tracing' (consisting of 29 employees and 26,51 FTE) (E1). At LUMC, there are seven logistics teams including waste, inventory, washing beds, transporting beds/patients, warehouse/goods reception, general logistics and the post office (L3).

Waste management is responsible for safe transport and disposal of different waste streams. Moreover, they should see together with the waste handling partner if waste can be reduced (E7).

Inventory management is responsible that all inventory products go in the right numbers at the right time to the right departments. Inventory management uses big categories of MDs like syringes, needles, catheters (E9).

Procurement is responsible for purchasing and contracting of everything in the hospital, including its MDs. Because an academic hospital is spending tax-money, they must follow the European public procurement act that states when the Total Cost of Ownership, which are all costs related to a product or service from the moment of purchase onwards, is more than 215,000 EUR the procurement process should be performed in a European tender (L7). Moreover, procurement must follow the Dutch principles proportionality guide that ensures a fair, proportional, objective and transparent process and that states that a tender needs to happen every four years (L7). Procurement professionals that try and purchase sustainable solutions struggle under a so-called buy-supply trap (Nevi, 2023). This is a paradox where procurement professionals struggle that circular solutions do not exist on the market, while suppliers of MDs say there is no demand for circular solutions (E8). Moreover, to bring new circular solutions to the EU market can be challenging because of the difficult laws and regulations, including the MDR, leading to some MD suppliers already withdrawing from EU market (E8).

5.2. Material logistics infrastructure elements in the two case hospitals

This section describes how the different elements of the material logistics infrastructure from the typology look like at Erasmus MC and LUMC. Different problems and already some solutions are identified that are present at either one of the case hospitals or at both. The sub-sections are structured by going over different requirements mentioned in the typology for that material logistics infrastructure element. The overview of identified problems can be found in Appendix B.

5.2.1. Transport

Supplier → Central warehouse (or direct arrival)

The biggest difference between the two case hospitals when looking at how MDs flow through the hospital and are transported between them is that Erasmus MC has an external central warehouse in Barendrecht, while LUMC has its central warehouse at the hospital.

At LUMC everything arrives directly at the hospital. Most MDs arrive at goods reception, and this are around 35 orders each day. Other post arrives at the post office and pharmaceuticals arrive at the pharmacy. There are a few exceptions when products arrive in other unofficial places, for example a direct delivery to the CSSD, or deliveries for some radioactive materials or animal material. MDs that arrive at the goods reception are placed on their dedicated trolley or closed cart to be send either directly to the decentral storage locations at different departments, which happens with most orders, or first to the central warehouse from where MDs will be picked when needed (L1).

At Erasmus MC around 60% of the order lines does not arrive directly at the hospital, but through Barendrecht in a truck 3 or 4 times a day. When looking at order lines that are MDs, around 80% arrives through Barendrecht (E1). All other order lines arrive directly at Erasmus MC, which are around 100 orders per day (E5). Barendrecht is not just a central warehouse but rather a distribution center, as it not only

consists of sterile and non-sterile storage racks for inventory products and some emergency storage racks, but also some storage racks for non-inventory products that are cross docked there. This means that the non-inventory products in these racks cannot lie there more than a day before being loaded in one of the trucks that goes to Erasmus MC (E6). At Erasmus MC, there are 13,419 total SKUs, of which 2,016 are inventory products and 11,403 are non-inventory products. Whether a SKU arrives through Barendrecht or directly at Erasmus MC depends on how they are ordered by healthcare employees. There are two order systems, and two ways orders can be placed manually by healthcare employees. The first order system is for inventory products and is a 2-bin Kanban system called *Auto Bevo* that places orders at Barendrecht, which triggers an automated order system called *Slim 4* that places orders at the suppliers. The second order system is for so called 'scan relevant' MDs which are more expensive MDs such as implants that are all non-inventory products ordered directly at the supplier. MDs that are ordered via both these systems will arrive through Barendrecht and more details about how these two systems work will be further explained in the next section '5.1.2. Tracking and tracing'. Then there are two ways orders can be placed manually, and the first is though the *catalogue*, which consists of 95% of all SKUs, both inventory and non-inventory products and these will also arrive through Barendrecht. The second way orders can be placed manually for both inventory and non-inventory products is through the *Iprocurement portal*, which places orders directly at the supplier and these will arrive directly at Erasmus MC. An example of when this portal is used and why it exists is when a specific MD will be tested, because this MD will not be in the *catalogue* and therefore must be ordered via the *Iprocurement portal*. However, it is also possible to order inventory products and non-inventory products that are also in the *catalogue* via this portal. This is problematic because then they will not arrive through Barendrecht, which is the normal route of these products [P1] (E1).

MDs that arrive through Barendrecht are placed in closed carts that are dedicated to a specific decentral storage location, with a blue sign on the cart for sterile MDs, and a white or yellow sign for unsterile MDs. These closed carts are loaded into trucks and as mentioned, a truck leaves for Erasmus MC 3 to 4 times a day. Upon arrival at Erasmus MC the truck is unloaded, and the closed carts are brought directly to the decentral storage rooms (E1).

Around 100 orders of non-inventory products arrive directly at goods reception at Erasmus MC which has two loading docks and one plateau elevator. These MDs are placed in trolleys dedicated to specific decentral storage location. Trolleys are transported to the decentral storage locations following a standard schedule. According to this schedule, most trolleys are transported ones a day but for some locations like the OR or emergency care, this is not enough and therefore to these locations, trolleys are transported multiple times a day. Cooled products are an exception of products that arrive directly at Erasmus MC, as these are transported directly instead of first waiting in their trolley to be picked up according to the schedule (E5).

Central warehouse (or direct arrival) → Decentral storage location

Both trolleys with MDs that have arrived directly and closed carts with MDs that have arrived through Barendrecht can be attached to each other, making a train, so that multiple trolleys or carts can be transported at the same time. They are transported by logistics employees driving electric vehicles (*Spijkstaal*) through underground logistics hallways that connect all buildings (except one) with each other, as presented in figure 11, left. These hallways are created especially for logistics purposes, to transport MDs, waste and beds. Patient transport happens at the third floor and not in these hallways (with some exceptions of when an ambulance comes with a psychiatric patient). However, the logistics hallways are also being used by other healthcare employees for storing products and as a walking pathway from one building to the other, taking space away from logistics transport and causing some safety issues [P2] (E1).

These logistics hallways are a second big difference between Erasmus MC and LUMC, as LUMC does not have such hallways connecting different buildings. LUMC consists of different floors. On the first floor is goods reception and the warehouse, emergency care is at the second floor, CSSD at the third floor and the

OR at the fourth floor. They do have elevators dedicated to logistics, just like Erasmus MC, to bring MDs from the warehouse to the decentral storage locations (L1).

Problems that might arise when transport increases are that there are no more logistics employees available [P3], as there is a lowering trend in the number of applications among all Dutch academic hospitals (LUMC, 2022) or that the elevators reach their capacity, meaning they are always full and cannot transport more [P4].

Figure 11

Left: logistics hallways at Erasmus MC (E1), middle: preparation cart for one surgery at LUMC (L2), right: unpacking table in preparation room at Erasmus MC (E15).

Decentral storage → Patient care

Transport from the decentral storage locations to the patient care location is not performed by logistics employees as MDs are picked from the decentral storage locations by healthcare employees. These same healthcare employees bring the MDs to the patient care location to use the MD on the patient. An exception is at the OR, where the logistics team called OR logistics oversees two processes. Not only are they responsible for inventory management, which will be explained in the next sub-section '5.1.2. Tracking and tracing', but also for transporting MDs to the CSSD and for a so called 'preparation procedure', where all MDs are picked and transported to the patient care location for surgeries for tomorrow and emergency surgeries for today. This preparation procedure starts with printing out a list from the patient information system called *Hix* (used in both case hospitals), with all MDs that are required for one procedure for one patient. This list contains both SU and RER MDs and thus are picked from both the sterile storage racks at the CSSD as well as other decentral storage locations at the OR (E10, E11, L2). Each procedure also requires one procedure tray to be picked. These procedure trays lie at the sterile storage racks at the CSSD, where all reprocessed, sterile, RER MDs also lie, but in contrary procedure trays consist of SU MDs such as surgical gowns, surgical drapes, and some small SU MDs such as hoses/tubes, knives and gauzes (E11). There are more basic procedure trays and procedure trays for more specialized operations. At LUMC there are 50 of these procedure trays used per day (L2). When all MDs are picked, all packaging except the last sterile packaging is removed at the unpack location and all MDs placed on a preparation cart, as presented in figure 11, middle (L2). Afterwards, these preparation carts are placed into the preparation room, which is the cleanest area (L2). At Erasmus MC there is one preparation room between two ORs (E15) and at LUMC there is one dedicated to four ORs (L2). The last step, just before a procedure, is removing the final sterile packaging from the MDs and opening the procedure trays on an unpacking table, as presented in

figure 11, right (L2, E15). The procedure trays are packed ergonomically that unpacking the procedure tray in a preparation room is easy for the OR logistics employees (E15).

Patient care → CSSD → Decentral storage

Transport to the CSSD happens with dirty carts with RER MDs, after being used at an operation (E3, L4). At LUMC, when an operation is finished, they notify OR logistics via a system called *Arta* so that they can pick up the dirty carts with RER MDs up as fast as possible, because otherwise blood will be more difficult to get off. At LUMC the CSSD has a dirty and clean elevator. The dirty elevator is connected to the start of the process and is used when bringing dirty MDs to be reprocessed. The clean elevator is at the side of the sterile storage, where all RER MDs are stored, and is used for bringing the picked MDs to the patient care location (L1).

Patient care → Point of collection

Waste is created all throughout the hospital, at the offices, hallways and at the different patient care departments (e.g., OR, IC, emergency care). Cleaning employees empty small waste bags from all over the hospital, put it into bigger bags, which are put on big roll-containers that are placed at their dedicated waste location throughout the hospital (E7). These dedicated waste locations could be a place in the hallway only for residual waste and paper waste roll-containers or a small or big environmental station, which is a room that also allows some more waste streams to be separated, depending on the size of the room. Separated waste streams might be transported to the environmental stations by other employees than cleaning employees, for example at the OR this could be done by OR logistics, students or OR assistants themselves (E15). From the dedicated waste locations throughout the hospital, the logistics team dedicated to waste transport picks up the roll-containers and other waste streams and transports it to the waste department situated at the logistics center, where the waste streams are emptied inside the right container, to be picked up by the waste partner (E7). There are separate roll-containers for the blue (paper) and green (residual waste), but there is not a separate cart for other separated streams that are to be recycled [P5]. This is a problem, because nurses sometimes see the logistics employees put the recycled bags on the cart together with paper or residual waste and this makes them think that it won't be recycled (E2). These waste pick-ups happen in standard rounds for example, they go six to eight times a day to the OR, three to four times a day to care departments, and ones to policlinics (E7). How the different waste streams and the containers at the waste department exactly looks like will be explained further in section '5.2.6. Point of collection space'.

As explained in the typology, besides waste streams, MDs might also be brought to a point of collection to be picked up for reprocessing or repair. At Erasmus MC, reusable medical textiles are transported by logistics employees from the dedicated waste locations throughout the hospital down to the logistics hallway close to the waste department and from there are picked up by the external laundry service (E7). When a MD, reaches its EOL, mostly they are discarded (E10), but in some cases, they are repaired internally or externally or sent back to the supplier for either parts recycling or repair (L5, L6 E14). At LUMC, repair of simple SS MDs is performed externally at *Van Straten Medical* that are picked up at the hospital, and more complex devices are send back to the supplier through the post-office or also picked up at the hospital, which will be further explained in section '5.2.5. Repair' (L6). Transport of all MDs to be externally reprocessed or repaired is performed by logistics employees.

5.2.2. Tracking and tracing

Tracking and tracing of data is the most important material logistics element as it helps to make informed decisions. Both hospitals use different data systems to track and trace information to support the material logistics infrastructure. Both have a main ERP (enterprise resource planning, purchase-to-pay) system, *Oracle* at Erasmus MC, and *People soft* at LUMC. Both have an asset management system called *Ultimo*. Facility management information system used at Erasmus MC is called *Slim 4* and LUMC use *People soft*.

The system used at the CSSD of Erasmus MC is called *Hix* and at LUMC they use *T-doc*. Information for patients is tracked in *Hix* in both hospitals. Scanning MDs also has its own system at both hospitals. At LUMC they also have a system for alerting logistics when a dirty cart needs to be picked up to be transported to the CSSD called *Arta*.

Inventory levels

In the previous sub-section, the distinction between two order systems and two ways orders can be placed manually by healthcare employees has been explained. For MDs that can be ordered via the two order systems, inventory levels are being tracked and traced at one point in the process.

The first order system is for inventory products, that are stored at the central warehouse, but also at the decentral storage locations. The inventory level at the decentral storage locations is not being tracked and traced, as these decentral storage rooms are managed by a 2-bin Kanban system called *Auto Bevo*. All MDs are stored in closets and for each separate SKU there are two 'bins' with MDs inside. The idea is that when one bin is empty, there is always one extra to make sure MDs are always available. If a healthcare employee sees that one bin is (almost) empty when picking MDs, a badge is placed inside the door of the closet to signal that for that SKU new MDs need to be ordered. These rooms are checked during so called 'scan rounds' by logistics employees several times per day, depending on how frequently the MDs inside the storage room are used. During this 'scan round' all badges hanging in the doors are manually scanned that triggers an order for those SKUs at Barendrecht [P6] (E2). In Barendrecht, picking lists of all MDs that were scanned during the 'scan rounds' are printed out and MDs are picked from the racks on a product level. This means that packaging that holds multiple MDs needs to be opened to be able to pick the MD on a product level, which takes time [P7]. In the sterile storage, the even bigger outer box in which the MDs are transported must be removed before they go into that sterile room these are not allowed to go inside. Only the packaging that holds multiple MDs is allowed to be placed in the racks (E6). After all MDs are picked form the picking list, one last (manual) check is being performed by another employee. If this was done correctly, MDs are placed in random order in closed carts to be send to Erasmus MC. This is problematic, because unloading the MDs at the decentral storage locations therefore takes some time [P8] (E6). The inventory level at the central warehouse is being traced and traced and managed by an automated order system called *Slim 4*. This system follows a min-max inventory strategy where, when a minimum inventory level has been reached, because orders are picked and send to Erasmus MC as explained above, a replenishment order is placed automatically so that if that order would arrive instantly, the maximum inventory level would be reached. Also, the system takes delivery times of suppliers into account to make sure MDs arrive in time (E9). Thus, inventory levels of inventory products are only being tracked and traced at the central warehouse and not at the decentral storage locations [P9]. Managing the inventory level of the central warehouse is possible because it is known exactly how much inventory lies there. MDs that arrive should always have an order receipt with an order number, but this is not always the case and is therefore checked first upon arrival. This order receipt is then used to book the MD into *Oracle*, which is the purchase-to-pay system that is used to track and trace MDs, and a barcode sticker is printed. When this barcode is scanned, *Oracle* tells where the MD should go. Because MDs are booked into *Oracle*, it is known exactly how much goes in. Because MDs are picked with picking lists and then scanned to the right trolley, it is also know exactly how much goes out. MDs that arrive directly at goods reception at Erasmus MC are also booked *Oracle* in the same way. *Oracle* tells what trolley the MD should go, and the MD is scanned to that trolley (E5). Upon arrival at the decentral storage location MDs that have arrived directly at Erasmus MC and MDs that have arrived through Barendrecht both scanned to the decentral storage location. Therefore, at the decentral storage locations it is also known how much goes in. However, here it is not known how much goes out, as MDs are not scanned when picked but are managed by the *Auto Bevo* system as explained. At LUMC, this is also the case where the inventory level is only being tracked at the central warehouse where they keep two weeks of inventory (L3).

The second order system is for 'scan relevant' MDs at the OR, which are more expensive MDs such as implants. For these MDs the hospital does manage the inventory level at the hospital again with a min-max inventory strategy. This is possible because, in contrary with the above-mentioned inventory products, these MDs are scanned when they are picked from their storage location (E1). When the minimum inventory is reached an order is triggered automatically at the supplier, but these non-inventory products will arrive through Barendrecht where they are cross docked (E1). A special rule LUMC has with implants is that these need to be unpacked already at delivery to check straight away if the right products are inside. The package inside is scanned and this data is coupled to patient data for registration. This is in contrary with other packages that are not unpacked until the patient care location to see if the right products are inside (L1). These 'scan relevant' MDs are managed by OR logistics. As mentioned in the previous section, OR logistics is responsible for two processes, the preparation procedure and inventory management. Inventory management at the OR means making sure there is enough and placing backorders if necessary. These backorders are placed via the *Auto Bevo* system during 'scan rounds' as explained, or manually via the *catalogue* or the *Iprocurement portal*, if a special type size is needed, that is not on inventory at OR (E11).

Current location of unique MDs

Like explained in the typology, the current location of MD is already important for SU MDs. To be able to track a unique MD, the MD should have a unique barcode. GS1 is the market leader in standards for unique identification barcoding, with around 95% of all unique identification barcoding being from GS1. Each barcode is a unique identification of the MD that consists of four elements including a product identifier (to identify the version a specific type of MD and its OEM), expiry date (to know when MDs will be expired, or for RER MD this expiry date will be a production date), batch number (to identify in what batch it was made) and serial number (to identify one MD from another). Some MDs such as bandages or plasters the barcode will probably not get a serial number. By law all MDs will need a barcode from 2025 onwards. For high-risk MDs ('scan relevant' MDs) this is already required since 2021, and for low-risk MDs this will be required from 2025 onwards. For SU MDs the barcode can be on the outside of the packaging, but for RER MDs the barcode should be placed on the MD itself (S3). So currently, not all MDs have such a unique barcode on them [P10], but this will happen from 2025 onwards.

The current location of a unique MD is important because of two reasons. First, when there has been a mistake in a production batch and those MDs need to be recalled, the hospital should be able to identify the location of MDs that were made in that specific batch to be able to send them back to the supplier. However, identifying the location of MDs from bad a production batch is difficult [P11], because the current system both case hospitals use for tracking and tracing the current location of unique MDs does not always work, except for 'scan relevant' MDs that all have a unique barcode that is scanned at every movement [P12]. For other MDs the system does not work because scanning happens minimally, only with certain movements [P13]. Every time a MD is scanned, *Oracle* (Erasmus MC) or *People soft* (LUMC) will know where the MD is at that point. Moreover, scanning is not always done properly because it is prone to human error [P14], especially because not all MDs have the right unique barcode on them yet [P10] (E1). A second reason why tracking and tracing the location of a unique MD is important is because when a MD has expired, the hospital should also be able to identify that MD to pick the MDs that will expire the fastest earlier to avoid spillage. At Erasmus MC, currently the expiration date is only checked at goods reception and the MD is refused when it is below 6 months. If the MD is not refused, then the expiration date will be checked in manual counting rounds at Barendrecht. MDs that have passed their expiration date might be send to low-income nations as 'second chance' MDs, which will be further explained in section '5.2.6. Point of collection space'. Information of *Oracle* is coupled to *Slim 4*, and with that *Slim 4* should be able to see when a MD is almost expired and help to identify where it is stored, but this module is not used currently [P15] (E1).

Waste generated from separate streams

In a yearly overview of the separated streams, the waste handler, which in both hospitals is *Prezero*, shares per waste stream the number of pick-ups, the weight, the volume, and the costs. An overview of the separated waste streams, as of the year overview 2022, which will be presented in sub-section '5.2.6. Point of collection space' in table 17.

Like explained in the conceptual background a report of the World Health Organisation (2014) already mentioned that hospitals should obtain accurate data about specific locations where waste segregation is going well and where it can be improved by setting improvement targets. Despite this advice in 2014 already, the yearly waste overview of both case hospitals only consists of the total waste generated from separate streams and not for specific departments or operations [P16]. Therefore, no improvement targets on specific department or operation level are set [P17] and waste pick-up routes are suboptimal [P18]. As explained in the previous sub-section '5.2.1. Transport', at Erasmus MC, waste is picked in standard rounds. Because of this they do know how often they go to the different departments. However, both case hospitals do not know exactly how much waste is generated for the different streams, as waste bins are also often not completely full when they are being picked up [P19] (E7).

Unique MD (and RER subparts) history: location, #repairs, #cycles

When a MD is RER or MOD with RER subparts, there is an additional requirement for tracking and tracing information about that RER unique MD or about the RER subparts. Now, not only the current location should be tracked and traced, but also the past locations to know where it has been, including where it has been repaired and used so that also the number of repairs and cycles are being tracked and traced.

The great thing with unique identification barcoding is that it can be coupled to all different kinds of software tools and systems, so for RER MDs also other information can be coupled to the unique MD such as its location but also #cycles and #repairs. All this information can be coupled to the unique MD under the requirement that the MD is scanned, and information is added at these different steps in the process. *Oracle* already has a module to track and trace this information of unique RER MDs (S3). At both case hospitals, a software tool for tracking and tracing information about the history of unique MDs, such as the module available in *Oracle* is not yet used [P20] (E1).

Tracking and tracing the number of cycles of a RER MD or RER subparts of a MOD MD now happens at the CSSD with either *Hix* at Erasmus MC (E4) or *T-doc* at LUMC (L3, L4), but is not yet coupled with a software tool for tracking and tracing information about the history of unique MDs, such as the module available in *Oracle* [P21]. *Hix* and *T-doc* work the same, the only difference is that *Hix* can couple patient data with CSSD data, which *T-doc* can't do (L6). During different moments in the reprocessing process MDs are scanned and this will be further explained in sub-section '5.1.4. Reprocessing'. Currently almost all MDs are either designed for reuse, to be reprocessed an infinite number of times or designed for SU to be discarded after one use. Only a few MDs are designed for a predefined number of cycles, that will be tracked by the CSSD in *Hix* or *T-doc* (E3) and there are even fewer MOD MDs that are designed for disassembly, where different parts of the MD are designed for different number of cycle (L6). As also explained in the conceptual background, an OEM decides if they design their MD for SU, RER with infinite number of cycles, RER with a predefined number of cycles or MOD (E4). Examples of MDs designed for a predefined number of cycles are MDs used for robotic surgery that have a chip inside and are designed for eighteen, ten or fifteen cycles (E14). Robotic surgery is one of the three types of surgery, besides open surgery and minimal invasive (L2). There are two *Da Vinci* robots at Erasmus MC, one owned and one leased, that do four operations per day. (E3). At Erasmus MC the *Da Vinci* MDs however almost never reach that predefined number of cycles. This might be because the user uses it wrong (E10), because at LUMC they also have them and there they won't break earlier than that often (L5). However, the reason for earlier breakage of a MD, or a missing MD, cannot be analysed because a software tool for tracking and

tracing information about the history of unique MDs, including for example by what doctor, at what operation or by what repairer it has been used or repaired, such as the module already available in *Oracle* is not yet used [P22].

As explained in the previous sub-section '5.2.1. Transport', repair happens both internally as externally. When it happens internally the hospital itself should add information about the repair to the unique MD history to track the number of repairs. However, again because both case hospitals do not use a software tool for tracking and tracing information about the history of unique MDs, such as the module already available in *Oracle*, the number of repairs is also not yet being tracked and then coupled to this software tool [P23].

5.2.3. Storage space

According to the typology storage space is required in a central warehouse and at decentral storage locations. When moving to a RER version the amount of storage space required at these two locations might increase or decrease for different reasons mentioned in the typology.

Central warehouse

At Erasmus MC the central warehouse is in Barendrecht and the central warehouse at LUMC is at the hospital. At Erasmus MC, after arriving at the central warehouse and being booked into *Oracle*, MDs then go to their dedicated storage space in the racks (E6).

Since COVID-19 ended, all hospitals went open again and had to catch up on the demand of care. This combined with the raw material shortages made the healthcare sector especially vulnerable for shortages in MDs. Ever since, supply chains are having a lot of disruptions, so suppliers cannot really predict their production and their inventory levels very well. This has a direct impact on hospitals because many so alternative MDs, called 'alternatives', are bought right now. At Erasmus MC there are two employees who have a fulltime job to find these 'alternatives' (E9) and LUMC also has one fulltime job for this (L2). These 'alternatives' have the same dedicated slot in the racks as the MD it is replacing, while the dimensions of the 'alternative' might be different. This results in that an 'alternative' sometime does not fit in the racks and is placed on top of the racks [P24] (E6).

Decentral storage location

Besides being kept in Barendrecht, the inventory products of Erasmus MC are also kept across 189 different decentral storage rooms at the hospital. Some big departments have multiple of these storage rooms and other smaller departments share one storage room together. Sterile and unsterile need to be in separate rooms. This is the case in the central storage location in Barendrecht, but in some decentral storage rooms sterile and non-sterile are in closets next to each other which is not allowed [P25] (E4).

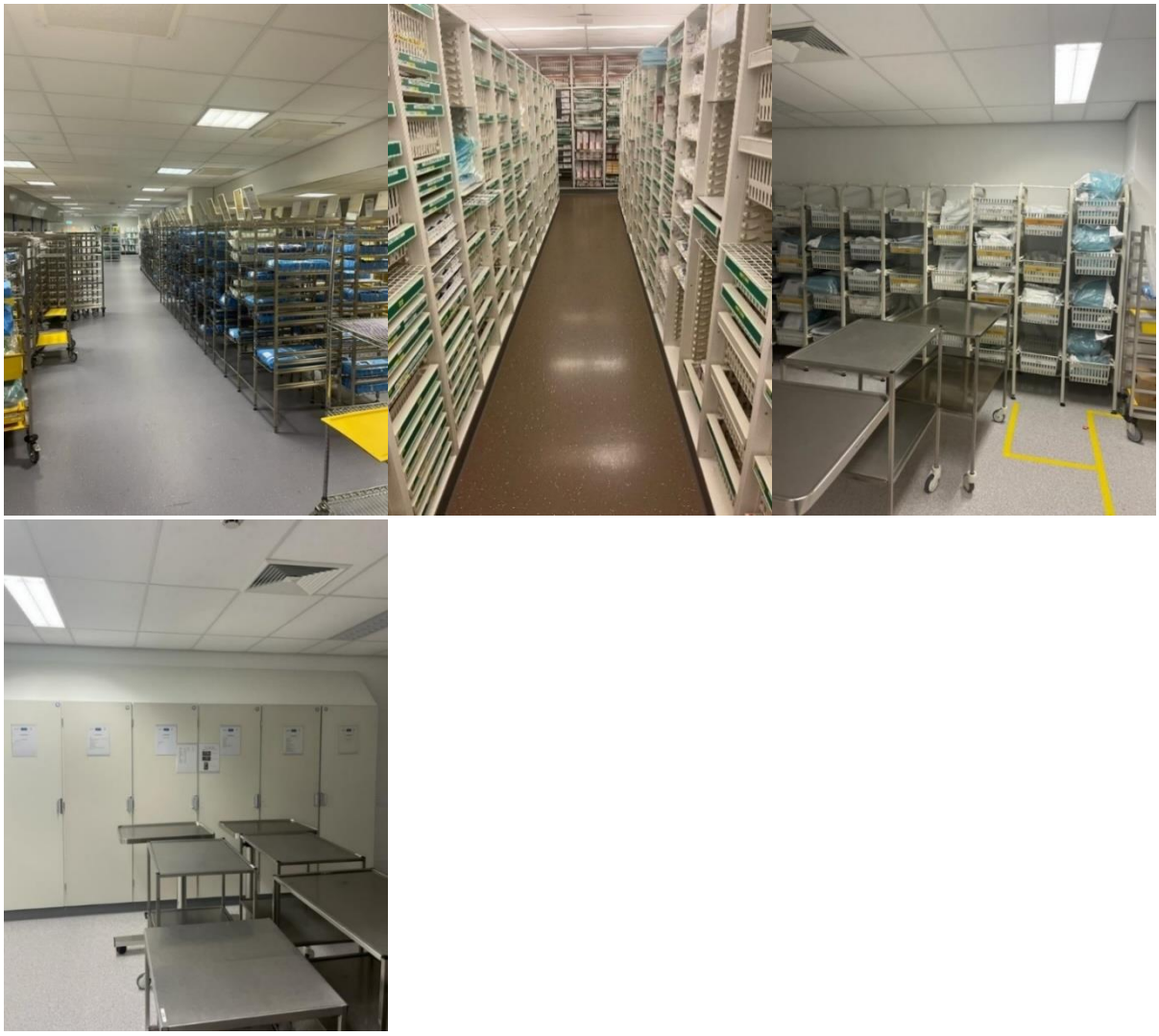
At Erasmus MC, the IC consists of all isolated rooms. To supply all these rooms with the right MDs, many different storage locations exist. First, there are two big decentral storage location at the IC one for sterile and one for non-sterile MDs. Next to these big storage location, smaller storage closets closer to the IC rooms exist. These smaller storage locations are for 40 beds. Besides the big and smaller sterile storage rooms, MDs are also kept on so called day-carts. Then, just outside every IC there is also some storage consisting mostly of PPE for dressing up before entering. Inside every IC room are also MDs stored. This consists of a full drawer with around 350 EUR worth of MDs. Besides this drawer, tubes, iv bag and some other MDs are placed besides the bed. All these MDs will be discarded after an infected patient leaves the room, regardless of whether the MDs are used or not [P26]. Lastly, there are some carts on the department with emergency storage. It is unclear whether the same MDs are stored at all these different storage locations. If that is the case, this results in way more inventory than necessary (E2). As mentioned in the previous sub-section '5.2.2. Tracking and tracing', at both case hospitals inventory levels are not being tracked and traced throughout the hospital (except for 'scan relevant' MDs). Therefore, just like at the IC,

there is no way of knowing if a decentral inventory location that is close to another decentral inventory location store the same MDs [P27]. The upgraded version of *Slim* 4 would have a module that is able to optimize the storage space available by for example consolidating the storage location of a MD from three decentral storage rooms close to each other to only one (E1). However, this module for optimizing decentral storage rooms throughout the hospital is not yet used, as it would also require MDs to be tracked and traced in the hospital better [P28].

At the operating theatre there are also multiple storage locations. As explained in sub-section '5.2.1. Transport', RER MDs have their own sterile storage location at the CSSD (including spare parts), as presented in figure 12, top left. SU MDs lie in the decentral storage rooms in closets at the OR for which there are sterile rooms, as presented in figure 12, top middle, and unsterile rooms. Then, at the OR rooms itself anesthetics and OR assistants keep their own day-storage of SU MDs (E15). Lastly, at the OR there is also emergency inventory on carts and in closets. Officially, they are not allowed to have emergency inventory inside the preparation room, because it is the cleanest area. Nonetheless, at LUMC there are currently emergency carts, as presented in figure 12, top right, and emergency inventory closets, as presented in figure 12, bottom left, inside the preparation room for when surgeons need to grab something quickly during a surgery [P29] (L2).

Figure 12 (next page)

Top left: Sterile storage of MDs in nets at LUMC (L2), top middle: Decentral sterile storage room OR at Erasmus MC (E15), top right left: Emergency carts inside the preparation at LUMC, bottom left: emergency inventory closets inside the preparation room at LUMC (L2).



5.2.4. Reprocessing

According to the typology, reprocessing can happen internally, mostly at the CSSD, or externally. Erasmus MC and LUMC both have their own CSSD, where at LUMC around 80-90% of MDs that are being reprocessed are for OR and the IC, and the rest is glass among others (L1). Smaller hospitals might have their RER MDs reprocessed at an external CSSD. For hospitals like Erasmus MC and LUMC this might only be necessary when their own CSSD is at full capacity. Capacity of a CSSD might be reached because there are not enough reprocessing employees available, to do all the manual labour such as manual cleaning, scanning, preparing nets and placing everything inside the machines [P30], or because there are not enough machines available (for example when they have breakdowns) to reprocess everything in the time it needs to be ready [P31], or because the maximum space at the CSSD is taken up so that there is no more available space to place more machines [P32] (E3, E4, E10, L2, L3, L4). Those problems will be explained further below. Capacity problems that can cause bottlenecks in the process occur on different moments during the day, because the stream is not constant with not so busy mornings and a peak moment in the beginning of the evening [P33] (E10).

Internal reprocessing

Reprocessing at the CSSD starts when dirty enter the CSSD. Sometimes, MDs are returned with urgency, which means they get priority to go to the process first (E10). Dirty cars will enter with plastic bag around them (L4). At Erasmus MC, dirty carts with MDs that are needed for the next day need to be ready within 12 hours, carts with emergency MDs need to be ready within 6 hours. The total throughput time of all

machines is at least 4 hours, so with 6 hours they got some margin for possible breakdowns of machines (E3, E10). The CSSD of Erasmus MC only differentiates between individual MDs (which they call single instruments), flexible endoscopes, and MDs in a net (which they call trays) (E10). Individual MDs and nets go through the normal washing machines and sterilizers and flexible endoscopes go through endoscope reprocessing machines (E10).

The first step of the sterilization process of nets and individual MDs happens in the disinfection area or dirty area. Here MDs are manually cleaned and for MDs on a net is if everything is still inside that net. This step might take longer for some nets or individual MDs than others. For example, *Da Vinci* MDs take longer to clean manually, because pipe cleaners must be used in the long, small tubes (E3, L4, E10). As explained in sub-section '5.2.2. Tracking and tracing' the system that is used to track and trace nets and individual MDs at the CSSD of Erasmus MC is called *Hix* (E3) and at LUMC *T-doc* (L4, L6). Each net and individual MD have its own QR-code that when scanned the system knows the wash instructions. Each net and individual MD are then coupled with a wash tag and are scanned to the right washing machine (L4).

The second step is the washing machines. At Erasmus MC there are eight washing machines for washing MDs and two cart washes, dedicated to washing carts and clogs. Each washing machine can run four different programs. A normal program, which takes about an hour and fifteen minutes, a second program with an extra rinsing step takes an hour and fifteen minutes, a third program for *Da Vinci* devices takes 2 hours, and a last program for chemical disinfection also takes 2 hours (E3). At LUMC there are six washing machines for washing MDs and one cart wash. Next to the washing machines there is a hatch to pass carts or MDs back when they need to be cleaned again. (L4) Also at LUMC there are four different programs that the washing machines can run. The glass program takes 75 minutes and all other programs 60 minutes (L4). Washing is the most important step, and the goal is to get all visible dirt off. The goal of disinfection is to kill most micro-organisms and happens for safety of CSSD personnel. This disinfection is skipped in low-income countries (L2).

The third, fourth and fifth step happen in the clean area (L4). The third step, after the washing program is finished is checking if all tubes were connected correctly onto the devices. If the washing step went correctly, this is put it in *Hix* or *T-doc* again (E3). Because carts that come out of the washing machine are hot, there are some spots where the carts need to stand to cool down (L4).

The fourth step is "preparing a net". This step includes checking again if all MDs are inside the net, just like in the beginning. Then everything is put in its place in the net. The net is also weighed and again put in the *Hix* or *T-doc*. This weighing is an extra control step to reduce the chance that MDs inside the net go missing. For individual MDs this step is not existent because they are not part of a net (E3). Missing MDs are picked from storage closets at the department. Around 90% of all MDs are here, 10% are specific MDs, that are ordered manually by instrument management when needed (which can take 1 week up to a month), so there is no storage from those. (L4)

The fifth step is (sterile) packaging. After a net is prepared, blue wrap and special tape that changes color in the sterilizer are put around it. Individual MDs are packaged in laminate pouches (E3, L4). For individual MDs that do not need to be sterilized, and high-level disinfection is enough, this packaging is the last step, and they are brought to their storage location afterwards.

The sixth step is the sterilization machines. At Erasmus MC there are six autoclaves (of which 2 were out of order at the time of the visit) and one *Sterrad* which is a hydrogen peroxide gas plasma sterilizer. One of the six autoclaves is a hybrid version that can make steam from electricity. Moreover, of all these autoclaves there are three, including the hybrid version, that can sterilize at 121 degrees Celsius and all six that can sterilize at 134 degrees Celsius. The 121 degrees Celsius program is for MDs that are a bit heat sensitive like tubes or silicones. MDs that are even more sensitive to heat go into the *Sterrad* hydrogen peroxide

sterilizer. Nets inside the sterilizers take one hour for the program and half an hour to cool down, because of the blue wrap (E3). At LUMC there are four autoclaves and one *Sterrad*. Because the autoclaves of LUMC are old, the bottom middle part is not working properly and therefore the expert sterile MDs has decided that the bottom middle part of carts cannot be filled when using the autoclaves, costing sterilization capacity (L4). The goal of sterilization is to kill all microorganisms that are still present after disinfection (L2).

The seventh and last step is sterile storage. From here OR logistics employees take over from CSSD employees (E3, L4). Sterilized MDs are placed in the sterile storage racks at CSSD. Nets are sterile for six months and individual MDs are sterile for three months (E3) OR logistics checks monthly if there are MDs that have reached their sterile expiration date (E3). Each net or individual MD has a code, that is used to track and trace its current location, as presented in figure 13 (L2).

Figure 13

Net with code to track and trace its current location.

The first step of the endoscope reprocessing process is manual cleaning & disinfection and a this is put in *Hix* or *T-doc*. In this step endoscopes are also put under high pressure to see if they are not leaking. At LUMC, if they are leaking, they go to medical technology to be repaired (L4). The second step is the endoscopic washing machines. At Erasmus MC here are three endoscopic washing machines at the CSSD, that all can wash two endoscopes, so six endoscopes in total can be washed here. The washing takes about 35 to 40 minutes (E3). There are also some endoscopic washing machines at the departments, besides the three at the CSSD, including four at ENT (ear nose throat) and five at gastro-enterology (E10). At LUMC there are two endoscopic washing machines at the CSSD, four at gastro-enterology and two at urology. The endoscopic washing machines at urology do not have the separation between dirty and clean, because they open at the top instead of on the other side in another room (L4). The third step is drying. At Erasmus MC they have recently switched from drying in drying closets, which took 90 minutes to a scope drying machine called *PlasmaTYPHOON+ from Plasmabiotics*, which that only takes four minutes and takes less space (E3). At LUMC they still have drying closets (L4). After drying, the scopes are just like other individual MDs packaged in laminate pouches (E3, L4).

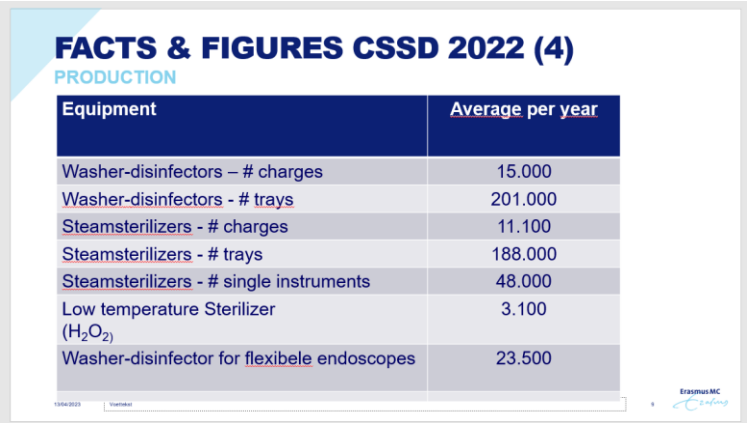
At the CSSD of Erasmus MC, during weekdays employees work in shifts 24/7 and there are fifteen employees per shift. On Saturday and Sunday there is a normal shift from 7:30 till 17:30 and between 17:30 and 7:30 there is an on-call shift, but in which the employee will almost always be called upon (E3). There are 53 FTE, of which eight students and two and a half support employees, so there are 50.5 FTE on the process including eight students who can't do weekend and night shifts. Moreover, employees that are 58 years or older are not allowed to do evening and night shifts and this are again eight employees. Therefore, Erasmus MC already has sixteen less employees that can be scheduled in weekends and thus with their current number of employees, it will not be possible to be open 24/7 (E4). In conclusion, at Erasmus MC, getting enough employees is a capacity problem, combined with time available [P34].

At the CSSD of LUMC, there are 25 FTE and they do not work 24/7. They have a day shift from 7:30-16:00, a between shift from 12:30 -21:00 and a night shift from 14:00 – 22:30. In the hours that they are not open they also have one employee who can be called upon if necessary. In the weekends the shifts are shorter. At the CSSD in LUMC employees that are 58 years or older do work evening and night shifts, while this is not allowed (L4). At LUMC, time is not a capacity problem right now as they do not yet work overnight. Also, there is enough space available, so this is also not the capacity problem. However, getting enough employees is their biggest capacity because of the tight marketplace, and the washing machines are also often the bottleneck at LUMC because these are often out of order [P35] (L4, L6).

Extracting data from *Hix* or *T-Doc* is not easy and therefore only limited data is extracted from *Hix* about the capacity of certain machines and its programs (E10). An example of this is presented **in figure 14**, showing the number of charges at Erasmus MC, which is the number of times a machine has run in a year. One charge of a washer-disinfector or steam sterilizer can be filled with nets or individual MDs, which is data that is now difficult to extract [P36]. Moreover, they do not know how well each charge is loaded [P37], meaning how many nets are in one washing program. This is problematic because this could otherwise be used to discover the root cause of irregularities, or to calculate much capacity is taken up by different washing programs (E10). Therefore, with this information lacking, it is not possible to assess how much of the total capacity (in time and load space) of a specific machine is taken up by a specific RER MD category, and therefore it is also not possible to assess for a specific machine if the capacity of that machine would be reached when the hospital would increase the use of that specific RER MD reprocessed by a reprocessing type for which that specific machine is required [P38].

Figure 14

Number of charges of the CSSD at Erasmus MC (E10).



Note: low temperature sterilizer = *Sterrad* hydrogen peroxide gas plasma sterilizer

At LUMC there are around 2,500 nets, with 2,000 different ones in rotation. Around 84,000 nets are sterilized, and 12,000 endoscopes are reprocessed per year (L2). At Erasmus MC there are around 5,000 nets in rotation. Nets and individual MDs are both used 120,000 times per year and endoscopes are used 23,500 times per year (E4).

There are several other problems identified at the CSSD. First, there might be MDs on a net that remain unused. Nonetheless, the whole net including the unused MDs needs to be reprocessed again [P39] (E10). At LUMC, they are now seeing if they can optimize the net content by using a combination of conversations with surgeons and OR assistants and filming the actual use of the MDs in a net in the OR. They would like to use Artificial Intelligence (AI) to analyse this data but are still looking for experts or students to help them with this (L2). Second, MDs that run out of sterile expiration date are checked in a list every two

weeks (L6). At LUMC this are not that many MDs, while at Erasmus MC these are 6 full carts each month of unused MDs of which the sterility has expired. Therefore, these 6 full carts need to go through the complete process of reprocessing again [P40] (E10). A third problem, identified at Erasmus MC, happens when an MD breaks or is missing inside a net, it is either replaced from the inventory or when it is not on inventory the OR is called. If they say they can do the surgery without that MD inside the net, the blue wrap is put inside out, so that the outer wrap will be white instead of blue to indicate that a MD from that net is missing (also stated on the label). The problem is that if there is an identical net, OR logistics picking the MDs for surgery will almost always pick the full net instead of the incomplete one. Therefore, the incomplete nets will almost always end up expiring, thus monthly being reprocessed again [P41] (E10). Lastly, a problem identified at LUMC, is that they have so called 'theme boxes' which are yellow boxes filled with SU MDs that are pre picked. Problem with those is that when there are MDs inside that will remain unused, they will need to be discarded unused [P42] (L4).

External reprocessing

At Erasmus MC, MDs are now only reprocessed externally when washing machines or sterilization machines have breakdowns and therefore cannot be used. If this happens, they go to Den Haag or Maasstad hospital. (E3) At LUMC when washing machines or autoclaves have breakdowns, they go to Alreine leidendorp hospital and when their *Sterrad* breaks down they go to VU (L4). When they only need to sterilize, washing and preparing the net still happens at their own CSSD and are transported to Alreine leidendorp hospital to sterilize during the night (L4). Some nets of LUMC are always sterilized externally (*Pectus* nets) because their own autoclaves are not able to sterilize these (L4).

Like already mentioned in the typology, reprocessing externally will require more MDs and therefore storage space is required, because MDs cannot be picked while they are away, and the throughput time increases compared to internal reprocessing [P43]. Other problems include that the hospital does not have control over the process [P44] and MDs might get lost in the process [P45]. When reprocessing at another hospital, like both case hospitals sometimes already do, there is a lot of paperwork that needs to be checked [P46]. When a hospital chooses for commercial sterilization, this will come at a high price [P47]. Lastly there are two problems related to transport. The transport method needs to ensure sterility for MDs that are required to be sterilized [P48]. When blue wrap is used this can happen in closed carts, or when rigid sterilization containers are used this can happen in open carts (E3). LUMC uses yellow boxes with blue covers around them to transport sterile over the hallways. This is done when sterilized carts need to be transported back to civic where the OR Thorax is situated (L4). The biggest scare with external sterilization when blue wrap is used is it might get holes/tears in it during transport and therefore loses its sterility [P49] (L4).

5.2.5. Repair

RER MDs might stop working, for example when a MD does not let light through anymore while this is required for the MD to work (E14). This can be notified by the CSSD who does performs a visual inspection or by the end user, for example a doctor, who performs a functional inspection (L6, E14). When a MD, designed to be RER for an infinite number of cycles stops working, mostly they are dicarded (E10), but in some cases, they are repaired internally or externally at the supplier or somewhere else (L5, L6 E14). However, as explained previously, because both case hospitals do not use a software tool for tracking and tracing information about the history of unique MDs, such as the module already available in *Oracle*, the number of repairs is also not yet being tracked and then coupled to this software tool [P23].

At LUMC repairs for MDs are mostly performed externally as their medical technology department focusses on developing new stuff, not on repairing (L6). Only high value MDs with a plug, are repaired internally at the clinical technology who are situated at the OR (L2, L6). All MDs that are reprocessed at the CSSD however, are repaired externally. Some devices like drills and burs are sent back to the supplier

for repair or when that is not possible, parts recycling. When that happens, the MD is first booked in *People soft* and then send to or picked up by the supplier (L6). *Stäppler*, uses an incentive mechanism that when their MDs are send back at the end of its life, which is done though the post-office, the hospital will get a discount on a new one they receive back (L6). *Braun* sends someone to pick the MDs themselves. Some other MDs have maintenance contracts and are also send back through the post-office (L5, L6). All other, more simple MDs, mostly surgical MDs from SS, are sent to *VSM* via an account manager from *VSM*, who picks up a box of several dozen MDs each week (L6).

At Erasmus MC, medical technology does perform internal repairs of MDs but also some are sent back to the supplier. MDs should first be cleaned at the CSA and can then go to medical technology for repair or maintenance (E15). For Medical technology, everything they need to know is inside *Ultimo*, which is an asset management system (E14).

5.2.6. Point of collection space

As explained in the typology, point of collection space consists of waste and MDs to be picked up for external repair, reprocessing or recycling.

Waste

As mentioned in sub-section '5.2.1. Transport', there are multiple dedicated waste locations throughout the hospital, which could be a place in the hallway or a small or bigger environmental station. Some environmental stations allow for more separate streams to be collected because there is enough space, while in others there is only enough space for a few separate streams (E7). Even at the biggest environment station at the OR at Erasmus MC, there is a lack of space to collect all streams separately as there is no dedicated place for styrofoam there for example [P50] (E15). From here, waste is transported to the waste department situated at the logistics center, where the waste streams are emptied inside the right container (E7).

At Erasmus MC, the waste department consists of a press container for residual waste, one for paper and one for food, that all stand inside (E1). There are also some containers outside at Erasmus MC, that are mostly filled with products by the moving service. These containers include three metal containers, one white goods and electronics container, one wood container (also for pallets that do not go with the pallets recycler) and one bulky waste container. Moreover, there are containers for soft and hard plastics (E7).

At LUMC, the full waste department is outside and consists of two residual waste presses, one paper press, one specific hospital waste container, one COVID-waste container, one PMD container, glass bins, one chemical/radioactive container, a kitchen waste press which is not used anymore because the machine did not function properly and therefore it was financially not viable, and lastly different storage locations of bulky waste. For bulky waste an internal marketplace is created. Computers, furniture, printers etc. are ordered by employees with their personal budget. Employees order new stuff because otherwise their budget will be 'for nothing'. With the marketplace the goal is to find a new user for products instead of throwing it away (L1).

From the waste department different containers are emptied by the waste handling partner, which is *Prezero* for both hospitals. Erasmus only recently switched from *Renewi* to *Prezero* (E7). An overview of all waste streams collected by *Prezero* in both hospitals in 2022 is presented in table 17.

Table 17

Overview of waste streams at LUMC and Erasmus MC in 2022 (S2, L3, E7).

Category name	Description	Present at
Paper / carton	Receive money from this (collected in container)	Both hospitals
EPS (expended polystyrene)	Styrofoam. Costs LUMC money, Erasmus MC receives money because it is shredded	Both hospitals
PP - nonwoven	#5 Polypropylene, mostly blue wrap from CSSD	Both hospitals
PMD from firm	For Erasmus this is a small collection of water bottles with blue cap	Both hospitals
Solvents, rich in halogens	(Collected in jerrycans)	Both hospitals
Hard plastic	#1 PET, pipette trays transported in red specific hospital waste bins, which are emptied in a container outside. Also, plastic pallets go in this container.	Both hospitals
Glass		Both hospitals
Wood B	(Collected in container)	Both hospitals
Clean up waste/filters with chem. residues	Filter systems at some departments	Both hospitals
Low-calorific liquids	(Collected in jerrycans)	Both hospitals
Archive materials	Confidential paper	Both hospitals
White goods		Both hospitals
Bedding waste	Organic fibrous material that has been applied as bedding in housing of experimental animals	Both hospitals
Commercial waste	Waste from trauma chopper and at the distribution center	Both hospitals
Solvents, low in halogens	(Collected in jerrycans)	Both hospitals
Swill	Food waste	Both hospitals
Dangerous waste	Sharps waste	Both hospitals
No waste	Costs of hiring containers	Both hospitals
Hospital waste, not specific	Residual waste, the goal to be 25% in 2030	Both hospitals
Hospital waste, specific	Specific hospital waste, collected in WIVA kegs	Both hospitals
Office waste	Cartridges, batteries	Erasmus MC
Medicines	Medicinal waste (collected in black tubes)	Both hospitals
Foil	#4 LDPE soft plastic like bedcovers, wrapping film, plastic bags (collected in paper container, separated at waste handler)	Erasmus MC
Laboratory glass, empty		Erasmus MC

Non-specific hospital waste (Pharmafilter)	Certain MDs that would otherwise be discarded as specific hospital waste from the IC can go in the Tonto shredder, that is attached to the pharmafilter system that removes harmful materials. What is left is non-specific hospital waste.	Erasmus MC
Batteries (dry)		LUMC
Fluorescent lamps, straight		LUMC
Grease	(Collected in jerrycans)	LUMC
Construction and demolition waste		LUMC
Inorganic acids		LUMC
Green waste		LUMC
PMD from healthcare institutions	PMD collected inside the hospital with source seperation	LUMC
Chlorine bleach lye solution		LUMC

In the Green deal 3.0 the goal that is formulated about waste is that in 2026 there should be 25% less unsorted residual waste compared to 2018 and in 2030 their unsorted residual waste should be 25% (Dutch Government & Healthcare sector, 2022). Unsorted residual waste is the non-specific waste stream of a hospital, and the percentages are percentages of the total weight, as waste is always calculated per 1,000 kg (E7). 25% unsorted residual waste does not mean that 75% of the total weight of the waste should be recycled, as this 75% also includes hazardous waste streams that cannot be recycled. As mentioned before in the conceptual background, around 15% of all waste is considered hazardous waste that cannot be recycled (World Health Organization, 2014).

The biggest streams in weight of both hospitals are non-specific residual hospital waste, followed by specific hospital waste and then paper/cartons. In volume non-specific residual hospital waste is the biggest followed by paper/cartons as the volume of specific hospital waste cannot be measured because the specific hospital waste bins are burned with the lid closed.

There are some differences in other categories that are being collected by both hospitals. The biggest differences are because of a project called 'source separation'. In this project, three big streams will be separated at the source, meaning at the patient care location: PMD (plastic metals and drink cartons) which will soon be called PD (plastics and drink cartons), Green (swill, food waste), and cartons. The goal of the project is to make sure these streams do not end up as residual waste to be burned (E7). In LUMC they have already started with this a couple years ago (L2). Soft plastics (#4 LDPE) and hard plastics (#1 PET) could in theory be collected at PD, but in practice not because these types of plastic will interrupt the process of sorting PD. All hard plastics are too strong and soft plastics includes long wrapping foils that are also too strong, so that it might get into the hinges of the sorting belts and cause failures in the sorting process (S2). Since 1 January 2023, PD is subsidized so there are no costs for waste collection or rent of the container (S2). There are two types of contamination in PD stream. First, a precalculated contamination where 85% is recycled and 15% is contaminated. Second, like explained above it can be that PD gets rejected. When a waste handler picks up a bag of PD and it is way heavier, than they leave that bag behind. That bag should then be removed of the heavy content and be offered again as PD. However, what happens is that this bag will probably end up in non-specific hospital waste. What also can happen is that a waste handler that comes pick up the bag sees a bag that is contaminated with some needles or blood. Then out of precaution the whole container gets treated as if it is residual waste (S2), which currently happens too often at LUMC (L3). At Erasmus MC, they have only recently started (1/4/2023) the 'source seperation' project in hallways and offices and are going to start in care departments soon. At those departments (including OR, IC, Emergency care) a lot of packaging waste is created by unpacking MDs that are packaged by mostly plastic with some paper. Currently these streams end up in the residual waste to be burned but with this project will then go in the same PD press container. Now without the 'source separation' project, Erasmus MC already separates some soft plastic (#4 LDPE) and hard plastics (#1 PET) for it to be recycled, but this can be improved. Soft plastics are foils around bed carts, wrapping film, plastic carrying bags and soft packaging materials and seals. Hard plastics are dialysis pouches, citrate pouches and dialysis bags (with a certain part removed) (E2). An example of where it can be improved is at the IC where when a room is prepared for a next patient, clean plastic packaging is now still discarded at the residual waste bin, figure 15, bottom left (E2). With the source separation program this should be avoided (E15). The board of directors form Erasmus MC invested 450,000 EUR to execute this project (E7). Erasmus MC still must decide on the location of the PD press container. Inside at the waste center there is no space for another press container, while outside there might be some problems with noise disturbance for the neighbors (E7). In conclusion, when hospitals move towards the green deal goal of only 25% unsorted residual waste, more and more streams will be collected separately. Executing this however will be challenging, as there is not enough space available to separate all streams at every dedicated waste location throughout the hospital, including environmental stations [P50], and limited space is available at the waste department to place more containers for separate streams [P51] (E7).

Costs of streams depend on the number of pick-ups and the kilograms of waste generated. Specific hospital waste is the most expensive category because this requires extra careful handling and transportation, and it will eventually be burned with the lid still on in Dordrecht (L2). Most streams cost money but for some streams the hospital can also earn money. Both hospitals earn money from the #5 PP stream, which is generated mostly by blue wrap from the CSSD. Another stream that generates some money is paper / carton, however the hospital still pays for transport costs (L3). A stream that generates some money for Erasmus MC since January 2023, is the collection of water bottles with blue cap. Lastly the EPS stream generates money for Erasmus MC because they have invested in a machine that shreds EPS into long beams (E7). LUMC currently still pays quite some money for their EPS stream, which is a problem they are looking into [P52] (L1). Other cost differences are based on differences on where waste is being reprocessed. Moreover, the LUMC contract has been made in 2019 and Erasmus MC contract in 2022, so this might also explain some differences. Lastly, the number of pick-ups also has an impact on the price. *Prezero* offers containers from 140 liters till sea containers from 40 cubic meters. With a bigger container, there will be less pickups.

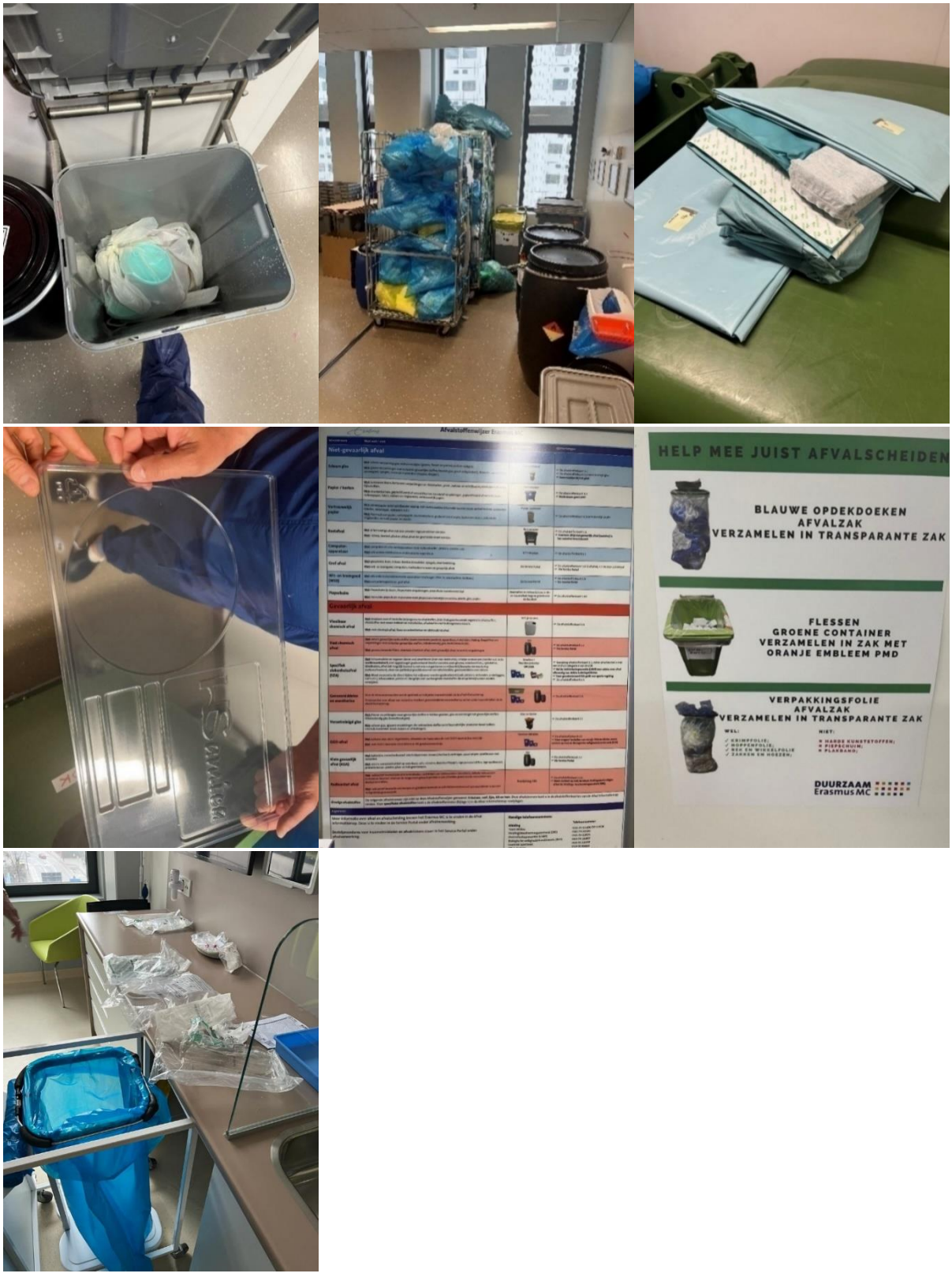
At Erasmus MC, there are some departments that collect some streams themselves, but they are out of sight of the waste manager. This will be partially solved with the 'source separation' project that will start soon, as PD plastics then have a dedicated stream with appropriate waste bins. All streams should go through *Prezero*, but there could be some exceptions. For example, the printer cartridges go back to *cannon*, except for cartridges from some offices that are collected separately to be donated to a charity. The same happens with some batteries for example. *Prezero* knows and allows this. (E7).

At both case hospitals, specific hospital waste is often collected when bins are not completely full (L1, E15) [P53]. At Erasmus MC the started reusing small hard plastic specific hospital waste bins, as presented in figure 15, top left. By putting specific hospital waste in a bag, they can empty these inside a bigger bin and reuse the smaller specific hospital waste bin. This saves hard plastic from the bins (E15).

Other problems have to do with that in the end it is people that need to separate the streams correctly, which is therefore prone to human error [P54]. At LUMC it has already been shown in the 'source separation' that this can go wrong as PD containers are rejected too often (L3). As explained in subsection '5.2.1. Transport', at Erasmus MC, OR logistics, students or OR assistants all can bring waste to the environmental station at the OR. They all need to be informed on how to separate streams correctly, but when this goes wrong the hospital does not know who did it wrong, and who was not informed correctly as this data is not being traced [P55]. These behavior changes are difficult and have gone wrong in the past. One time a full garbage bag with clogs was found by an attentive cleaning personnel. Another case where it did go wrong is with scrub suits, where 60,000 EUR with of scrub suits went missing in one year. They were then not thrown in the laundry bag, but discarded in the waste bin (E16). This also became visible in observations during a visit at the environmental station of the OR at Erasmus MC. At Erasmus MC, when MDs are unused but clean, they are collected separately for 'second chance'. (E15) These MDs can be used either for education purposes, send to the lab to be used during animal experiments or send abroad to low-income countries (E15). As explained in sub-section '5.2.2. Tracking and Tracing', MDs that have passed their expiration date might also be collected separately for 'second chance'. Figure 15, top middle shows the 'second chance' cart at the environmental station at the OR. Figure 15, top right shows all sorts of unused MDs that were found in the residual waste bin instead of the 'second chance' cart. Figure 15, middle left shows hard plastic (#1 PET) that should be collected separately but was also found in the residual waste bin. Moreover, information on how to correctly separate streams might be outdated, just like the waste guide of Erasmus MC presented in figure 15, middle middle, that does not show separate streams [P56]. Next to it also hangs some information about how to correctly separate (some) streams correctly, figure 15, middle right.

Figure 15

All at Erasmus MC. Top left: small specific hospital waste bins that will be reused. Top middle: unused MDs on 'second chance' carts. Top right: unused MDs found in residual waste bin. Middle left: hard plastic #1 PET found in residual waste bin. Middle middle: outdated waste guide without separated streams. Middle right: information about how to correctly separate (some) streams (E15). Bottom left: clean plastic found in residual waste bin at IC (E2).



Medical devices

Space is also required for pickup of MDs for external repair, reprocess or recycling, and therefore these MDs are then not picked up by the waste handler *Prezero*. In the repair sub-section '5.2.5. Repair' some examples of suppliers that pick-up their own MDs at their EOL for either repair or when that is not possible parts recycling were mentioned. There are also some suppliers that pick up their own MD for reprocessing, including the external laundry service that reprocesses medical textiles and one supplier that reprocesses a part of a SU MD, which will be explained in their sub-sections '5.3.7. Reprocessing medical textiles' and '5.3.8. Reprocessing single use medical devices' respectively. When more suppliers pick-up their own waste stream, this will lower the waste generated by the hospital, but it still needs to be collected somewhere separately and stored till it is being send back or picked-up to the supplier, repairer or reprocessor. Therefore, this will result in the same problems mentioned earlier about available space at dedicated waste locations [P50] and at the waste department [P51].

5.3. Medical devices per reprocessing type in the two case hospitals

This section describes how the material logistics infrastructure around each reprocessing type from the typology looks like at Erasmus MC and LUMC. More specific, the MDs identified from the LCA (and LCC) studies will be analysed in the two case hospitals. The first sub-sections present an overview of all those MDs and whether the two case hospitals have a SU, RER or MOD version of those MDs in **table 18**. Why it is important but was difficult to assess the number of uses for each MD will also be explained in this first sub-section. All sub-sections after that discuss what reasons, problems and sometimes already some solutions are there of why the two case hospitals have a certain version of specific types of MDs, from the different reprocessing types from the typology. Not all MDs will be discussed, and some more extensive than others because of available data and time limitations, further discussed in section '7.4. Limitations', and because the problems and solutions for switching to the right version of a MD are more interesting than others. Moreover, some MDs will be discussed that do not have an LCA (and LCC) study, but nonetheless have some interesting findings. The overview of identified problems can be found in Appendix B.

5.3.1. Medical devices from LCA (and LCC) studies at the two case hospitals

A goal of the green deal sustainable healthcare 3.0 is to move to 20% RER MDs by 2026, however the two case hospitals both did not know how much % of their MDs are RER or SU and thus how far they are with this goal. They do not even make a distinction from all orders what products are MDs or non-medical products, and therefore also not what if MDs are a SU or RER version [P57] (E1). A rough indication which can be used is that almost all SKUs that are bought, and can be found in procurement data, are SU MDs (E9) and that all MDs that are reprocessed at the CSSD are RER. Therefore, it was difficult to find out if Erasmus MC or LUMC had a SU or RER version of specific types of MDs. Filling in **Table 18** relied on procurement data from 2021, mostly for the SU versions, and expert knowledge of the respondents. Therefore, when a specific type of MD could not be identified in the procurement data from 2021 and respondents also did not know whether there is SU version, this is indicated with a question mark. A green row indicates a MD with LCA studies that found the RER version to have lower GWP, a red row indicates a MD with LCA studies that found the SU version to have lower GWP, and a yellow row indicates a MD with LCA studies that had mixed results on what version has lower GWP.

Table 18 (next page)

Versions of specific types of MDs from LCA (and LCC) studies at Erasmus MC and LUMC

Specific type	SU at Erasmus MC	RER at Erasmus MC	SU at LUMC	RER at LUMC
Laryngoscope handle	Yes	Yes	?	No
Blood pressure cuff	Yes	Yes	Yes	Yes
Anesthetic drug tray	Yes	No	Yes	No
Laryngoscope blade	Yes	No	No	Yes
Bedpan	Yes	No	?	No
Sharps container	Yes	No	Yes	No
Suction receptacle	?	No	Yes	No
Central venous catheter insertion kit	Yes	No	Yes	No
Laryngeal mask (airway)	Yes	No	Yes	No
Sterile packaging	Yes	No	Yes	No
Surgical scissors	Yes	Yes	Yes	Yes
Laparascopic trocar/port	Yes	Yes	Yes	Yes
Laparoscopic clip applier	Yes	No	Yes	Yes
Laparoscopic scissors	MOD (SU attachment)	MOD (RER handle)	?	Yes
Lumbar fusion set	?	Yes	?	No
Vaginal speculum	Yes	Yes	Yes	Yes
Duodenoscope	?	Yes	?	Yes
Bronchoscope	Yes	Yes	Yes	Yes
Flexible cystascope	?	Yes	?	Yes
Flexible ureteroscope	?	Yes	?	Yes
Scrub suit	No	Yes	No	Yes
Surgical drape (and tape)	Yes	No	Yes	No
Surgical gown	Yes	No	Yes	No
Body coverall	Yes	No	Yes	No
Isolation gown	Yes	No	Yes	No
Face mask	Yes	No	Yes	No
Incontinence underpad	Yes	No	Yes	No
Electrophysiology catheter	Yes	No	?	No

What was even more difficult data to find out, was the number of uses of a specific type of MD from this list. This makes it difficult to make an informed decision to switch to a RER version based on the LCA (and LCC) study result tables, as it then cannot be estimated how much the environmental impact or costs the hospital will save, and how much will change on the material logistics infrastructure requirements for example capacity at the CSSD, when switching to another version. It was difficult to identify the number of uses of a specific type of MD for multiple reasons.

First, for a specific type, for example a surgical scissors, many different versions are being bought and it is difficult to identify all these different versions of a specific type within procurement data, especially because currently many 'alternative' MDs are bought [P58]. Second, most MDs are part of a net [P59]. This is a problem, because instrument management at LUMC could only check the number of cycles of an individual MD, for example scissor number 34528, or get an overview of all individual MDs. However, because surgical scissors are inside multiple nets and it is not known how many of these scissors are inside the net or how many of these specific nets there are in circulation, it is not known how many surgical scissors are used per year (L5). Third, like mentioned before in sub-section '5.2.4. Reprocessing', the MD might be part of a net and remain unused, but still the whole net is reprocessed [P39]. Therefore, counting the reprocess cycles of every net the MD is on, will not be accurate as some MDs might be unused. Fourth, some SU MDs, are part of a procedure tray [P60], which is a ready to go sterile package, like explained in sub-section '5.2.1. Transport'. A similar thing happens with procedure trays as with nets, that is that some MDs will remain unused [P61]. MD inside such a procedure tray that remain unused, will need to be discarded, and at Erasmus MC these are supposed to be placed on a 'second chance' cart, like explained previously in sub-section '5.2.6. Point of collection space'. Moreover, like LUMC is trying to optimize what is inside a net, Erasmus MC has tried to optimize what is inside of the procedure trays. On each procedure tray, there is a list of MDs that are inside, as presented in figure 16, left. On that list they kept track of what MDs were not used after a procedure during a month. By doing this they could see what MDs are often discarded without being used. One thing that they found was that a procedure tray has four surgical gowns inside, but that these procedures are more often only performed by three surgeons. This fourth gown will then need to be discarded, unused. Another finding and problem with the procedure trays at Erasmus MC is that they do not have many very specific procedures, and therefore have many generic procedure trays. They have some specific procedure trays (laparoscopic, hip, knee) and when those were used, less MDs end up being unused compared to when more generic procedure trays were used [P62] (E16). When they asked *Molnlycke*, their supplier of procedure tray, to remove some specific MDs from a specific tray, *Molnlycke* responded that this will result in a higher price. Therefore, the optimization did not yet happen, and Erasmus MC will wait on the next tender for procedure trays to change MDs inside their procedure trays, because changing things outside of this tender is difficult as the supplier will almost always ask a raise in price (E16).

Figure 16 (next page)

Both procedure trays from Molnlycke at Erasmus MC. Left: list of MDs inside. Right: storage racks at the CSSD at Erasmus MC (E15).

5.3.2. Light disinfection

Erasmus MC has RER, but also SU blood pressure cuffs. SU ones are used at emergency care and at isolation care. At emergency care because there is a big chance that it will get into contact with blood and ones that happens, then light-disinfection is not enough, and they should be high-level disinfected in a solution with chlorine. At isolation care because everything inside an isolation room should be discarded after an infected patient leaves the room [P26]. Nonetheless, the LCA (and LCC) study of Sanchez et al found lower GWP and LCC in all their situations which also included an inpatient ICU situation with patient dedicated MDs. Therefore, RER versions should be considered for isolation care as well. A problem with blood pressure cuffs is that they contain a part made of Velcro which cannot be cleaned [P63] (E17).

5.3.3. High level disinfection

Erasmus MC has SU bedpans, but these are not the same type as studied in the LCA study of Sørensen & Wenzel (2014). The SU bedpans Erasmus MC uses are made to be shredded in the *Tonto*, which is connected to the *Pharmafilter* system as explained in sub-section '5.2.6. Point of collection space' (E10).

Laryngoscope blades are RER at LUMC, but still SU at Erasmus MC. At Erasmus MC they have had a student look at the possibility of RER blades, but they are yet to be implemented (E8).

RER sharps containers do not exist yet in the Netherlands, because of current laws and regulations [P64]. However, at Erasmus MC they have another smart solution to reduce environmental impact and costs from sharps waste. They started using carton boxes (with the correct UN sticker) instead of specific hospital waste containers to put the UN certified sharps containers in, as presented in figure 17, left. This saves space, costs and is better for the environment, because less plastic is used. A Grey bin costs about 4 EUR, while the box costs 1.27 EUR (E2, E7).

LUMC is aware that a RER suction receptacle system exists, being the *Neptune 3* surgical waste fluid system of *Stryker*. This is MD sucks fluid which is then discarded in the sewer, just like would happen with the fluid from the RER suction receptacle from the LCA study. This MD has no initial procurement costs, and the hospital would then pay the supplier on a pay-per-use basis. However, LUMC has not implemented this system, because these pay-per-use costs would be higher than the procurement costs of a SU fluid cup, as presented in figure 17, right [P65] (L2). It is unclear whether they have compared the LCC, including waste handling costs in their decision.

Figure 17 (next page)

Left: collecting sharps containers in boxes instead of specific hospital waste container at Erasmus MC (E2), right: SU suction fluid cup at OR LUMC

5.3.4. Steam sterilization

Inside an OR there are around four employees inside a 'protected area', which is a three-by-three sterile area that blows cold air down so that particles will not enter the patient. There are around ten employees inside the OR room in total during an operation, including anesthetics who stand outside the protected area (E15). Everything inside this protected area will need to be sterilized, so this includes a so-called kidney dish, which is used as a tray for everything (E4) or surgical light handles (L4). So, this includes more than only MDs that enter tissue or the vascular system, as defined earlier by the Spaulding scale (McDonnell & Burke, 2011). At both case hospitals, some nets still have RER kidney dishes (L2, E4), at Erasmus MC mostly those from Jaw clinic, ENT (ear nose throat), and OR Thorax (E4). Again, here it is up to the user to decide whether they want to use a RER or SU kidney dish. The disadvantage of putting a RER kidney dish inside a net is that it takes a lot of space [P66]. In one full charge with nets without kidney dishes fit 15 basic nets, while in one charge with nets with kidney dishes only fit 10-12 nets at the same time (E4). As presented in figure 18 left, a RER kidney on a net takes a lot of space in the net and even sticks out at the top of the net, while a SU kidney dish, as presented in figure 18, right, does not have this problem.

Figure 18 (next page)

Left: RER kidney dish on a net at Erasmus MC (E3). Right: SU kidney dish at LUMC (L2)

Both hospitals use and recycle blue wrap and not rigid sterilization containers (L2, E4). *Prezero* collects the blue wrap and it is recycled into chairs (L2). Other hospitals that work with *Renewi* as waste handler, have their blue wrap transported to *VSM*, who recycle the PP into other products including a new MD. More about *VSM* will be explained in the sub-section '6.2.3. Point of collection space solutions'. As mentioned in the typology, switching from blue wrap to rigid sterilization containers would require way more space (E3, E4) [P67]. Other additional material logistics requirements are that the containers would need to be inspected if they are damaged and special filters need to be put on and off, which both require some extra time (E4). A counterargument is that packing nets in blue wrap also takes some extra time compared to rigid sterilization containers. In the Netherlands there are stricter guidelines compared to other countries and therefore blue wrap is used here, while in for example Germany they use rigid sterilization containers (E4). One example is a hospital in Hamburg, that can use rigid sterilization containers because they have a lot more space and a lower production (E3). LUMC will renovate the OR and CSSD. They are still discussing the map and routes on where everything needs to be. The most difficult thing here is that dirty clean and sterile transport routes need to be separated. The goal of the renovation is to make a CSSD that is more sustainable, and able to reprocess more RER MDs. One way in which they wish to achieve this is that they will renovate it in such a way that there is enough space to start using rigid sterilization containers for around a quarter of all nets, reducing the environmental impact (L2, L4). According to LUMC, blue wrap can be reused up to ten times, which is another option to lower environmental impact of sterile packaging before recycling, but then the blue wrap should be inspected for holes which is the reason they have not implemented this themselves [P68] (L2).

As visible in table 18, the laparoscopic trocar, vaginal speculum and surgical scissors both have SU and RER versions at the two case hospitals. The Laparoscopic scissors is a MOD version, with a RER handle and SU attachment (E16). Many MDs used to be RER back in the days, made from RVS, but are now SU MDs, including laparoscopic trocars, staplers or endoscopic staplers, all presented in **figure 19**. These MDs have become SU mostly because cleaning them is difficult (E15). The laparoscopic trocar could be a MOD device with some RER part, like in the LCA study of Rizan & Bhutta (2022). The endoscopic stapler is a complex MD and thus parts recycling might be a better option, which is currently being tested by *VSM* and will be explained further in sub-section '6.2.3. Point of collection space solutions'.

Figure 19 (next page)

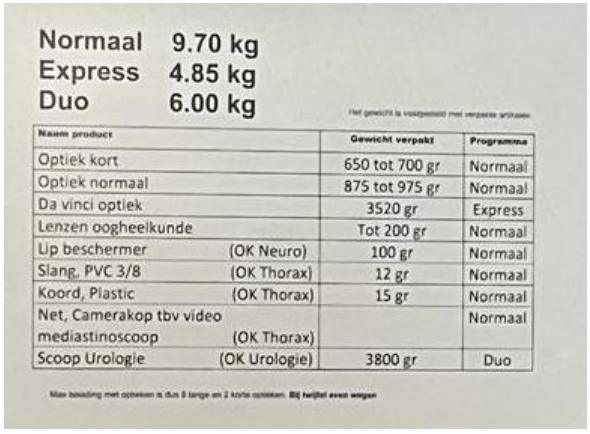
All SU MDs in inventory at the OR that used to be RER made from RVS (E15). Left; laparoscopic trocar. Middle: endoscopic stapler attachment. Right: stapler.

5.3.5. Hydrogen peroxide gas plasma sterilization

As mentioned in sub-section '5.2.4. Reprocessing', both case hospitals have a hydrogen peroxide gas plasma sterilizer the *Sterrad*. Not that many MDs are reprocessed in the *Sterrad*, as presented in **figure 20** that shows all MDs required to go in the *Sterrad* at Erasmus MC.

Figure 20

MD reprocessed in the Sterrad at Erasmus MC (E4).



Normaal 9.70 kg
Express 4.85 kg
Duo 6.00 kg

Naam product		Gewicht verpakt	Programma
Optiek kort		650 tot 700 gr	Normaal
Optiek normaal		875 tot 975 gr	Normaal
Da vinci optiek		3520 gr	Express
Lenzen oogheelkunde		Tot 200 gr	Normaal
Lip beschermer	(OK Neuro)	100 gr	Normaal
Slang, PVC 3/8	(OK Thorax)	12 gr	Normaal
Koord, Plastic	(OK Thorax)	15 gr	Normaal
Net, Camerakop tbv video mediastinoscoop	(OK Thorax)		Normaal
Scoop Urologie	(OK Urologie)	3800 gr	Duo

5.3.6. Reprocessing endoscopes

Almost all endoscopes are RER in both case hospitals. As described in sub-section '5.2.4. Reprocessing', most of them are high-level disinfected in special endoscope reprocessing machines and some are also sterilized by hydrogen peroxide gas plasma. The flexible ureteroscope is an example of an endoscope that is required to be high-level disinfected at Erasmus MC, as presented in figure 20 (Scoop Urologie).

As explained in section '4.6. Reprocessing endoscopes' there are mixed results in the LCA (and LCC) studies whether a RER or SU endoscope is better for the environment, but studies that found the SU version to be better studied a specific version and mentioned the name of this specific version and its OEM and thus considering switching to this SU version should be done with extreme care because the results might only be valid for that specific version and interdependency of the authors might be questioned. Moreover, the reprocessing machine and its detergents used, PPE use, number of cycles and different number of cycles all also could affect the results of these studies. Interpreting the results of LCA (and LCC) studies will be further discussed in subsection '7.4. Limitations'.

5.3.7. Reprocessing medical textiles

Both case hospitals have a contract with a laundromat to reprocesses their textiles, including some medical textiles. Medical textiles that are already RER in both hospitals are the scrub suits. Scrub suits are put on when entering the operating theatre (which consist of multiple OR's) and when leaving put in a laundry bag in the dressing room (E13). Both these laundry bags with scrub suits as laundry carts with non-medical textiles are placed at their dedicated waste location throughout the hospital. As explained in sub-section '5.2.1. Transport', logistics employees at Erasmus MC then bring the dirty medical textiles to the logistics hallway downstairs. From here, the laundromat enters the hospital building and picks it up from the hallway. This partner then takes it to their laundry facility, washes it and brings new washed textiles.

Overall, there are multiple challenges with finding the right characteristics of RER medical textiles, that are more or less present in the different MDs. These characteristics include permeability, user comfort, strength, shape and size, thickness and when used in a sterile area such as the OR, that it does not release too many particles [P69] (L1, E8, E15).

Medical textiles that have an LCA study but are not yet used at the two case hospitals include surgical drape (and tape), surgical gown, huck towel, body coverall, isolation gown, face mask and incontinence underpad. Other medical textiles that have a RER version available, but do not have an LCA study, include surgical hats, warming blankets, warming gowns, doctors' gown (used when a doctor goes to another department), and visitors gown (E15, S6).

Surgical drape (and tape) is currently part of procedure trays. Going to a RER version, the most important characteristics are that it should have the right permeability, shape and should stick to the patient, and therefore RER versions might not be ideal (E13, E15). Back in the days, surgical drapes and surgical gowns, which will be explained further below, both were RER and were thrown in a laundry bag at each OR. They used to be made from cotton, but cotton is now not allowed at the OR, because of the particles it releases (E15). Now surgical drapes are made of *Gore-tex*, but this material has problems with permeability, and this is the biggest argument against RER versions. Another argument against RER versions is that it might return with holes made with patches or unremovable spots on it, and therefore the sight of RER versions will be not as pretty as SU versions. These spots also are on the floor of every OR, as visible in **figure 21**, which shows that it cannot be removed.

Figure 21

Unremovable spots on OR floor at Erasmus MC (E15).

While scrub suits are RER, surgical gowns are still SU at both case hospitals. These gowns are put on over the scrub suit before entering an OR room. Currently, these surgical gowns are just like the surgical drapes part of the procedure trays, and after one procedure they are discarded in the specific hospital waste bin together with all specific hospital waste from that one procedure (E13). LUMC did a test to implement RER gowns with their laundromat *Cleanlease*. These RER surgical gowns were then delivered by *Cleanlease*, and stored in the sterile warehouse at the CSSD, similar to where the procedure trays are stored. After the procedure, the surgical gowns had to be put in a closed plastic, green bag for infection prevention reasons. These bags where than, just like the scrub suits, brought to a place where they can be picked up by *Cleanlease*. With the characteristics of the RER gown was nothing wrong, however this test showed that the costs were 2-3 times higher for the RER gowns and SU gowns cost around 200.000 each year [P70]. Therefore, they now still use SU laundromat partner from 2024 onwards *Nedlin* (E12, E13). For the material logistics infrastructure at Erasmus MC, this would mean they have to place laundry bags in each OR room, which are 26 in total (E13). Just like at LUMC, infection prevention at Erasmus MC also requires surgical gowns to be placed in closed bags after one use, however also mentioned an alternative. When plastic bags are used, they can be transported in open carts. When no plastic bags are used, they should be transported in a closed cart and after dumping the insides of the carts in a container where it can be collected, the inside of the container should be cleaned. All medical textiles can be placed in the same container if it were up to infection prevention (E17). However, the laundromat required sterile medical textiles, such as the surgical drape, surgical gown and huck towel to be collected separately from other medical textiles, because these are washed and sterilized at another place than where medical textiles are washed (S6).

Isolation gowns are used throughout the whole hospital (including IC) and are also still SU at both case hospitals (L7, E13). Just like the surgical gown, RER isolation gowns have similar transport requirements, either in a closed bag on an open cart, or in a closed cart that is cleaned after being dumped. This, because both surgical gowns and isolation gowns might be infected with micro-organisms and therefore the logistics employee transporting the carts should be protected against the risk to get infected (E17). At LUMC they recently had a tender for new Isolation gowns where they did not decide to buy RER versions because of the test with RER surgical gowns mentioned above where they found the RER version to be 2-3 times more expensive. However, they included some criteria on environmental sustainability in the tender, which they used to select among the 40-50 suppliers. They asked the location of the manufacturer, preferring manufacturers in Europe or the US instead of Asia, if it can be delivered by the greenest vehicles, and for a ISO14001 certificate for environmental management that proves that they have action plan to improve sustainability in their organisation. Such sustainability criteria or wishes in a tender are almost always included as 'nice to haves' and never as 'critical' criteria (L7). Other examples of wishes that can be included in a tender are different options from the R-ladder, recyclable or RER packaging, good working conditions (L7) or EOL pickups by suppliers. (E14).

The Amsterdam UMC already uses reusable surgical hats. When using these, they should be made in different shapes and sizes as employees with a different hair type with a lot of hair also need to be able to wear a RER hat (E15). Another important thing to mention is that RER hats are required by the laundromat service to be collected in separate laundry nets from other medical textiles. This, because they are small and would otherwise get lost (S6). At LUMC, they now still have SU, but are going to start using RER hats (L2).

Nedlin, the to be laundromat of Erasmus MC, recognizes that RER versions are more expensive than SU versions [P70]. Normal textiles are managed with a big pool because there is a lot of demand for that, while medical textiles are bought specifically for one hospital, based on their usage. The hospital will pay rent on the medical textiles, plus a fee for laundry. The rent will fall away a specific timeframe, mostly 260 weeks, and then the hospital will be owner of the medical textiles. Medical textiles are RFID-chipped so that *Nedlin* can track and trace the number of cycles at their laundry facility. One exception is for incontinence underpads, that are only visually inspected (S6). In conclusion, when going to RER medical textiles,

environmental impact will be lower, but costs will probably be higher [P70]. Material logistics infrastructure requirements are that non-medical textiles, unsterile medical textiles and sterile medical textiles should be collected separately, and within medical textiles the surgical hats should be collected in laundry nets.

5.3.8. Reprocessing single use medical devices

As explained in section '4.9. Reprocessing SU MDs', the only LCA (and LCC) study that studied a specific MD was the electrophysiology catheter. Other SU MDs that might be reprocessed include face masks, arthroscopic shaver, pulse oximeter, deep vein thrombosis (DVT) compression device, *Ligasure*, endoscopic trocar, ultrasconic scalpel and scissor tip.

From all these MDs, the only SU MD that is send back to the supplier are pulse oximeters from *Masimo* that Erasmus MC sends back to enable them to reprocess the sensors (E14).

In both case hospitals they have a SU *Ligasure*. Instrument management at LUMC was aware that there is a RER version, however, he recognized, just like identified form the typology, the impact this would have on storage space required because the *Ligasure* cannot be used while being reprocessed (L6).

6. Solution design

In the previous chapter, 70 different problems were observed at either one or both case hospitals. This chapter will design solutions for most of those problems, by answering SQ4. Before designing the solutions, design requirements are defined by answering SQ3 in the first section of this chapter.

SQ3: *What are requirements for design solutions in a circular hospital?*

SQ4*: What are the alternative design solutions for the observed problems to create a material logistics infrastructure that is required in a circular hospital?*

6.1. Design criteria

In this section SQ3 is answered by listing requirements for design solutions, or design criteria, to make sure that the solutions that will be designed are according to those requirements. Some design criteria are valid for all solutions that will be designed, one design criterium only holds for LUMC and lastly some design criteria were mentioned by respondents but are not used as design criteria.

Design criteria for all solutions

The most important design criterium that holds for all solutions is that it should **help to achieve at least one of the goals of the green deal 3.0, directly or indirectly** (European Commission, 2020; Government of the Netherlands, 2016). Therefore, a designed solutions should either help to decrease unsorted residual waste, to increase RER MDs, to decrease raw materials used or to decrease CO2 emissions, or a combination of some of these. It is possible that a solution does not directly impacts one of these goals but helps to achieve it indirectly, by helping to solve a problem or requirement from one of the identified material logistics infrastructure elements from the typology and with those solutions in place, other solutions can be implemented that do directly impact these goals.

The second design criterium is that a designed solutions should **be safe**. This can have multiple implications. First, before RER MDs can be used, they should be considered safe to use by infection prevention first (L6, E8). Second, when transporting sterile MDs over hallways this should ensure sterility of those MDs (E3) and third transporting possibly infectious material over hallways such as RER surgical gowns and RER isolation gowns, should ensure that no potential infections can take place, by transported in closed bags on open carts or in closed carts, with the inside of the cart being cleaned after each use (E17).

A third important design criterium is that a solution should **comply with current laws and regulations** (E7), however it is important to realize that laws and regulations might change and that some solutions that are not possible now, might be possible in the future.

Design criteria for LUMC

A design criterium that is specifically important currently for LUMC, is that it can be proven that an **investment pays itself back** and therefore a good business case is made (L1, L3, E8, E13). Currently LUMC is having some monetary problems, and this is therefore used as design criterium for LUMC. For Erasmus MC, this design criterium can help to implement a solution faster, but it is not a prerequisite, thus not a design criterium for Erasmus MC. It is important to recognize that money is divided over different cost centers. Thus, a LCC approach should be used, and some budget money might be required to switch from one cost center to another. For example, a SU surgical gown needs to be bought from the budget of procurement, while when switching to a RER surgical gown, this needs to be bought from the department responsible for the laundromat, because they order it directly at the laundromat (E13).

Design criteria that are not used

Other design criteria that were mentioned by respondents are that solutions should **fit within current processes** (L3, E11, E13, E14), **fit within the available space** (L1, L3, E7, E11, E13), and should not

take a lot more **time** (and preferably less time) as there is limited **man-hours** available (L1, E11, E13, E14). However, all these three design criteria are within the boundaries of what currently is, while new processes could be made, additional space could be created or solutions could be made outside of the hospital and some solutions could create extra time, that than can be used for solutions that take extra time. Thus, because outside the box thinking is required and possible, these criteria are not used.

6.2. Solutions

In this section, SQ4 is answered by designing solutions for most of the 70 observed problems that were identified at either one or both case hospitals in the previous chapter.

***SQ4**: What are the alternative design solutions for the observed problems to create a material logistics infrastructure that is required in a circular hospital?*

Some solutions are expected to be more impactful on the most important design criterium, that it should help to achieve at least one of the goals of the green deal 3.0, directly or indirectly. An indication that can be used to estimate how impactful a solution will be, and therefore how important the solution is, is the number of identified problems the solution could solve directly or indirectly because the solution is required to be implemented before other solutions can be implemented that also solve one or more problems. Because of this sequential nature of some of the solutions, a solutions flowchart is created and presented in figure 22, that shows the sequential order between solution steps with arrows. This figure also shows the number of problems a solution steps could solve directly. Solution steps on the left-hand side of the dotted line are all solutions steps that do not require another solution step to be implemented first.

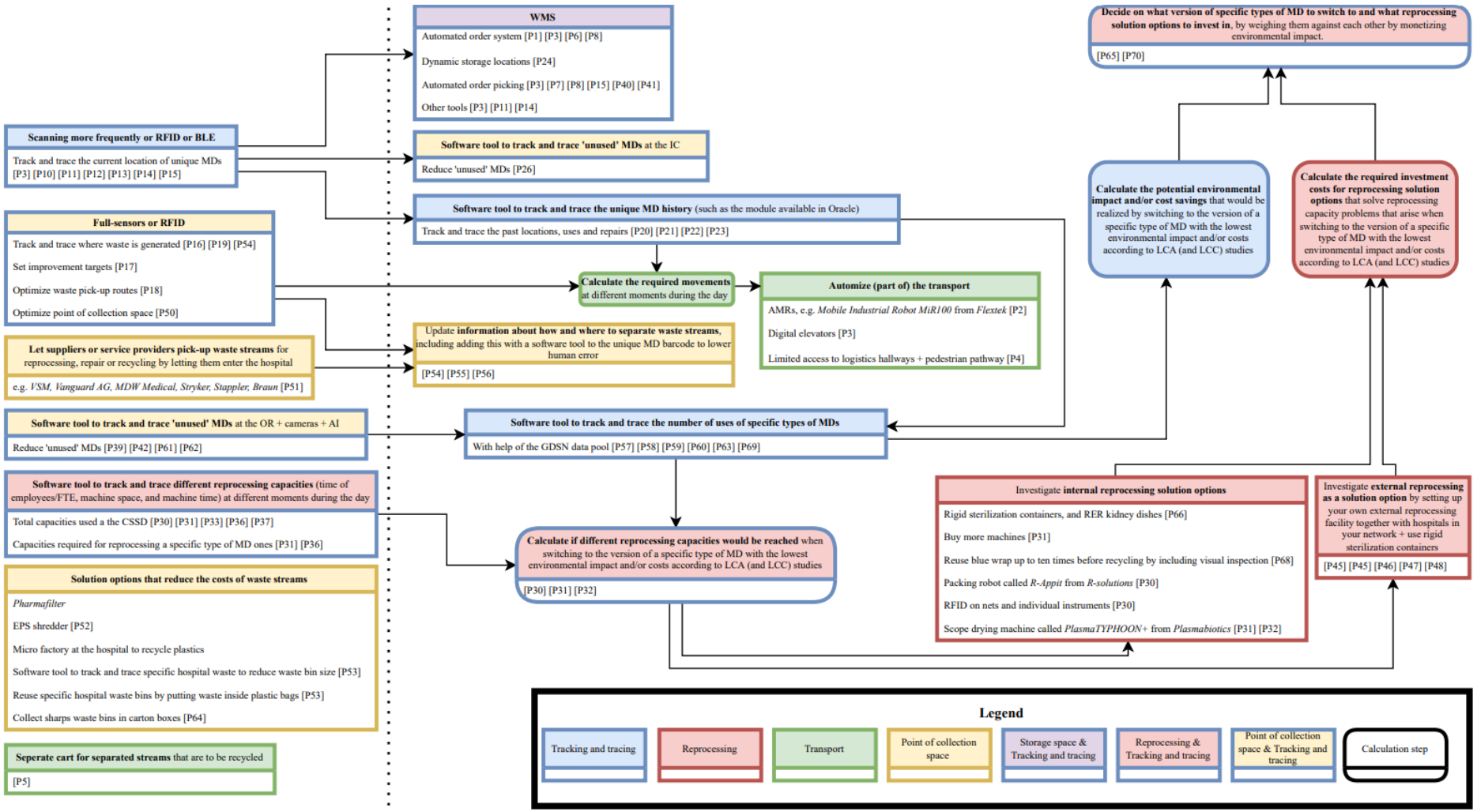
Solution steps are all presented in a rectangle shape. Calculation steps that are required to decide on what solutions to invest in or on what version of MDs to switch to are presented with a rounded shape. Some solution steps contain multiple solution options that a hospital could implement that are bundled in one solution step.

The problems are presented in Appendix B based on the sub-section of the previous chapter they were discussed in. However, the solution steps to solve these problems were structured by color coding them to either one or two material logistics elements from the typology. For example, a solution step that contains solutions to track and trace where waste is generated throughout the hospital has something to do with 'tracking and tracing', but also with 'point of collection space' and is therefore color coded to both. The legend of figure 22 shows what color codes are used to indicate what material logistics elements from the typology the solution steps have something to do with.

The rest of this chapter will go over different solution- and calculation steps, by mentioning the text that is presented in bold in figure 22. Sub-sections of this chapter include solutions of four material logistics elements; tracking and tracing solutions, reprocessing solutions, point of collection space solutions and transport solutions. Because solution steps could have something to do with multiple material logistics elements, they will only be discussed at one of their sub-sections. The first material logistics element that will be discussed is 'tracking and tracing' because this element contains the most important solutions, based on the indication that can be used to estimate how impactful a solution will be, as explained above.

Figure 22

Solutions flowchart



6.2.1. Tracking and tracing solutions

Scanning more frequently, Radio Frequency Identification (RFID) or Bluetooth Low energy (BLE)

The first and most important solution is to improve tracking and tracing the current location of unique MDs, solving [P12]. This was identified in the typology to be important for both SU and RER MDs, because SU MDs from a bad production batch might need to be recalled and when MDs that expire first are picked, their location can be identified with this solution, solving [P11] and [P15] respectively. However, the reason why this is the first and most important solution is because it is a requirement to be implemented first for many other solutions to follow as visible in figure 22.

This solution for [P12] consists of three options a hospital can choose from. The first and most straightforward option is to scan MDs more frequently with every movement, including when a MD is picked from the decentral storage location by a healthcare employee, which currently does not happen because of the 2-bin Kanban system that is used, solving [P13]. From 2025 onwards all MDs will have unique barcode, solving [P10], and with each delivery the supplier also adds digital information about all the MDs it has send (all information that is also on the unique barcode of all MDs). This will make scanning unique MDs possible, and reduce human error, partly solving [P14]. As explained above, this solution will lower the workload of logistics employees [P3], however, it will increase the workload of hospital employees who pick MDs from the decentral storage locations, because now they need to scan it with every movement. Convincing and training them will be the biggest challenge, but eventually it needs to become a habit. At the OR this problem will not exist, because here OR logistics pick MDs from the decentral storage locations, so this might be a good place to start with this solution.

The second and third option are RFID and BLE which are more complex, more expensive options to track and trace the current location of unique MDs, but ones working they will reduce the required logistics employees even more [P3], and healthcare employees also do not need to scan MDs with every movement. An RFID system works with RFID tags and readers that identifies where a tag is. There are two types of RFID tags. Active tags that have quite a long range but are expensive and passive tags with a shorter range but also smaller and cheaper (a few cents per tag). Passive RFID tags are already used on nets at the CSSD in some hospitals, that have gates in the process with readers in it. Moreover, some hospitals use this to track and trace bigger MDs such as beds, wheelchairs, and infusion pumps. One hospital in Belgium placed readers on moving carts (for food, drinks, medicines, and cleaning) which allowed them to have to buy less readers, but still get quite accurate information on where their beds, wheelchairs and infusion pumps are in the hospital. When a hospital wants to implement RFID technology, they would have to add the tags on the MDs themselves for now. Maybe in some point when more hospitals ask for this, the supplier will add the tags on the MDs. An example where this already happens is at Decathlon where all products have a passive RFID tag imbedded in the product placed by the supplier and there is a reader at each check-out that reads all products in a customer's basket (S3). A disadvantage of RFID is that it requires complex wiring, and that RFID tags memory is limited as it records temperatures and humidity (Zapt tech, 2023). Examples of companies that have implemented RFID systems in hospitals are *Mieloo & Alexander* and *Improvement IT* (S3). An BLE system makes use of Bluetooth and the local Wi-Fi network (S3). BLE can be less accurate compared to RFID but is easier to install as it does not require complex wiring and it is able to transmit larger amounts of data (Zapt tech, 2023).

WMS

The second solution, that will solve many problems as visible in figure 22, is to implement a WMS. A WMS is a software that can be integrated with the ERP system to help to optimize all operations around warehouse management, including inventory- and order management, dynamic storage locations, automated order picking, optimizing decentral storage locations and many other useful tools. When the first solution is implemented, and the current location of unique MDs is not only known at the central

warehouse, but also at all decentral storage locations throughout the hospital, a WMS can then optimize all these things at every storage location including those inside the hospital.

When the first solution is implemented, inventory levels of inventory products can now be tracked and traced at the hospital and not only at the central warehouse, solving [P9]. With inventory levels known, the workload of logistics employees will be reduced [P3], because orders will no longer need to be placed manually by manual scan rounds that take a lot of time [P6], but that this can happen automatically with a min-max system just like already happens for at the central warehouse or at the hospital with 'scan relevant' MDs. This automated order system could be done with the current facility management information systems used for inventory – and order management *Slim 4* at Erasmus MC and *People soft* at LUMC, but a WMS is also able to do this and more, making these systems redundant and replacing them (E1). For Erasmus MC, with an automated order system in place, employees should still be able to order products that are not in the *catalogue* through the *Iprocurement portal*, however ordering *catalogue* products through the *Iprocurement portal* should be made impossible, solving [P1].

A second thing a WMS can do besides tracking and tracing inventory levels and automating the order system is to implement dynamic storage locations. As explained in sub-section '5.2.3. Storage space', currently MDs have their dedicated storage place in the racks, while a WMS will use dynamic storage locations. When a WMS knows the dimensions of a MD and the dimensions of the different storage places in the racks, as well as the current location of MDs including which racks are not full yet, it can couple this information to indicate where a MD should be placed in the racks (E1, E6). This will solve the problem that currently many alternatives do not fit in the racks [P24], as the dimensions of an alternative can also be added to the system so that a fitting storage place will be assigned to them.

With dynamic storage locations, order picking should also be automated which is a third thing WMS can help with, because without a system that tells where to pick a MD it would be impossible to find the right MDs in the racks at the central warehouse or closets at decentral storage locations. Automated order picking helps to increase the routing to improve speed and accuracy, again lowering the workload of logistics employees [P3]. Other problems identified at Erasmus MC, that when solved by an automated order picking system of a WMS will lower the workload of logistics employees [P3] are first to start picking MDs on a bigger packaging level at the central warehouse, solving [P7], which can simply be adjusted in the settings and second to place picked MDs from the central warehouse in a smart order in the carts so that unloading them at the decentral storage location is faster, solving [P8]. Lastly, an automated order picking system of a WMS can also indicate MDs that expire first to be picked first, because the expiration date is included in the unique MD information as explained in sub-section '5.2.2. Tracking and tracing', solving [P15] (S3). A module in *Slim 4* is also able to do this, but as explained a WMS will make *Slim 4* redundant. At the sterile storage of the CSSD, the automated order picking system of a WMS will also make sure that individual MDs and nets with the shortest sterile expiration date are picked first, which will partly solve two related problems identified at Erasmus MC that there are 6 full carts each month with nets that need to be reprocessed because their sterile expiration date has past [P40] and that this are often incomplete nets, because they are not picked while they could be used [P41]. These problems could be eliminated completely when a hospital would stop reprocessing these nets immediately when their sterile expiration date has past and only reprocess them, with emergency if necessary, when they are required for an operation.

A fourth thing a WMS can do is to optimize decentral storage locations, for example when two storage locations close to each other store the same MD, it can consolidate them, solving [P27] and [P28]. An upgraded version of *Slim 4* would also be able to do this, but again a WMS will make *Slim 4* redundant. A solution for a specific problem for Erasmus MC that optimizing decentral storage locations by a WMS will provide is ensuring that sterile and unsterile storage are in separate rooms [P25], and a solution for a specific

problem for LUMC that optimizing decentral storage locations by a WMS will provide is ensuring that emergency inventory and carts are close to the OR, but do not at the preparation room [P29].

Lastly, there are many other useful tools a WMS can provide. As mentioned in the first solution, unique barcodes will partly solve the human error problem [P14]. However, scanning will still be somewhat prone to human error and therefore a hospital would still have to count their inventory levels ones in a while. A WMS can help to count inventory levels in pieces at smart moments, reducing the amount of logistics employees required to do that [P3]. For example, when the inventory level of a certain MD is low (almost at the minimum) that is a good moment to count the inventory (S3). Moreover, a WMS can give a trigger when a MD has reached a certain phase of its life cycle, putting specific MDs from a bad production batch on recall, solving [P14], and presenting other sorts of reports and analytics about the performance of warehouse management (E1).

Software tool to track and trace the unique MD history

Like already presented in the typology, an important requirement for RER MDs or RER subparts of MOD MDs is to track and trace the history of those unique RER MDs or RER subparts. As explained in sub-section '5.2.2. Tracking and tracing', the great thing about unique MD barcodes is that it can couple all different kinds of software tools and systems to the barcode to add information. Tracking the history of unique MDs should be done in a software tool, such as the module that is already available in *Oracle*, solving [P20]. Information that should be tracked and traced here about unique MDs include its past locations, use information, reprocessing information, and repair information, so that when a MD breaks earlier or goes missing earlier, the reason for this can be analysed, solving [P22]. Because the current location of a unique MD is being tracked and traced better, like explained in the first and most important solution, this should be coupled to the software tool for unique MD history that then only needs to record all these past locations. For the use phase it is important that it records at what operation by what doctor a MD was used. The most important reprocessing information that needs to be recorded is the number of cycles, and this and more is already recorded in another software tool at the CSSD, that only needs to be coupled to this software tool, solving [P21]. Lastly, repair information such as the number of repairs and spare parts used should also be tracked and traced and coupled to this software tool, solving [P23].

Software tool to track and trace 'unused' MDs

As visible in figure 22, these solutions are split into two solution steps at the IC and at the OR, as solutions at the IC require the first and most important solution of tracking and tracing the location of unique MDs to be implemented, while solutions at the OR do not. However, both solution steps will be discussed here.

Multiple problems were identified that include either throwing away or reprocessing unused MDs. This includes MDs inside an in-patient IC when an infected patient leaves [P26], MDs inside nets [P39], MDs inside procedure trays [P61] and [P62], and for LUMC also MDs inside 'theme boxes' [P42]. The solution for almost all these problems is to implement a software tool to track and trace the unused MDs to see where and how they can be reduced to avoid that they will remain unused in the future and meanwhile using a 'second chance' cart instead of throwing away unused MDs.

All MDs inside an in-patient IC need to be discarded when an infected patient leaves the room, including unused MDs [P26]. Tracking and tracing what MDs remain unused can be done when the first and most important solution of tracking and tracing the location of unique MDs is implemented. Then seeing how it can be reduced means what MDs can be taken out in the storage of a standard in-patient setting.

All MDs inside a net need to be reprocessed when the net has been used, including MDs that remain unused [P39]. Tracking and tracing what MDs remain unused can be done, just like LUMC is already doing as explained in sub-section '5.2.4. Reprocessing', by a combination of conversations with surgeons and OR

assistants and filming the actual use of the MDs in a net in the OR. Then seeing how it can be reduced means optimizing the net content by removing some MDs on a net, and AI might be able to help with this.

All MDs inside a procedure tray need to be discarded when the procedure tray is opened, including unused MDs [P61], and as identified at Erasmus MC, this are often the more generic procedure trays [P62]. Tracking and tracing what MDs remain unused can be done either by indicating this on the procedure tray list, just like Erasmus MC already did, as explained in sub-section '5.3.1. Medical devices from LCA (and LCC) studies at the two case hospitals', or just like LUMC is doing with nets with by a combination of conversations with surgeons and OR assistants and filming the actual use of the MDs inside a procedure tray in the OR. Then seeing how it can be reduced means optimizing the procedure tray content by asking for changes in the content of a procedure tray during a tender, because otherwise the supplier would ask for a raise in price to change something. Again, AI might be able to help with optimizing the content. A second option to reduce unused MDs on a procedure tray is to try and find a good balance between generic and more specific procedure trays. More generic procedure trays have a bigger chance that MDs inside end up being unused [P62], but more specific procedure trays will require more storage capacity.

All SU MDs of a pre-picked 'theme box' are discarded, including unused MDs [P42]. The solution for this problem is simply to just stop using them, and only pick SU MDs when they are needed.

For all unused MDs, a 'second chance' cart, just like Erasmus MC is already doing as explained in sub-section '5.2.6. Point of collection space', is always a better option than throwing something away.

Software tool to track and trace the number of uses of specific types of MDs

Hospitals should use a software tool that creates an overview of all versions of specific types of MDs that are being used, including indicating whether these are SU or RER, to be able to track progress of moving to RER devices, solving [P57]. This software tool should include all different versions of specific types of MDs, including alternatives [P58], MDs on nets [P59], and MDs on procedure trays [P60], so that the number of uses of SU and RER versions of specific types of MD can be tracked and traced. Moreover, this software tool should be able to consider MDs on nets that remain unused but are reprocessed, as this influences their number of uses [P39].

The Global Data Synchronization Network (GDSN) data pool, which is besides unique barcoding another service *GS1* is offering, could be useful to help with creating such an overview. This data pool collects data from suppliers from all over the world about their MDs such as material composition, production location, but also if a MD is RER or not and if there is a maximum number of cycles. The material composition data can be used to identify MDs from LCA studies that only show information about their material composition and to find MDs with the right material composition such as a RER blood pressure cuffs made without a Velcro part, solving [P63], and RER medical textiles with the right characteristics, solving [P69]. This database started, just like with the barcoding, with implants but does now also contains other MDs. Working towards a circular hospital, they want to include packaging material information in this data pool as well (S3).

As visible in figure 22, this is an important solution as it will eventually help to decide on what MDs to make RER and what reprocessing solution options to invest in.

Calculate the potential environmental impact and/or cost savings

When the number of uses of specific types of MDs are being tracked and traced by a software tool as explained in the previous solution step, they can be used in combination with LCA (and LCC) results, presented in tables 4, 6, 8, 11, 13 and 15 of this study to calculate what the environmental impact and/or cost savings would be when switching to the version with the lowest environmental impact and/or costs according to those LCA (and LCC) studies. This was already identified as an additional goal in chapter '4. Problem definition'.

Costs should be corrected for inflation, as the studies were performed in different years, and then converted to the right valuta, as the studies were performed in different locations. This potential environmental impact and/or cost savings can only be used as an indication because the actual environmental impact and/or cost reduction when a hospital switches to another version will never exactly be the same as the calculated environmental impact and/or cost reduction because of the limitation of interpreting LCA (and LCC) study results that will be discussed in sub-section '7.4. Limitations'.

The next solution step, as visible in figure 22, is to decide on what versions of specific types of MDs to switch to and what reprocessing solution options to invest in. This solution step will be explained in the next sub-section '6.2.2. Reprocessing solutions', as that solution requires other reprocessing solution steps to be implemented first.

6.2.2. Reprocessing solutions

Because both case hospitals did already have a CSSD, this was also the default situation from where solutions need to be created. Different kinds of capacity problems could occur when reprocessing at the CSSD and there are multiple solutions to those problems. Capacity at the CSSD might be reached because there are no more employees available to do all the manual labour [P30], not enough machines available to reprocess everything in time [P31] or not enough space to place more machines [P32]. These capacity problems can cause bottlenecks in the process at different moments during the day [P33]. At Erasmus MC the biggest capacity problems are available employees and available time [P34] and at LUMC also employees/FTE and washing machines [P35]. However, both case hospitals, did not measure what MDs were inside one charge of a machine [P36] and how well each charge was loaded [P37] and therefore it is not possible to assess how much of the total capacity (in time and load space) of a specific machine is taken up by a specific RER MD category, and therefore it is also not possible to assess for a specific machine if the capacity of that machine would be reached when the hospital would increase the use of that specific RER MD reprocessed by a reprocessing type for which that specific machine is required [P38]. As visible in **figure 22**, deciding on what reprocessing solutions to invest in consist of several solution steps.

Software tool to track and trace different reprocessing capacities

The first solution step to decide on what reprocessing solutions to invest in, is a software tool to track and trace the current capacity at the CSSD in employees [P30] and hours that different programs of machines are running [P31], including what MDs are inside [P36] and how well each charge was loaded [P37], at different moments during the day [P33]. Moreover, for different specific types of MDs that that have an LCA (and LCC) study, a hospital should track and trace how much time of employees [P30] and time [P31] and space [P36] inside every machine is required for reprocessing that specific type of MD ones.

Calculate if different reprocessing capacities would be reached

As visible in figure 22, the calculation that is required in this solution step can be done when the hospital has implemented two other solution steps. First, the previous solution step of the software tool that tracks and traces the current capacity at the CSSD and the capacity requirements for specific types of MDs should be implemented. Second, the solution 'overview of specific types of MD in a software tool (with the help of GDSN data pool)' that was explained in the previous sub-section '6.2.1. Tracking and tracing solutions' should be implemented.

As explained in chapter '4. Problem definition' the main goal of the LCA (and LCC) study results tables 4, 6, 8, 11, 13 and 15 is to create an overview of all MDs that have an LCA (and LCC) study comparing a SU with a RER version, so that a hospital can use these tables to identify whether it should switch to another version of those specific MDs.

For all specific types of MD that a hospital identified that they should switch to another version, their number of uses should be multiplied with the reprocessing requirements of that specific type of MD. For

MDs that a hospital should switch from a SU to a RER version, the required capacities should be added to the current time of employee [P30] and time [P31] and space [P36] inside every machine that are used at the CSSD at different moments during the day. For MDs that a hospital should switch from a RER to a SU version, which should be considered with extreme care, the required capacities should be subtracted. Most of the time RER versions are better for the environment and for costs and therefore overall, more reprocessing capacity will probably be required when switching versions and the maximum capacity of either employees/FTE [P30] or machines [P31] could be reached.

Internal reprocessing solution options

After calculating if the different reprocessing capacities would be reached when switching to the version of a specific type of MD with the lowest environmental impact and/or costs according to LCA (and LCC) studies, different reprocessing solution options could be investigated. Internal reprocessing solution options are explained in this solution step and external reprocessing as a solution is explained in the next solution step.

A hospital that still has enough and machine time [P31] and available space [P36] could start using rigid sterilization containers instead of blue wrap for as many sets as possible, as this will lower GWP as shown in the LCA studies, but it will require more storage space [P67], both explained in section '4.4. Steam sterilization (T4 & T5)'. LUMC is going to do this with around a quarter of their nets after they have renovated their CSSD as explained in sub-section '5.3.4. Steam sterilization'. Besides using rigid sterilization containers, hospitals with enough available space could also use more RER kidney dishes, solving [P66].

A solution option for a hospital for which the maximum machine capacity at the CSSD would be reached [P31] is to expand the CSSD by buying extra machines, but this is only possible if there is enough space available at the CSSD to do that [P32].

A hospital that still uses blue wrap as sterile packaging could lower the environmental impact by reusing the blue wrap up to ten times, making a visual inspection part of the process, solving [P68] and when blue wrap cannot be used anymore recycle it, just like both case hospitals already do.

Moreover, a hospital that still uses blue wrap hospital could lower employee/FTE requirement [P30] by buying a packing robot called *R-Appit* from *R-solutions*. At a hospital called Jeroen Bosch Ziekenhuis (JBZ), they bought this packing robot to improve ergonomics as packing is physically stressful for employees and this can cause neck and back complaints. Moreover, the packing robot saves 1 full FTE, as it packs around 80% of all their nets. It operates from 8:00 till 20:30 and packs around 200-220 nets per day. A last benefit is that by packing with *R-Appit*, around 10% less blue wrap is used because the *R-Appit* cuts its own size wrapping paper, compared to the pre-cut sizes that are being used when packing manually. Besides the initial investment the extra energy-use should be taken into account as this has increases environmental impact and costs (J2).

Another option for a hospital to lower employee/FTE requirement [P30] is to place passive RFID tags on nets and individual MDs and readers in each machine. By doing this, MDs location in the process are being tracked and traced automatically and CSSD employees do not have to scan the nets and individual MDs at every step in the process. Passive RFID tags are placed on nets and not on individual MDs, because nets need to be checked if they are complete either way at one step in the process as explained in sub-section '5.2.4. Reprocessing', so tagging individual MDs on nets is also not required.

Lastly, a hospital could save available space [P32] and machine time [P31] requirements at the place where they reprocess endoscopes, by replacing endoscope drying closets by an endoscope drying machine called *PlasmaTYPHOON+ from Plasmabiotics*, just like Erasmus MC already did at their CSSD as explained in sub-section '5.2.4. Reprocessing'.

External reprocessing as a solution option

A hospital that despite the above-mentioned solution options have reached employee capacity and/or machine capacity and have no space for buying extra machines, external reprocessing might be required. Moreover, external reprocessing might be required for smaller hospitals that do not have enough demand, space, or personnel to make building their own CSSD a viable option in the first place as also explained in the conceptual background.

As mentioned in the conceptual background, Thalig et al. (2013) studied how hospitals in a network that do not have enough enough demand, space, or personnel could bundle their sterilization in a central service. When hospitals set up their own external reprocessing facility together with other hospitals that are close by, this would avoid the high prices of commercial sterilization, solving [P47], ensure that they remain control over the process, solving [P44], avoid a lot of paperwork that would be necessary with external reprocessing at another hospital, solving [P46], and lower the risk that MDs might get lost in the process, solving [P45]. If there is enough available space, using rigid sterilization containers will ensure sterility with whatever transport mode is chosen, solving [P48], and cannot get holes/tears in it, losing sterility, solving [P49].

The problem that was already visible in the typology, that more inventory is required as the throughput time increases [P43], will remain.

Calculate the required investment costs for reprocessing solution options

After investigating the different reprocessing solution options that would help to solve reprocessing capacity problems that arise when switching to the version of a specific type of MD with the lowest environmental impact and/or cost according to LCA (and LCC) studies, the required investment costs of these reprocessing solution options should be calculated.

Decide on what version of specific types of MDs to switch to and what reprocessing solution options to invest in

When the required investment costs for reprocessing solution options are calculated, they can be weighed against the environmental impact and/or cost savings, mostly realized when switching from SU to RER versions.

As explained in the conceptual background, monetization of impact can be used to be able to compare impact with a monetary value. The potential environmental impact savings should be multiplied with their monetization factor, such as 0.157 EUR/kgCO2e for converting GWP to EUR (Impact Economy Foundation, 2022). The LCA (and LCC) study results tables 4, 6, 8, 11, 13 and 15 only present GWP, but if a hospital would like to get the full picture, other impact categories from those LCA studies should be included and multiplied with their corresponding monetization factor.

When all potential environmental impact savings are monetized they can then, together with the potential cost savings or additional costs, be weighed against the required investment costs for reprocessing solution options. By doing this a hospital can decide on version of specific types of MDs to switch to and what reprocessing solution options to invest in.

For some specific types of MDs, the RER version will lead to additional costs even without the required investment costs for reprocessing solution options, such as the RER suction fluid system [P65] and RER medical textiles [P70]. Because for LUMC, currently an important design criterium is that the investment should pay itself back, these RER MDs might not be the best option for them. However, it is important that also LUMC should not steer only economic costs by monetizing the potential environmental impact savings to see whether they want to implement these RER medical devices nonetheless, because they also singed the healthcare green deal 3.0.

6.2.3. Point of collection space solutions

As explained in the typology, point of collection space consists of waste and MDs to be picked up for external repair, reprocessing or recycling.

Full sensors or RFID

Just like tracking and tracing the current location of unique MDs by scanning more frequently, RFID or BLE is an important solution step for other solution steps to follow, tracking and tracing at what departments or operation different waste streams are generated throughout the hospital with full sensors or RFID is an important point of collection space solution step for other point of collection space solutions to follow as visible in figure 22.

Possible solutions to track and trace at what departments or operations waste is generated, solving [P16] are twofold. First, a hospital could place full sensors on every waste bin throughout the hospital. A full sensor can detect when a waste bin is full and give a signal for that bin to be picked up, solving [P19]. These full sensors are already used on big containers at the waste department to signal when *Prezero* needs to pick-up waste (S2), but not yet on smaller containers throughout the hospital. The maximum capacity of a waste bin can then be multiplied with the number of full signals, to get the amount of waste created for each bin throughout the hospital. A second option is for hospitals that have added RFID technology on MDs and its packaging, to also add RFID readers in every waste bin (S3). This would be even more precise than the full sensors solution, as with full sensors it is only known that a bin is full and not exactly what is inside, while waste separation is prone to human error [P54].

When a hospital knows where their different streams are generated throughout the hospital, improvement targets can be set, solving [P17], pick-up routes can be adjusted accordingly, solving [P18], and the point of collection space available can be optimized, just like the decentral storage location can be optimized by a WMS. For example, hard plastic can be brought to the dedicated waste location at the second, fourth and sixth floor, and all soft plastics to the dedicated waste location at the third, fifth and seventh floor. Making such a distinction will solve the problem that there is not enough space available to separate all streams at every dedicated waste location throughout the hospital, including environmental stations [P50].

Let suppliers or service providers pick up waste streams

A solution option to lower the amount of waste that is generated is to let a supplier or a service providers pick up waste streams for external repair, reprocessing, or recycling. Recycling a hospital waste stream into raw material that can be sold is called 'hospital mining' (S1).

Currently, some waste streams are already picked up by or send to the supplier or a service provider. To solve the problem that there is limited space available at the waste department to place more containers for separate streams [P51], a hospital should prefer that suppliers or service providers come pick up the waste streams because then they could let them enter the hospital to pick it up at another location than the waste department itself, just like what happens with laundry. At Erasmus MC, laundry is picked up at the logistics hallway close to the waste department, but similar locations can be dedicated to pick-ups for other waste streams from MDs to be repaired, reprocessed, or recycled.

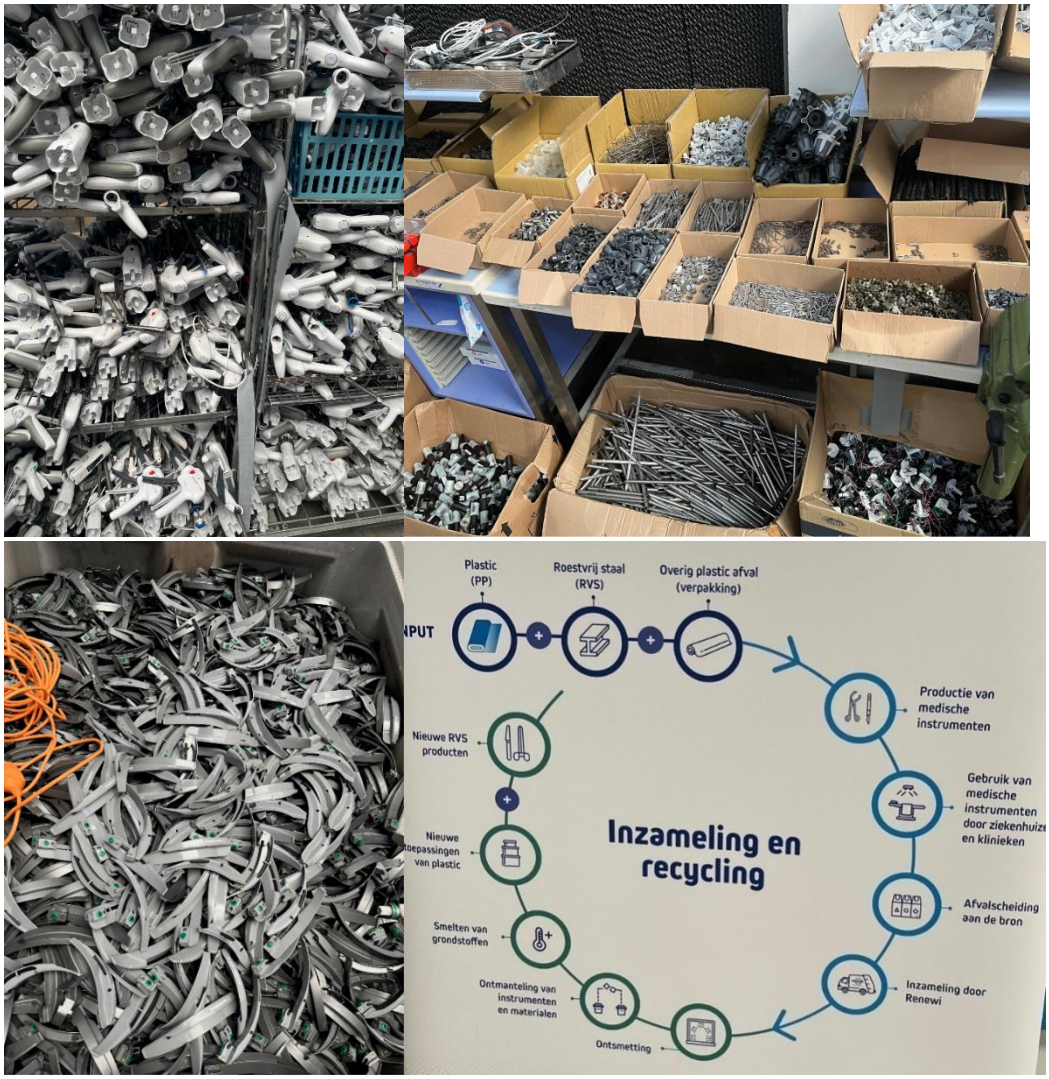
Many suppliers that pick up their own waste stream use an incentive mechanism to be able to sell a new device to the hospital. These suppliers might pick-up their waste steam only for this financial reason without actually repairing, reprocessing or recycling their waste stream. Therefore, a hospital should always ask for proof for what this supplier does with the waste stream, for example by asking for the location of the repair, recycling, or reprocessing facility (S1).

Examples of suppliers that already pick up their own waste stream include *MDW medical* for bigger medical equipment with a plug, *Vanguard AG* that reprocesses their SU catheters (E15), *Stryker* that reprocess their SU *Ligasure, Stäppler,* and *Braun* (L6).

An example of a service provider that picks up waste streams is *VSM*. As explained in sub-section '5.2.5. Repair' LUMC already sends its simple MDs, mostly surgical instruments from SS to *VSM*. As explained in the conceptual background, at *VSM* SS waste is first autoclaved, then either repaired, or if that is not possible recycled into instrument nets that use 30% of the recycled SS (van Straten et al., 2021). Besides SS, PP and other types of plastics are also recycled into new raw material at *VSM* in a process presented in figure 23, bottom right, including laryngoscope blades as presented in figure 23, bottom right. Moreover, *VSM*, currently also collects SU staplers to see if they can disassemble them to sell parts back to the OEM, as presented in figure 22, top left & right. SU staplers are used 150.000 times a year in hospitals in the Netherlands alone (S1).

Figure 23

Top left & right: disassembled staplers at VSM. Bottom left: SU laryngoscopic blades at VSM, bottom right: circular process for SS, PP and other plastics at VSM.



Information about how and where to separate waste streams

After the dedicated waste locations are optimized and separate locations for suppliers and service providers that come pick up a waste stream are assigned, this information about how and where to separate streams correctly should be known to everyone and should be updated at every online and offline location where information about waste segregation is presented, such as the waste guide at Erasmus MC, solving [P56],

to lower human error, solving [P54]. Another location where information about how and where to separate streams correctly could be added is at every unique MD barcode.

Moreover, a hospital could let their employees scan their badge first, then the unique MD barcode of the MD or its packaging they want to dispose of and then the waste bin in which the system tells them to separate it in. This will not only lower human error, because the system tells the employee exactly where and how to separate it correctly, solving [P54], but also when it still goes wrong a hospital can then trace back the employee who did it wrong, solving [P55].

Solution options to reduce the costs of waste streams

There are multiple options to reduce the costs of waste streams that are bundled in this solution step. Some solution options include investing in machines that turn a costly waste stream into a less costly waste stream or even recycling the waste stream so that it earns money, just like the 'hospital mining' process that happens at *VSM* (S1). Other solution options include solutions to lower the costs for required specific hospital waste bins.

A new hospital could install a *Pharmafilter* system that turns specific hospital waste into nonspecific hospital waste as explained in sub-section '5.2.6. Point of collection space'.

A hospital could invest in an EPS shredder, which will turn EPS form a costly stream into a stream that earns money solving the problem identified at LUMC [P52]. According to *Prezero* this investment will pay itself back in 3-4 years (L1).

In the future, a hospital can invest in their own micro factory to shredding and pressing PP and other plastics into raw material, just like already happens at *VSM*. The benefit when a hospital performs this at their own micro factory would be to avoid having to transport it first to *VSM* (S1).

For the problem that specific hospital waste bins are not completely full [P53] there are two possible solutions. First, a hospital could track and trace how full the specific hospital waste bins where at different departments or operations, either by making pictures or weighing. When a specific department or operation always has little specific hospital waste in their bin, a smaller bin could be used at that department or operation. Second, just like already happens at Erasmus MC as explained in sub-section '5.2.6. Point of collection space', a hospital could put their specific hospital waste in a bag, they can empty these inside a bigger bin and reuse the smaller specific hospital waste bin, saving hard plastic from the bins (E15).

For sharps waste, which is a type of specific hospital waste, a hospital could start putting the sharps containers in carton boxes instead of specific hospital waste bins, like already happens at Erasmus MC as explained in sub-section '5.3.3. High level disinfection', solving [P64].

6.2.4. Transport solutions

Calculate the required movements & automize (part of) the transport

Why the calculation step of 'calculate the required movements' is a requirement before a hospital can implement the solution step of 'automize (part of) the transport', will both be explained here.

At the JBZ they tried to implement autonomous guided vehicles (AGVs) in their hospital to transport everything from the logistics hallway, in elevators to the decentral storage locations at hospital care departments. It costed them around 1,2 million and they got 13 AGVs from *Egemin*. These AGVs moved with a radar on predefined lines, went in the elevator to special buffer zones at the decentral storage location. The goal was that this would reduce the workload of logistics employees [P3], but it is unclear with how much. The implementation however did not go as planned and eventually was stopped. Some valuable lessons can be learned from their failure that can be used to make it work in other hospitals (J1).

First, the biggest problem was that the AGVs had to go in the elevator. The AGVs were quite big so the elevator had to be empty for the AGV to enter. The elevators where analogue and not digital so communication between the AGVs and the elevators did not go well. Because the same elevators where also used for patients, beds and visitors the elevator often was not empty and the AGV could not enter. They overcame this problem by adding a weighing sensor at lift cages to see if it was empty and with this the AGV could make a reservation. Then the AGV could reserve a spot, however people could still enter and because emergency care used the same elevators the reservation could also be cancelled. Therefore, hospitals should use digital elevators where making reservations works and there should be elevators dedicated to logistics (J1).

A second problem was that AGVs could not overtake each other or people resulting in a waiting queue. When a buffer area is full at the first elevator an AGV would wait for that buffer area to be free so that it can go there. Meanwhile all AGVs that should go to the second, third, fourth or fifth elevator are also waiting because they cannot overtake the AGV that should go to the first elevator. Moreover, around 1,400 healthcare employees are allowed to enter the logistics hallway and an AGV can also not overtake them. This is a similar problem like identified at the logistics hallway at Erasmus MC, where many employees use the logistics hallway for walking and even for storage. To solve this a hospital should only allow entrance to the logistics hallway to the employees who need it and create a pedestrian pathway for them, solving [P2], and an AMR should be used instead of an AGVs because an AMR is able to pass obstacles in its pathway, which an AGV can't (J1).

A third problem was a miscalculation of the number of movements required on different moments of the day. As mentioned, AGVs could only enter one at a time in the elevator and with them there could only fit one cart with MDs, food or medical textiles or one 600-liter waste bin. While if this transport was performed by a logistics employee there would fit six carts or four waste bins inside one elevator. Therefore, there are already four to six times more movements through the elevators, resulting in one or two elevators from the five being already continuously in use. Moreover, in the calculations they did not include that movements could be time dependent. For example, food carts go at specific times in the morning, around noon and in the evening and waste pickups follow also standard times, mostly during the day because then most waste is generated. This resulted in big waiting times around lunch time and after that the AGVs were falling behind and could not rectify this. When calculating the number of movements required a hospital should include the number of carts and waste bins an AGV can transport in an elevator and include movements at specific moments on the day in the calculation. (J1). As visible in figure 22, the calculation of the required movements can happen after a hospital has implemented a software tool to track and trace the unique MD history and full sensors or RFID that tracks and traces where waste is generated throughout the hospital, because this data can be used to calculate the number of movements required during different moments on the day better. If required a hospital should invest in more digital elevators, solving [P4].

In conclusion, a solution for when there are no more logistics employees that transport MDs and waste are available [P3], is to start using autonomous mobile robots (AMRs) to automize (a part of) the transport. To make this a success a hospital should first calculate the movements required during different moments on the day, then invest in the right number of AMRs and digital elevators, solving [P4], that are dedicated to logistics and lastly only allow entrance to the logistics hallway to the employees who need it and create a pedestrian pathway for them, solving [P2].

One example of a successful implementation of an AMR system is a hospital in Denmark who successfully implemented one AMR called *Mobile Industrial Robot MiR100* from *Flextek* with a lift capacity of 100 kg that drives around ten carts (International Federation of Robotics, 2020).

Separate cart for separated streams

Besides investing in AMRs, a hospital should make sure they have a separate cart for recycled streams, solving a problem identified at Erasmus MC [P5].

7. Conclusion & discussion

This chapter consists of a conclusion by answering the research question, the theoretical contribution, the practical implications, limitations, and suggestions for future research. This study consists of four main deliverables that will be used to structure the first three sections of this chapter. The first deliverable is the LCA (and LCC) study result tables, presented in tables 4, 6, 8, 11, 13 and 15 of chapter '4. Problem definition'. The second deliverable is a typology that shows how the requirements of different material logistics infrastructure elements would change when switching from a SU to a RER version per type of MD, presented in table 16, sub-section '4.9. Typology'. The third deliverable is an overview of identified problems, identified at two case hospitals, presented in Appendix B. The fourth deliverable are designed solutions to most of these problems visualized in a solution flowchart, presented in figure 22 of sub-section '6.2. Solutions'.

7.1. Conclusion

This conclusion section provides an answer to the research question:

***RQ**: What are the implications on the material logistics infrastructure in a circular hospital?*

The four main deliverables of this study are used to structure this section as they all present some implications on the material logistics infrastructure in a circular hospital.

The LCA (and LCC) study results tables compare the environmental impact and/or costs of SU with RER versions of specific types of MDs, structured in tables per reprocessing type. These tables show that most of the time RER MDs have lower environmental impact and/or costs compared to SU MDs. This finding supports the goal of the green deal sustainable healthcare 3.0, that a hospital should increase the use of RER MDs. Besides lowering the environmental impact and/or costs, increasing the use of RER MDs also lowers the hospitals dependency on its suppliers and the availability of MDs in the market, that is currently having a lot of disruptions. The LCA (and LCC) study results tables show these implications in more detail.

The typology identifies eleven different types of MDs that have different requirements on six material logistics infrastructure elements when switching from a SU to a RER version. These material logistics infrastructure elements include transport, tracking and tracing, storage space, reprocessing, repair, and point of collection space. The typology shows these implications in more detail.

The overview of identified problems shows 70 different problems identified at two case hospitals by analyzing how the different types of MDs and the different elements of the material logistics infrastructure from the typology look like at two case hospitals. The overview of identified problems shows these implications in more detail.

The solution flowchart shows how and in what order almost all 70 problems can be solved by implementing the designed solutions. The designed solutions include solutions that are already implemented at either one of the case hospitals or solutions that are not yet implemented. Tracking and tracing is identified as the most important material logistics infrastructure element as the most important solutions have something to do with tracking and tracing. A hospital should increase tracking and tracing of everything that happens with a unique MD, including identifying where it would eventually end up as waste inside the hospital. Moreover, for specific types of MDs (especially those with LCA (and LCC) studies) a hospital should track and trace how much they are used and how much capacity at the CSSD they take up. Tracking and tracing solutions will eventually enable automation solutions for other material logistics infrastructure elements. Transport can be automated by investing in AMRs and digital elevators. Storage space can be optimized with a WMS that will also enable an automated order system, an automated order picking system, and many other useful tools. For reprocessing, different capacity problems at the CSSD might arise when switching to the versions of MDs with the lowest environmental impact and/or cost according to LCA (and LCC)

studies, which will mostly be from SU to RER. Automation solutions to these reprocessing capacity problems include a RFID technology, an endoscope drying machine or a packing robot. When weighing the required investment costs for these or other reprocessing solutions that can be invested in to solve reprocessing capacity problems with the potential environmental impact and/or cost by monetizing the impact a hospital can decide on what MDs to make RER and what reprocessing solutions to invest in. For point of collection space, automation solutions include optimizing the dedicated waste locations and adding information on correct disposal to the unique MD barcode. Besides these a hospital could recycle and sell some of their waste streams themselves, including plastics and EPS or let suppliers or service providers pick up some waste streams for reprocessing, repair, or recycling. The solution flowchart shows these and other implications in more detail.

When Dutch academic hospital managers implement the suggested solutions a material logistics infrastructure is created that is required in a circular hospital. These material logistics solutions will help hospitals to move away from SU MDs towards RER MDs and increase circularity in other ways to improve environmental and health impact and save on costs, reaching the research objective.

7.2. Theoretical contribution

This theoretical contribution section explains how this study contributes to theory and fills in the research gap of how the material logistics infrastructure in a circular hospital looks like, and what solutions are required to support the shift from SU towards RER MDs and increase circularity. Because of the novelty of this study, the theoretical contribution is also structured around the four main deliverables of this study. However, the most important theoretical contribution lies within the main deliverable of the typology, that builds forth on and consolidates existing terminology and theory from the emerging research field of 'healthcare sustainability science', by creating a novel structured framework that can not only be used in practice but also for future research.

Previous research has defined value retention strategies and circular business models for different types of MDs based on their product value and criticality. However, these studies lacked comprehensive inclusion of all MDs that have LCA (and LCC) study comparing a SU with a RER version and did not study their material logistics infrastructure requirements. This study addresses these limitations by highlighting the importance of reprocessing as a crucial value retention strategy when transitioning from SU to RER MDs. Where previous research used the Spaulding scale to measure the criticality of a MD, indicating how these MDs should be reprocessed, this study identified seven types of reprocessing offering more precision. For example, all MDs that are used inside the protected area at the OR are required to be sterilized, including MDs that do not enter tissue or the vascular system, which are the only MDs that require sterilization according to the Spaulding scale. Moreover, because 'healthcare sustainability science' is an emerging field of research, different LCA studies all use somewhat different terminology for similar reprocessing types. For example, researchers mentioning low level disinfection or light disinfection are referring to the same reprocessing type. Another example is remanufacturing MDs, which is the same as reprocessing SU MDs, only for a bit more complex MD. Consolidating these different terminologies for similar reprocessing types is a theoretical contribution to standardizing reprocessing terminologies in the field.

The LCA (and LCC) study result tables provide comprehensive and structured evidence for the theory that that most RER MDs have lower environmental impact and/or costs compared to SU MDs, as discussed in the subsections '2.3.1. Environmental benefits' and '2.3.2. Economic benefits', of the conceptual background. The different LCA (and LCC) study results on their own are not novel but providing a comprehensive overview of all study results together in seven tables, one for each reprocessing type, has not been done before.

The typology provides a novel structured framework for understanding how the requirements of six material logistic infrastructure elements change when switching from a SU to a RER version of eleven types

of MDs. The eleven types of MDs, the six material logistics elements and the requirements presented inside the typology are all new theory. The eleven types of MDs are created by indicating for each of the seven reprocessing types whether reprocessing can happen internally, externally or both. Besides the value retention strategy of reprocessing, other value retention strategies or technical cycles mentioned in previous research were still incorporated in this typology. Examples are repair and maintenance, that is incorporated in the material logistics element 'Repair', and recycling, that is incorporated in the material logistics element 'Point of collection space'. This study has also shown how the typology can be used as a structured framework to find potential problems and solutions to those problems, that could be repeated when researching material logistics infrastructure problems at other hospitals.

The overview of identified problems that consists of 70 problems identified at either one or both case hospitals provide examples of potential problems a hospital could encounter when moving towards more RER MDs and increasing circularity. Identifying these problems also is a theoretical contribution, as previous research mentioned the overall problem of that the material logistic infrastructure is not designed for handling circular MDs but did present little underlying problems for this. Some of the underlying problems that previous research did identify, were also found in this study confirming their theory. An example of such a problem is that hospitals have difficulties with waste segregation, because of limited space.

The designed solutions to these problems, as presented in the solution flowchart also present a theoretical contribution, because most of them are novel solutions to previously unidentified problems. Just like with the problems, some solutions are in line with previous research, confirming their theory. Examples are the importance for hospitals to obtain accurate data about their resource and waste management and that metrics following this data should encourage management decisions towards a better (circular) system. This is confirmed by this study as it identifies solutions related to tracking and tracing to be the most important and respectively using environmental impact monetization to encourage the decision making required for transition from SU towards RER MDs and increase circularity.

In conclusion this study contributes significantly to the 'healthcare sustainability science' research field by consolidating previous terminology and theory into a typology that presents a comprehensive and structured overview that has been used to identify problems and solutions for moving from SU towards RER MDs and increasing circularity in other ways. Future research can build upon these theoretical insights by refining the typology including its theory and terminology, or by using the typology as a structured framework to identify more problems and solutions for moving from SU towards RER MDs and increasing circularity in other ways, which will be further discussed section '7.5. Suggestions for future research'.

7.3. Practical implications

Because the research objective of this study is to design practical solutions that can be implemented by Dutch academic hospitals and the research question states what the implications on the material logistics infrastructure in a circular hospital are, the practical implications for hospitals are most important. Just like in the conclusion and theoretical contribution, the practical implications for a hospital will be explained based on the four main deliverables of this study. Besides the practical implications from these different deliverables for hospitals, some practical implications for external stakeholder groups are presented.

For hospitals

Overall, this study helps hospitals to create a material logistics infrastructure that enables them to shift away from SU MDs towards RER MDs and increase circularity in other ways to improve environmental and health impact and save on costs.

Hospitals can use the LCA (and LCC) study results tables to identify for specific types of MDs what version has the lowest environmental impact and/or costs. The solutions flowchart shows what hospitals can then

do with these results to eventually decide on what medical devices to make RER and increase circularity. Once the hospital has implemented the solution step that tracks and traces the number of uses of specific types of MDs, the potential environmental impact and/or costs savings can be calculated by multiplying the number of uses with the environmental impact and/or costs savings for one use. The environmental impact should then be monetized to compare the potential environmental impact and/or costs savings with the required investment costs for reprocessing solution options that solve reprocessing capacity problems that arise when switching to the version of specific types of MDs with the lowest environmental impact and/or costs. By doing this a hospital can decide on what specific types of MDs from the LCA (and LCC) study results tables they should make RER and what reprocessing solution options to invest in to become more circular.

Hospitals can use the typology to identify what the implications would be on the requirements of six material logistics infrastructure elements when switching from a SU to a RER version. These implications can be identified for specific types of MDs from the LCA (and LCC) study results, because these specific types of MDs are assigned to a reprocessing type from the typology. Moreover, for MDs that where not discussed in the LCA (and LCC) study results tables of this study, this is also possible after infection prevention has identified how the RER version should be reprocessed, so that these new MDs can also be assigned to a reprocessing type from the typology. For types of MDs where either internal or external reprocessing is possible, the typology can help a hospital to choose between these options because their implications on different material logistics infrastructure requirements can be compared.

Hospitals can use the overview of identified problems to identify problems that are already present, and potential problems that might arise at their hospital as well.

Hospitals can use the solution flowchart to identify what solutions to start with to increase circularity, either by finding a solution to a specific problem from the overview of identified problems or by finding the most impactful solutions, not for a specific problem. When hospitals are looking for a solution to a specific problem and that solution is presented to the right of the dotted line, the solution flowchart will show what solution- and/or calculation steps should be implemented or done first to give a guidance on what solutions to start with. When hospitals are not looking for a specific problem and want to start with the most impactful solution to increase circularity, the hospitals should look at the number of problems a solution step will solve directly or indirectly. By using this indication, the most impactful solution a hospital should start with is scanning more frequently, RFID or BLE to track and trace the current location of unique MDs.

For external stakeholders

Suppliers or service providers can use the findings to increase their own repair, reprocessing and recycling options for MDs, as hospitals will ask for these options more often. Also, business that support and advice hospitals on their in-house repair, reprocessing and recycling can use the solution flowchart to adapt their support and advice accordingly.

Healthcare insurances and banks can use the designed solutions to allocate their innovation budgets to hospitals that want to implement these solutions, because many of the solutions from the solution flowchart will require an investment to be made in the first place.

Governments and policy makers can use the findings to adapt current laws and regulations so that the Dutch healthcare system is allowed to use reusable sharp containers, just like in the UK and the US, and that Dutch hospitals are allowed to press, and shred their own PP and other plastics into raw material in their own micro factories, just like already happens at *VSM*.

7.4. Limitations

This section presents five limitations that affected the findings of this study. These limitations include minimal prior knowledge of and network in the healthcare sector of the researcher, the selected scope of

the two case hospitals, existing LCA (and LCC) studies, interpreting LCA (and LCC) study results, and a limited time span.

First, the results were limited by knowledge of and network in the healthcare sector that were minimal prior to this study. This limitation was partly addressed by joining the LDE thesis lab and going to the Nevi healthcare conference, to broaden the network of healthcare employees that could present more rich insights and connections to business offering solutions and experts by experience of some of the solutions. Nonetheless, with more prior knowledge of and a bigger network in the healthcare sector prior to this study, even more problems and solutions might have been identified to enrichen the results even further.

Second, the results were limited to the number of case hospitals that were used to identify problems and already some solutions in the analysis and diagnosis phase. The reason to choose two Dutch academic hospitals was made because of their size and willingness to cooperate. However, if more than two hospitals would be used as case hospitals more problems and maybe more solutions could have been identified. Moreover, if non-Dutch hospitals or non-academic hospitals were used in the analysis and diagnosis phase of this study, other problems and solutions might have been identified. Also, if smaller hospitals without a CSSD were part of the case hospitals, then maybe more external reprocessing problems and solutions would have been present, where now internal reprocessing problems and solutions are more present. Because of this scope choice, the solutions are designed for Dutch academic hospitals, however this does not mean that the designed solutions would not work in non-academic or non-Dutch hospitals as the typology was created based on all LCA (and LCC) studies from all over the world, from all kinds of hospitals, and therefore non-academic or non-Dutch hospitals might find some problems form the overview of identified problems and solutions in the solutions flowchart to be relevant in their hospital as well. Nonetheless, a hospital manager looking for solutions should always assess if the created solutions fit within their local context including its laws and regulations, as an important design criterion for the designed solutions was that they should fit within Dutch laws and regulations and thus the solutions are designed accordingly.

Third, because the types of MDs from the typology were based on existing LCA (and LCC) studies, the types of MDs from the typology were limited by MDs that already have such a LCA (and LCC) study comparing a SU and a RER version. As mentioned in section '3.3. Scope', there are 500,000 different MDs on the EU market, so when there would have been more LCA (and LCC) studies it could be that this study would have identified more types of MDs, extending the typology. Moreover, because the MDs from these LCA (and LCC) studies were later analysed at the two case hospitals to identify problems and already some solutions to those problems, it could be that more problems and solutions would have been identified when there were more LCA (and LCC) studies available.

Fourth, there are some limitations related to interpretating LCA (and LCC) study results. As mentioned in the designed solutions, the LCA (and LCC) study results should be used to calculate the potential environmental impact and/or cost reduction of switching to another version of a specific type of MD. However as mentioned in this solution, this potential environmental impact and/or cost reduction can only be used as an indication because the actual environmental impact and/or cost reduction when a hospital switches to another version will never exactly be the same as the calculated environmental impact and/or cost reduction because of the limitations related to interpretating LCA (and LCC) study results. First, there can be differences in the conditions under which reprocessing is performed across the different LCA (and LCC) studies, including differences in detergent and PPE used, the energy grid that was used, what machines were used, how old these machines are and how well the machines were loaded. Second, the 'system boundary' that explains the scope of different LCA (and LCC) studies, could differ across studies. This includes what phases of a MD life cycle are studied and the number of cycles they chose as their FU both across their different scenario's. Third, there can be differences in the environmental impact categories that are presented in the results. Some studies only include GWP, where others included many other

environmental impact categories as well, making their results more accurate when comparing the monetized environmental impact differences between SU and RER devices. Fourth, some LCA (and LCC) studies studied a specific type of MD and therefore the interdependency of the authors might be questioned. These limitations of interpreting LCA (and LCC) results are there because it is a still evolving field where researchers still have the freedom to have these differences. This study has addressed this limitation partly by performing a comprehensive and structured analyses of all LCA (and LCC) study results, so that conclusions can be made for different types of MDs when more studies show the same results, despite these limitations.

A fifth and last limitation, was the time span of this study. Because of this limitation not all medical devices are from LCA (and LCC) are discussed at the two case holders and the last phase of the problem-solving cycle, 'evaluation', was not performed. This study stopped after designing the solutions, as there was no time to implement the solutions at the two case hospitals to evaluate their long-term effectiveness. Evaluation could have been performed in other ways, for example by a 'walkthrough' with all respondents to gain their feedback. However, because of the limited time span of this study, by the time this walkthrough could take place it was holiday, and no respondents could attend, resulting in cancellation of this 'walkthrough' session.

Despite the limitations, this study has presented implications of the material logistics infrastructure in a circular hospital, including the LCA (and LCC) study result tables, the typology, the overview of identified problems and potential solutions that contribute significantly to theory and practice.

7.5. Suggestions for future research

This last section consists of five suggestions for future research, including evaluation and investment costs the designed solutions, more LCA (and LCC) studies, LCA (and LCC) study of a hospitals own reprocessing processes, how to use procurement to reach the goals of the green deal sustainable healthcare 3.0, and the social impacts of a circular hospital.

First, because this research stopped after designing the solutions, and the last phase of the problem-solving cycle, 'evaluation', was not performed, future research should continue by evaluating the long-term effectiveness of the designed solutions by implementing them. Moreover, as also identified as a calculation step in the solutions flowchart, the required investment of suggested reprocessing solutions should be calculated. Future research can help by researching investment costs and return on investment of these reprocessing solutions, and solutions from other material logistics elements. The created investment plan will not only help the hospitals, but also the healthcare insurances and banks that should allocate their innovation budgets accordingly.

Second, future research should include more LCA (and LCC) studies as those studies will contribute to the evidence-based shift from hospitals from SU MDs towards RER MDs. When more LCA (and LCC) studies are performed they can be assigned to one of the types of MDs from the typology or maybe a new type of MD should be added to the typology.

Third, each hospital should perform an LCA (and LCC) of their own reprocessing processes. As explained in the limitation, there can be differences in the conditions under which reprocessing is performed across the different LCA (and LCC) studies, including differences in detergent and PPE used, the energy grid that was used, what machines were used, how old these machines are and how well the machines were loaded. When a hospital knows these aspects about their own reprocessing processes, this will help them to compare LCA (and LCC) study results with their own reprocessing processes better.

Fourth, an important research subject for future research is how to include the goals of the green deal sustainable healthcare 3.0 in procurement. This study did not focus on procurement as this is not a part of

the material logistics infrastructure. However, procurement should be an important part of the solution to increase circularity in a hospital, as they will have to make the changes in their tenders.

Fifth, future research should investigate the social impacts of a circular hospitals as these have been underexposed in this study. Many of the suggested solutions lower employee requirements, thus lowering the job availability of these jobs. However, as also mentioned in the conceptual background, this might be countered in job creation in reprocessing, automation or creation of robotics.

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Appendices

Appendix A: Overview of consultations with respondents

Organisation	Function	Date	Code
LUMC	Teamlead Warehouse, goods reception, transport and waste manager	14/3/2023	L1
Erasmus MC	Logistics manager	17/3/2023 & 13/6/2023	E1
Erasmus MC	Project lead green team IC	20/3/2023 & 24/5/2023	E2
LUMC	OR & CSSD manager	22/3/2023 & 6/6/2023	L2
Erasmus MC	CSSD Employee	3/4/2023	E3
Erasmus MC	Teamlead CSSD	3/4/2023	E4
Erasmus MC	Logistics coordinator	3/4/2023	E5
Van Straten Medical	Managing Director	5/4/2023 & 12/6/2023	S1
Erasmus MC	Distribution centre (Barendrecht) logistics coordinator	7/4/2023	E6
Erasmus MC	Waste manager	12/4/2023	E7
Erasmus MC	Procurement manager (sustainability)	12/4/2023	E8
Erasmus MC	Inventory manager	12/4/2023	E9
Erasmus MC	Experts sterile medical devices (two employees)	13/4/2023	E10
Erasmus MC	OR Logistics manager	13/4/2023	E11
Erasmus MC	Purchaser	13/4/2023	E12
LUMC	Logistics manager	13/4/2023	L3
LUMC	Quality advisor OR & CSSD	20/4/2023	L4
LUMC	Instrument management	20/4/2023	L5
Erasmus MC	Project lead OR, IC & Emergency care / Chair green team OR	24/4/2023	E13
Erasmus MC	Medical technology team manager	26/4/2023	E14
Erasmus MC	Staff Advisor / Green team OR	1/5/2023	E15
LUMC	Instrument management	3/5/2023	L6
Erasmus MC	Operation assistant / Green team OR	10/5/2023	E16
LUMC	Purchaser	31/5/2023	L7
Erasmus MC	Infection prevention / Green team OR	1/6/2023	E17
Prezero	Account manager	2/6/2023	S2

GS1	Key account manager Healthcare	6/6/2023	S3
Jeroen Bosch Ziekenhuis	Logistics Manager	6/6/2023	S4
Jeroen Bosch Ziekenhuis	Teamlead CSSD	6/6/2023	S5
Nedlin	Account manager healthcare	15/6/2023	S6

Appendix B: Overview of identified problems

Transport problems

[P1] At Erasmus MC, Inventory and non-inventory *catalogue* products can also be ordered through the *Iprocurement portal*, and then these products will arrive directly at Erasmus MC instead of via Barendrecht which is their normal route.

[P2] At Erasmus MC, the logistics hallways are also being used by other healthcare employees for storing products and as a walking pathway from one building to the other, taking space away from logistics transport and causing some safety issues.

[P3] Logistics employees available might reach its full capacity, meaning there are no more employees available.

[P4] Elevators might reach their full capacity, meaning they are always full and cannot transport more.

[P5] At Erasmus MC, there is no separate cart for separated streams that are to be recycled.

Tracking and tracing problems

[P6]: Scan rounds are manual labour which takes quite some time.

[P7]: At Erasmus MC, MDs are picked on a product level at the central warehouse, meaning packaging needs to be opened which takes time.

[P8]: At Erasmus MC, MDs are placed in random order in the carts, so unpacking them at the decentral storage location takes some time.

[P9]: Inventory levels of inventory products at the decentral storage locations are not tracked and traced.

[P10]: Not all MDs have the right unique barcode on them.

[P11]: Identifying the location of MDs that need to be put on recall because of a bad production batch is difficult.

[P12]: The current system both case hospitals use for tracking and tracing the current location of unique MDs does not always work, except for 'scan relevant' MDs.

[P13]: Scanning happens minimally, only with certain movements.

[P14]: Scanning is prone to human error.

[P15]: At Erasmus MC, SU MDs are not picked based on their expiration date, while there is a module available for this in *Slim 4*.

[P16] Waste generated from separate streams is not tracked and traced at specific departments or operations.

[P17] No improvement targets at specific department or operations level are set.

[P18] Waste pick-up routes are sub-optimal.

[P19] Waste bins are often not completely full when they are picked up.

[P20]: A software tool for tracking and tracing information about the history of unique MDs, such as the module available in *Oracle* is not yet used.

[P21]: While the number of cycles of a unique MD is tracked and traced with a software tool at the CSSD, it is not yet coupled with a software tool for tracking and tracing information about the history of unique MDs, such as the module already available in *Oracle*.

[P22]: The reason for earlier breakage of a MD, or a missing MD, cannot be analysed because a software tool for tracking and tracing information about the history of unique MDs, including for example by what doctor, at what operation or by what repairer it has been used or repaired, such as the module already available in *Oracle* is not yet used.

[P23]: Because a software tool for tracking and tracing information about the history of unique MDs, such as the module already available in *Oracle* is not yet used, the number of repairs is also not yet being tracked and then coupled to this software tool.

Storage space problems

[P24]: At Erasmus MC, many alternatives do not fit in the racks.

[P25]: At Erasmus MC, in some decentral storage rooms, sterile and non-sterile are not in separate rooms but in closets next to each other.

[P26]: All MDs stored at an in-patient IC will be discarded after an infected patient leaves the room, regardless of whether it has been used or not.

[P27]: It is possible that there are different storage locations close to each other that store the same MDs.

[P28]: At Erasmus MC, a software tool for optimizing decentral storage locations, such as the module in an upgraded version of *Slim 4* is not yet used.

[P29]: At LUMC, there are emergency carts and emergency inventory closets inside the preparation room, which is not allowed.

Reprocessing problems

[P30] Capacity at the CSSD might be reached because there are not enough employees available, to do all the manual labour such as manual cleaning, scanning, preparing nets and placing everything inside the machines.

[P31] Capacity at the CSSD might be reached because there are not enough machines available (for example when they have breakdowns) to reprocess everything in the time it needs to be ready.

[P32] Capacity at the CSSD might be reached because the maximum space at the CSSD is taken up so that there is no more available space to place more machine.

[P33]: Capacity problems that can cause bottlenecks in the process occur on different moments during the day, because the stream is not constant with not so busy mornings and a peak moment in the beginning of the evening.

[P34]: At Erasmus MC, getting enough reprocessing employees is a capacity problem, combined with time available.

[P35]: At LUMC, getting enough reprocessing employees is a capacity problem, combined with the availability of washing machines.

[P36]: Hospitals do not track and trace information about what MDs were in one charge of a machine.

[P37]: Hospitals do not track and trace information about how well each charge was loaded.

[P38]: It is not possible to assess how much of the total capacity (in time and load space) of a specific machine is taken up by a specific RER MD category, and therefore it is also not possible to assess for a specific machine if the capacity of that machine would be reached when the hospital would increase the use of a specific RER MD category for which that specific machine is required.

[P39] There might be MDs on a net that remain unused, but the whole net including these unused MDs needs to be reprocessed again.

[P40]: At Erasmus MC these are 6 full carts each month of unused MDs of which the sterility has expired.

[P41] At Erasmus MC, incomplete nets in sterile storage are often not picked and will almost always end up expiring.

[P42]: At LUMC, the use of 'theme boxes' results in throwing away many unused SU MDs.

[P43]: When reprocessing externally, more inventory is required as the throughput time increases.

[P44]: When reprocessing externally, the hospital does not have control over the process.

[P45]: When reprocessing externally, MDs might get lost in the process.

[P46]: When reprocessing externally at another hospital, there is a lot of paperwork that needs to be checked.

[P47]: When sterilizing externally at a commercial sterilizer, this comes at a high price.

[P48]: When sterilizing externally, transport method needs to ensure sterility.

[P49]: When sterilizing externally and blue wrap is used is that it might get holes/tears in it during transport and therefore loses its sterility.

Point of collection space problems

[P50]: There is not enough space available to separate all streams at every dedicated waste location throughout the hospital, including environmental stations.

[P51]: There is limited space available at the waste department to place more containers for separate streams.

[P52]: At LUMC, they still pay quite some money for their EPS stream.

[P53]: Specific hospital waste is often collected when bins are not completely full.

[P54]: Waste separation is prone to human error.

[P55]: When a MD is discarded in the wrong bin, it is unclear who did this wrong and was informed incorrectly, as this data is not being kept.

[P56]: At Erasmus MC, the waste guide that hangs at the environmental station in the OR is outdated and therefore does not show streams that are to be collected separately.

MDs from LCA (and LCC) studies at the two case hospitals problems

[P57]: No distinction is made from all orders what products are MDs or non-medical products, and therefore also not what products are RER or SU MDs.

[P58]: Because there are many versions of a specific MD being bought, including alternatives, counting the number of uses of a specific MD (to use this as calculation for environmental and cost savings estimate) is difficult.

[P59]: Because some MDs are part of a net, counting the number of uses of a specific MD (to use this as calculation for environmental and cost savings estimate) is difficult.

[P60]: Because some MDs are part of a procedure tray, counting the number of uses of a specific MD (to use this as calculation for environmental and cost savings estimate) is difficult.

[P61]: Ones opened, everything inside a procedure tray needs to be discarded, even if it remains unused.

[P62]: At Erasmus MC, many generic procedure trays are used and when those procedure trays are used, more MDs end up being unused compared to when more specific procedure trays are used.

Light disinfection problems

[P63]: Blood pressure cuffs have a Velcro part that cannot be cleaned.

High level disinfection problems

[P64]: RER sharps containers do not exist yet in the Netherlands, because of current laws and regulations.

[P65]: RER suction fluid system is more expensive than buying SU suction receptacles.

Steam sterilization problems

[P66]: RER kidney dishes will take a lot more space and thus less nets can be washed at the same time.

[P67]: Switching to rigid sterilization containers requires a lot more space than using blue wrap.

[P68]: Reusing blue wrap is feasible up to ten times, but then it should be inspected for holes every time.

Reprocessing medical textiles problems

[P69]: RER medical textiles might not have the right permeability, user comfort, strength, shape and size, thickness, and when used in a sterile area such as the OR, it should not release too many particles.

[P70]: RER medical textiles are probably more expensive than SU medical textiles.