SENSING A SUSTAINABLE FUTURE

A Holistic Approach to Pulse Oximetery Product and System Design for Sustainable Medical Device Adoption

FIENE KUIPER
GRADUATION REPORT

“A ruined planet cannot sustain human lives in good health. A healthy planet and healthy people are two sides of the same coin.”

– Dr. Margaret Chan,
Executive Director of the World Health Organization

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Integrated Product Design
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IN COLLABORATION WITH
ESCH-R, creating circular hospitals together
Erasmus Medical Center
Philips Medical

COMMTTEE
Prof. Dr. Ir. Jan-Carel Diehl
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PREFACE

This project stems from a desire to make a meaningful impact on the world, driven by a strong concern for the health of our planet. In my personal life, I've always looked for ways to live sustainably, whether by purchasing and repairing secondhand items like furniture and clothes, adhering to a vegetarian diet, or finding other ways to reduce my environmental footprint. However, I often felt frustrated that my efforts seemed limited to my personal sphere. This led me to channel the knowledge and skills I gained throughout my studies toward making a more significant positive impact on the climate through this project.

Alongside my passion for sustainability, I have always been fascinated by the intricacies of the human body and the medical industry. This project sits at the intersection of these two areas, focusing on redesigning the pulse oximetry system and product to reduce its environmental footprint, both now and in the future.

Through this work, I aim to inspire others by demonstrating the diverse approaches that can be taken toward achieving circularity in healthcare. I also hope to emphasize that collaboration is essential to driving the transition to a more sustainable, circular future.

While the primary focus of this project is on environmental health, it's important to note that economic vitality and social equity remain just as critical. All three pillars of sustainability are interlinked, and none should be overlooked in the pursuit of a better world. By recognizing and addressing all aspects, we can build a healthy and inclusive future for everyone.

Enjoy the read,

Fiene Kuiper

ACKNOWLEDGEMENTS

I would like to thank a number of people, without whom this project would not have been the same.

First, I want to thank all the enthusiastic employees at Erasmus Medical Center. Thank you for generously sharing your insights during interviews and co-creation sessions, for providing data, giving me tours through your departments, or allowing me to shadow your work. Even though the EMC is flooded with research projects, everyone I met welcomed me with open minds and doors. Your willingness to help made all the difference, without it, my insights would not have been nearly as thorough or grounded in reality.

Secondly, I want to thank my graduation committee, JC, Sonja and Ayşegül. Thank you for your valuable feedback throughout the project and your ongoing encouragement. JC, thank you for your contagious enthusiasm and for opening up many opportunities to participate in various ESCH-R activities. Sonja, thank you for your detailed and thoughtful feedback on my reporting, and for the comforting conversations during the moments when the project felt like a bumpy road. And thanks Aysegul for the input and help organizing the final co-creation session.

A big thank you as well to the Philips team, especially Margot Honkoop for your friendliness and your willingness to help me navigate the organization, and to Steve Groen for sharing your vast knowledge of pulse oximeters, and for waking up at the break of dawn to help overcome the time difference between the Netherlands and the US.

A giant thanks to all my fellow graduating friends. Without your laughter, your support during tough times, spontaneous coffee breaks, and late-night encouragements, I wouldn't have stayed as motivated, or had nearly as much fun during this intense half year.

Lastly, thank you to my family, friends, and boyfriend for your support and belief in me.

EXECUTIVE SUMMARY

Pulse oximetry is an essential part of modern patient monitoring, but the current widespread use of single-use pulse oximeters in hospitals results in significant environmental impact (Duffy et al., 2023). Although reusable alternatives exist, their adoption remains limited (Noort et al., 2024). This graduation project, in collaboration with the Erasmus Medical Center and Philips, investigates the barriers to reusable pulse oximeter use and proposes a solution through product and system redesign.

A mixed-method research approach was used to identify key obstacles on system and product level. Barriers included poor cleaning compliance, sensor loss during patient transfers, off-label use in low-perfusion patients, sensor instability, alarm fatigue and discomfort for patients. Through interviews, observational studies, and co-creation sessions with hospital stakeholders, these barriers were mapped.

Short-term solution directions, such as monthly sensor redistribution, clearer cleaning responsibilities, and market research into low-perfusion sensors, were identified through co-creation and can form interventions in the current system to create sustainable change now.

To address barriers through product redesign, the Philips Nova was developed (figure 1), a hybrid pulse oximeter consisting of a reusable sensor base and a single-use adhesive patch. The design supports reuse through cleaning, cable repair to extend product lifespan and critical material recovery through recycling, while improving patient comfort. An integrated tracking system, Philips Connect, enables lifecycle data collection, supports circular business models such as product-as-a-service, and helps prevent unnecessary sensor loss or repurchasing. The Philips Nova builds on the existing system, minimizing workflow disruption and allowing easy adoption.

Together, the product concept and system recommendations form a practical roadmap for sustainable pulse oximetry in Dutch hospitals, bringing it closer to achieving circularity.

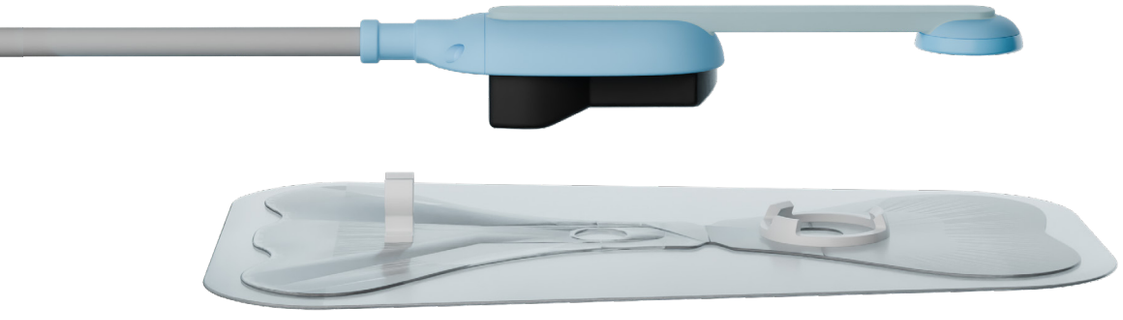

Fig. 1: Final design impression Philips Nova

LIST OF ABBREVIATIONS

ESCH-R	Evidence-based Strategies to create Circular Hospitals: Applying the 10-Rs framework to healthcare
EMC	Erasmus Medical Center
ICU	Intensive Care Unit
OR	Operating Room
PC	Pulmonary Clinic
ER	Emergency Room
MT	Medical Technology
IR	Infrared
EOL	End-of-Life
LCA	Life Cycle Assessment
PaaS	Product-as-a-Service
PPU	Pay-per-use
HB	Hemoglobin
CO2	Carbondioxide
EEPROM	Electrically erasable programmable read-only memory

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1

PROJECT INTRODUCTION

The healthcare sector is becoming increasingly aware of its contribution to global warming and waste production, which is caused partly due to its heavy reliance on single-use products. Studies indicate that pulse oximeters are the second most environmentally impactful single-use product in University Medical Centers in the Netherlands. This insight serves as the foundation for this graduation project, which focuses on enhancing the sustainability of pulse oximetry.

The primary objective of this research is to redesign the pulse oximeter sensor and its surrounding system to reduce the environmental footprint and material consumption of Dutch hospitals.

This chapter provides an overview of the project, detailing its context, approach, and the parties involved.

1.1 / BACKGROUND

Unsustainability in healthcare

Research suggests that the Dutch healthcare sector is responsible for 7.3 % of the national climate change footprint in CO_2 emissions (M. A. Steenmeijer et al., 2022). Contrary to popular perception, this is roughly double the emissions of the aviation sector (Environmental Impact of the Healthcare Sector, 2024). Regarding raw material consumptions the Dutch health care sector is responsible for 13% of national consumption (M. Steenmeijer et al., 2022). Alongside CO_2 emissions and raw material extraction, release of toxic substances, depletion of natural resources and the vast amount of waste materials contribute to the significant impact of the healthcare sector on the environment.

The European Green deal, signed in 2021, obliges EU members to achieve net-zero emissions by 2050. These goals were tailored specifically for the healthcare sector in the Green Deal 3.0 (2023), demonstrating a commitment to achieving net-zero emissions and eliminating the use of primary raw materials by 2050 (Green Deal Duurzame Zorg 3.0, z.d.). Achieving these goals requires us to rethink and transform the current linear system.

As with any sustainable transition, a holistic perspective is essential, considering social and economic development alongside environmental protection. The World Health Organization defines sustainable healthcare as care that "improves, maintains, or restores health while minimizing negative impacts on the environment and leveraging opportunities to restore and improve it, to the benefit of the health and well-being of current and future generations." (Environmentally Sustainable Health Systems, z.d.)

Fig. 2: Pile of medical blue wrap waste, at GreenCycle

Pulse oximeter sensor impact

A national inventory of medical single-use products by the University Medical Centers (UMC's) in 2024 ranked single-use products based on their estimated CO_2 impact (Noort et al., 2024). This list revealed pulse oximeters to be the second most impactful single-use product in the UMC's. Therefore, these sensors form an important target area on the journey to circularity. Pulse oximeters are non-invasive electrical sensors that measure blood oxygen levels as well as pulse (Nitzan et al., 2014). These measurements are part of the vital sign patient monitoring system, alongside body temperature and blood pressure, that give an indication of the body's basic functioning and are critical to patient care (Lockwood et al., 2004).

The pulse oximeters exist in many forms (discussed in chapter 2.2), but an important distinction can be made between the single- and reusable options. Among these, the single-use devices have been shown to have approximately five times the environmental impact of their reusable counterparts (Duffy et al., 2023). Though Dutch hospitals try to actively transition towards more reusable devices, 144.000 single-use pulse oximeters are purchased annually by the seven Dutch UMC's (Noort et al., 2024). This raises the question:

What product and system features form barriers for reusable pulse oximeter use?

This questions forms the starting point for this research project.

Fig. 3: Reusable pulse oximeter in use, *by Alamy*

1.2 / SCOPE

The goal of this graduation project is to redesign the pulse oximeter at both the product and system levels, focusing on reducing the CO_2 emissions and material consumption. The project will begin by examining the hospital context, identifying challenges and opportunities for implementing circular strategies in both the device and its surrounding system.

The project scope is limited to the Dutch healthcare sector, with the EMC serving as the primary research focus. Within the hospital, the study will concentrate on adult care departments, excluding the Sophia Children's Hospital.

Figure 4 illustrates the Green Deal 3.0 objectives over time and provides a timeline for product redesign implementation. Given that medical device development typically takes around 10 years, the redesigned pulse oximeter could be ready for launch by 2035. Since patient monitoring systems are usually replaced every decade, the redesign would be applicable between 2035 and 2045 (Sleutelen op de werkplaats, 2022). As a result, the product should be optimized for near-complete circularity.

Final project deliverables

1. An analysis of the use of pulse oximeters within the hospital context, focusing on barriers and opportunities for circularity.

2. Implementable solution directions to optimize the current hospital system for increased adoption of reusable pulse oximeters, developed through multi-stakeholder co-creation.

3. A proposed product journey, of the full product lifecycle, detailed with interactions of hospital stakeholders.

4. An evaluated product redesign aimed at reducing the environmental footprint and waste generation of the pulse oximeter, presented as a proof-of-concept prototype.

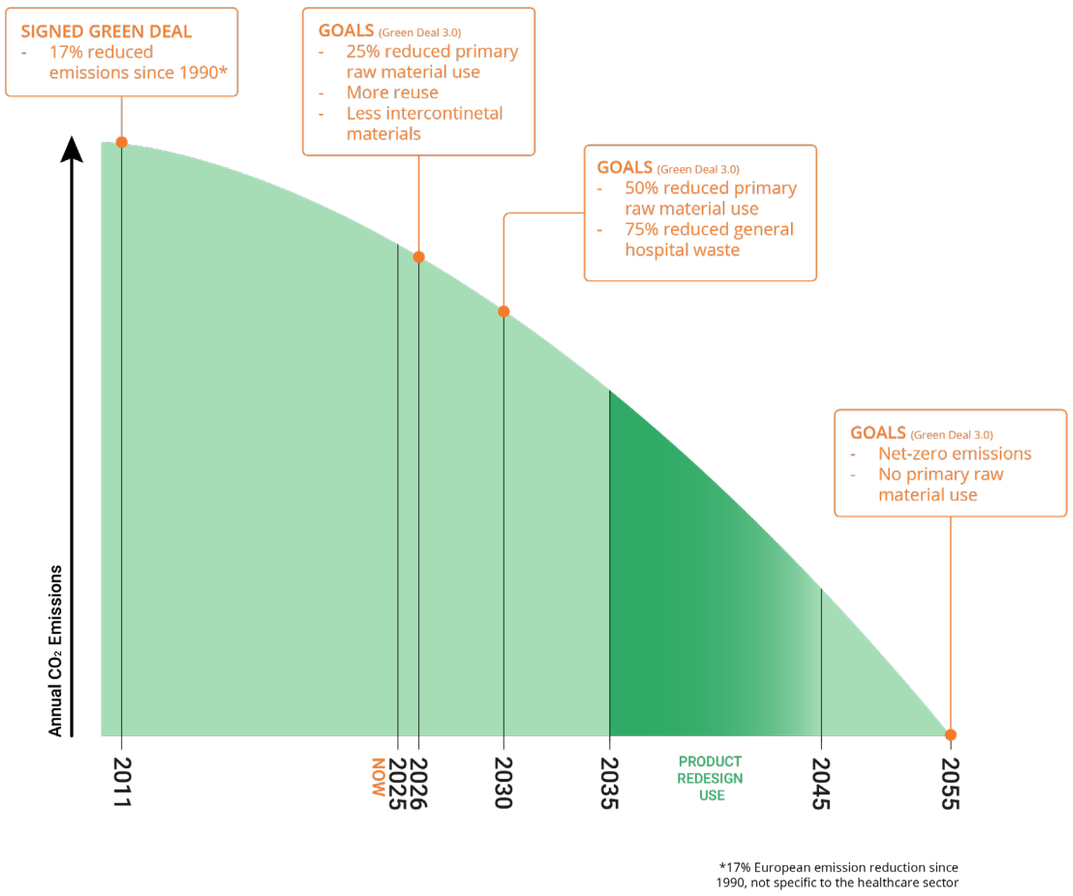


Fig. 4: Timeline of circular transition, highlighting the project scope

1.3 / RESEARCH QUESTIONS

A list of research questions and subquestions was formulated to guide the analysis phase of this project, based on an initial exploration of sustainability challenges in hospital pulse oximetry. The chapter in which each question is addressed is indicated next to the question.

1. WHAT PRODUCT AND SYSTEM FEATURES FORM BARRIERS FOR REUSABLE PULSE OXIMETER USE?		CHAPTER
1.1	What is the current market landscape of pulse oximeters and what circular strategies have been applied?	3.4
1.2	What is the environmental impact of reusable and single-use pulse oximeter in the context of Erasmus Medical Center, how do they compare, and how can it be improved?	4.2
1.3	What points of failure limit the current pulse oximeter's lifespan and how can this be improved?	4.3
1.4	With what ease can the current pulse oximeters be disassembled, and how can this be improved to open up opportunities for end-of-life strategies?	4.4
1.5	What journey do pulse oximeters currently make through their entire lifecycle and what barriers and opportunities unveil themselves for the implementation of circular strategies?	5.1
1.6	What product and system features form barriers for reusable pulse oximeter use?	5.2

2. HOW CAN THE CURRENT HOSPITAL SYSTEMS BE IMPROVED TO ELIMINATE BARRIERS FOR REUSABLE PULSE OXIMETER USE?		CHAPTER
2.1	How can we implement multi-stakeholder co-creation in the hospital setting?	7.1
2.2	What interventions could lower the systemic barriers for reusable pulse oximeter use in the current hospital system?	7.2

3. HOW COULD A PRODUCT BE REDESIGNED TO OVERCOME THE BARRIERS FOR THE REUSABLE PULSE OXIMETER WITHIN THE HOSPITAL?		CHAPTER
3.1	How can product level barriers be overcome in a sensor redesign?	8
3.2	How can we make the product traceable through the hospital and over its lifetime?	9.5
3.3	How can we extend product lifespan by improving its durability?	9.2
3.4	How can end-of-life strategies maintain product/ material value after its life in use?	8.5
3.5	How does the Philips Nova compare to the current single-use and reusable pulse oximeters in terms of useability?	9.4

1.4 / APPROACH

This project follows an iterative diverging-converging design structure, known as the Framework For Innovation (formerly the Double Diamond) (Framework for Innovation, z.d.). This design methodology consists of four main stages that transform a challenge into an outcome: Discover, Define, Develop and Deliver.

Figure 5 shows that, in order to tackle both the systemic and product related challenges, these design journeys ran parallel. Within the overarching Framework for Innovation, many other design methodologies were used, displayed in figure 5. These methodologies will be explained in greater detail throughout this report.

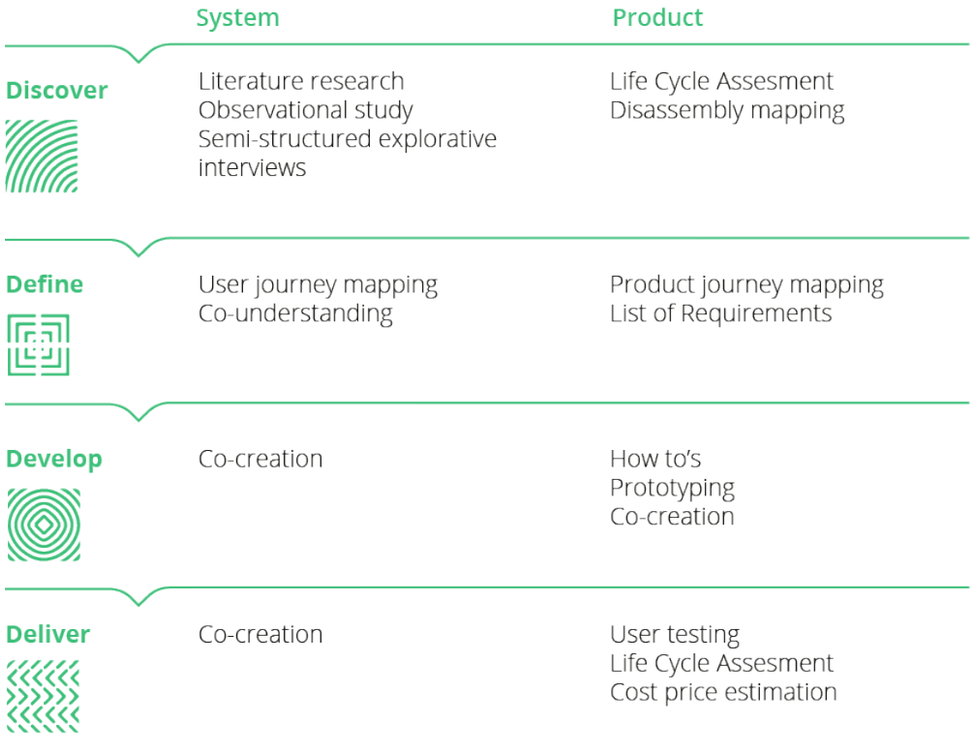


Fig. 5: Research approach

1.5 / INVOLVED PARTIES

ESCH-R Consortium

ESCH-R is an interdisciplinary research consortium funded by the Dutch Research Council under the Dutch Research Agenda. ESCH-R aims to accelerate the adoption of circular strategies in hospitals to lower the environmental footprint of healthcare. The acronym ESCH-R stands for "Evidence-based Strategies to create Circular Hospitals: Applying the 10-Rs framework to healthcare." (ESCH-R, z.d.) (Huijben et al., 2025)

This graduation project is part of the ESCH-R consortium, which serves as the client. The consortium includes various collaborating partners, with TU Delft, EMC, and Philips being actively involved in this project.

TU Delft

This graduation project concludes the Master's program in Integrated Product Design at Delft University of Technology. TU Delft offers academic guidance and design expertise throughout the project, with Jan-Carel Diehl and Sonja Paus-Buzink serving as members of the graduation committee.

Erasmus Medical Center

Erasmus Medical Center (EMC) is the largest academic hospital in the Netherlands, located in Rotterdam. The EMC is known for its cutting-edge research, patient care, and medical education.

Within this graduation project, the EMC provides valuable research possibilities and expertise into the hospital context and product use.

Philips

Philips healthcare is a Dutch based market leader in the development and manufacturing of innovative medical technologies. They aim to improve people's health and wellbeing through meaningful innovation (About Us, z.d.).

Within their Patient Monitoring division, they design advanced patient monitoring devices, including pulse oximeters. Philips offers extensive expertise in pulse oximeter development, helping guide the creation of a feasible and viable product design. This was done through progress meetings with two Philips employees who focus on pulse oximeter development and sustainability. These employees gave feedback and guidelines throughout the concept design phase.

The analysis phase of this thesis was conducted independently from Philips.

2

EXPLORING THE CONTEXT AND USE OF PULSE OXIMETERS

Pulse oximeters play a vital role in clinical care, providing a non-invasive method to measure blood oxygen saturation. At the EMC, three main types of pulse oximeters are commonly used, each suited to different monitoring needs and clinical contexts.

These sensors function through two key components: infrared lights and a detector, working together to deliver real-time data on a patient's oxygen levels.

This chapter explores the clinical applications of pulse oximeters, their variety in sensor types within the EMC, and the underlying technology that makes them essential in patient monitoring.

As the analysis phase was conducted independently from Philips and was focussed on the context of the EMC, Masimo sensors will be referenced.

Methodology
The information presented in this chapter was obtained through a combination of research methods. A literature review was conducted to explore the clinical and technical use of pulse oximeters. Additionaly, a semi-structured interview with a biomedical engineer was conducted. Lastly, product use within the EMC was investigated through interviews and observations.

2.1 / CLINICAL PULSE OXIMETER USE

Pulse oximeters are a widely used and essential device in hospitals, providing measurements of the blood oxygen levels and pulse rate. By analysing this sensor data, clinicians can gain valuable insights into a patient's overall health (Nitzan et al., 2014). One of the primary functions of pulse oximeters is the early detection of hypoxia, a condition characterized by reduced oxygen saturation of the tissue (Zacharis et al., z.d.). Hypoxia can result from various factors, including heart and long conditions, infections or medication. Prolonged hypoxia can result in organ damage, which can put a patient at risk of death. Consequently, early detection, diagnosis of the underlying cause and treatment are critical to patient care. Pulse oximeters play a key role in this process (Zacharis et al., z.d.)(Wiebe & Machulla, 1999).

In hospitals, pulse oximetry is conducted through two main types of monitoring: continuous and intermittent. Continuous monitoring provides uninterrupted measurements by keeping the patient connected to the sensor for an extended period. This data is often displayed on a central monitor located outside the patient's room, allowing healthcare providers to observe changes in real time. Continuous monitoring is typically reserved for patients in critical conditions, where rapid detection of physiological changes is vital.

Intermittent monitoring, on the other hand, is used for patients in less critical states. In this process the pulse oximeter is connected to the patient for periodic checkups, after which the device is removed. The frequency of these measurements varies per patient, but is usually performed one to three times a day.

Pulse oximeters are utilized across a broad range of hospital departments. Units such as the intensive care unit, operating room, and emergency room rely heavily on continuous monitoring due to the severity of cases they handle. Additionally, inpatient clinics and specialized departments, such as pulmonary and endoscopic clinics frequently use pulse oximeters for intermittent monitoring.

Figure 6 visualises the use context of the pulse oximeter for continuous monitoring at the ICU department. The figure shows the pulse oximeter alongside two essential elements, the 'broodje' and the bedside monitor.

'Broodje': The pulse oximeter is directly plugged into the 'broodje'. This powers the sensor, processes and displays the data. A 'broodje' is portable, meaning that is moves along with the patient in case of department transfer.

Bedside monitor: The 'broodje' is connected to a bedside monitor, which displays detailed data and integrates with a broader monitoring system. A central monitor in the department hall allows healthcare providers to observe real-time changes from a distance.

TAKEAWAYS

- Hypoxia detection is the main purpose of pulse oximeters.
- Two types of monitoring are performed: Continuous and intermittent monitoring.
- The pulse oximeter functions in a system with the 'broodje', bedside and central monitor.

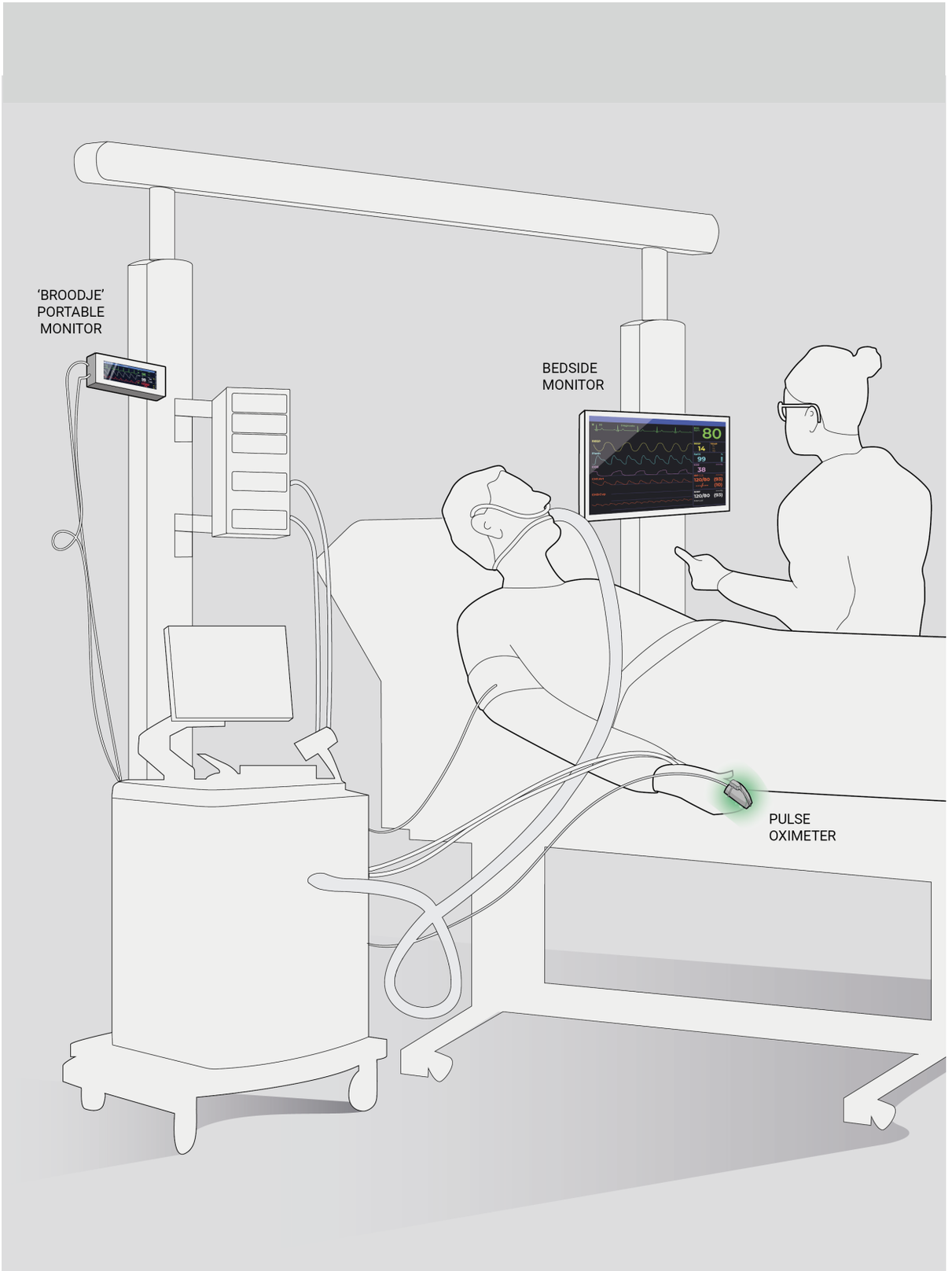


Fig. 6: Pulse oximeter use context, continuous monitoring on the ICU department

2.2 / SENSOR VARIATIONS

Within the EMC, they use a range of Masimo pulse oximeters. The most commonly used variations are the RD SET Adt single-use sensor, RD SET DBI reusable finger sleeve and the RD SET DCI reusable finger clip. Figure 7 shows alle three sensor variations.

Single-use sensor

Figure 8 shows the intended use scenarios of the single-use finger adhesive sensor as described by Masimo. After removing the sensor from its packaging, the adhesive tabs allow the sensor to be stuck onto the finger, focussing on correct alignment of the detector and LEDs. Afterwards the sensor is plugged into an adapter cable. This 3.5 m long cable connects the device to the ‘broodje’. This sensor type is intended to be replaced twice a day to ensure proper functioning.

Reusable sensors

Figure 9 shows the intended use of the reusable pulse oximeter sleeve. This sensor is kept in position through friction with the silicone material. The finger clip sensor interaction closely resembles that of the finger sleeve, and is therefore not shown. The reusable sensor can be connected to the same patient cable as the single-use sensor, as they share the same connector. The monitor can detect which device is connected through the connector pins. This allows compatibility of multiple sensors with the same adapter cable, benefiting the nurse’s workflow. The reusable sensor connector features the addition of a protective latch cover, to prevent the sensor from disconnecting.

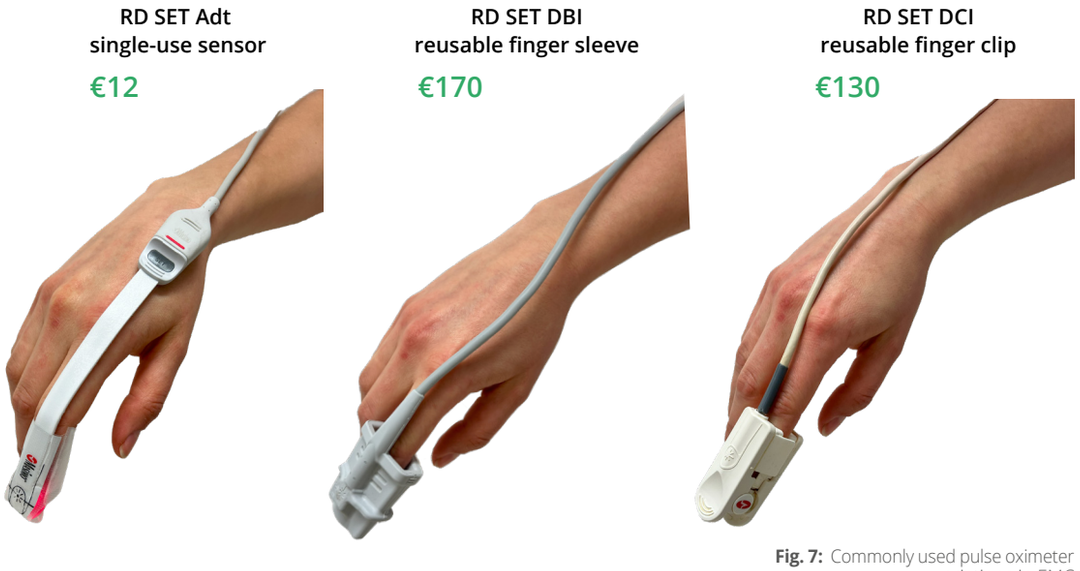


Fig. 7: Commonly used pulse oximeter variations in EMC

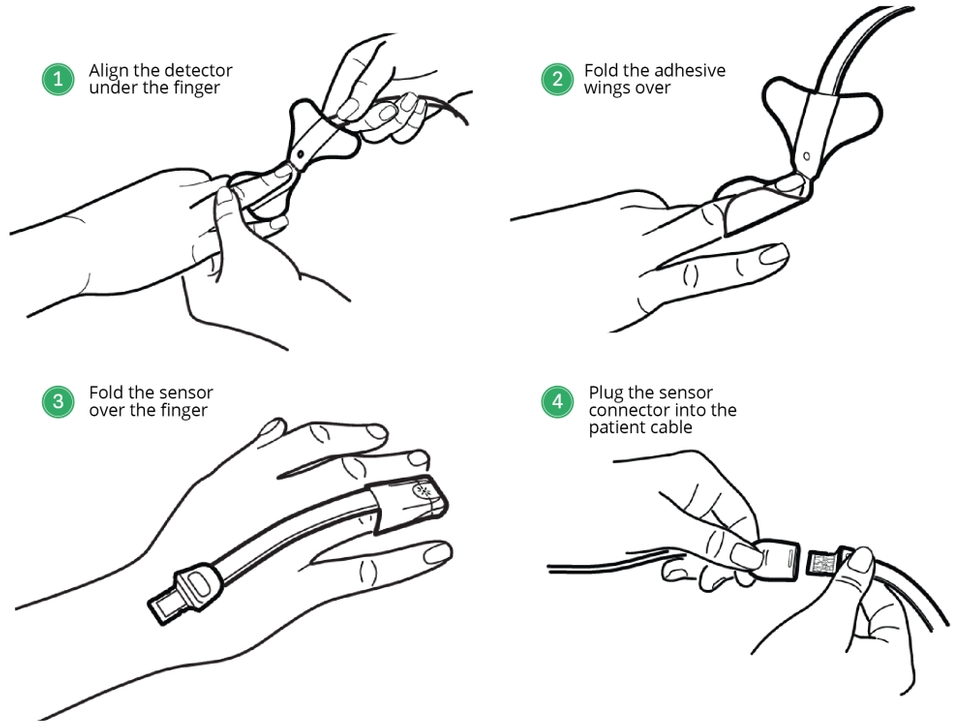


Fig. 8: Single-use RD SET Adt sensor use

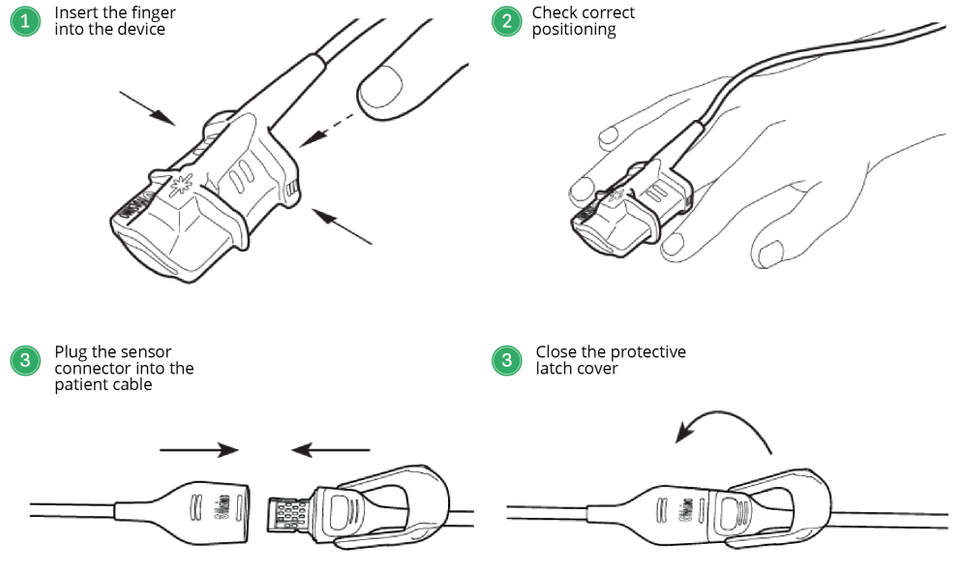


Fig. 9: Single-use RD SET DBI sensor use

2.3 / TECHNICAL PRODUCT FUNCTIONING

The absorption of oxygen into the blood is achieved through the binding of oxygen to the hemoglobin (Hb) protein. This allows oxygen to travel from the lungs through the body. Pulse oximeters sense the level of blood oxygen saturation (SpO_2) though a technique called pulse oximetry. This non-invasive method is based on light pulses, often in two wavelengths in the red and infrared regions. Oxygenated hemoglobin (HbO_2) absorbs light in different wavelength-spectra than non-oxygenated hemoglobin (deoxyhemoglobin) (Hb). Detecting the non-absorbed light, therefore forms an indicator for the ratio of oxygenated to deoxyhemoglobin. This ratio expresses the SpO_2 as a percentage, ranging between 96% to 98% in healthy patients (Nitzan et al., 2014).

Transmissive and reflective oximetry

Most commonly, transmissive pulse oximetry is used for SpO_2 measurements. Transmissive pulse oximetry detects the light after it is transmitted through an organ. This technique is therefore limited to the finger, earlobe and nose, due to their high blood flow and thin skin (Nitzan et al., 2014). Reflective pulse oximetry detects reflected light, allowing the light source and detector to be on the same surface of skin. This measurement technique allows more freedom for measurement sites, but has a lower clinical development level (Lee et al., 2016).

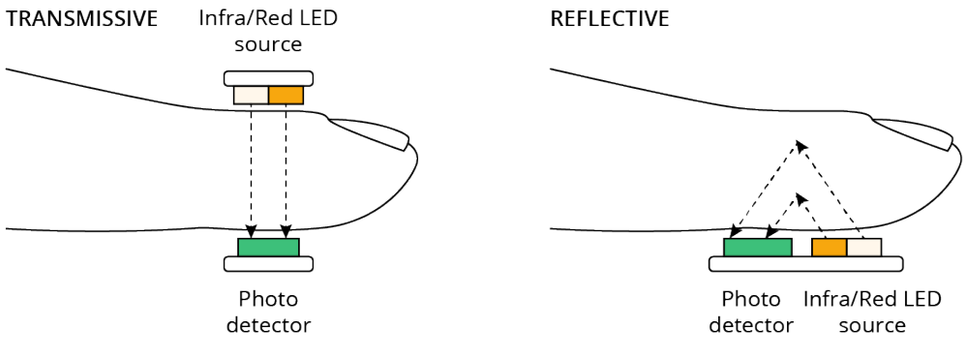


Fig. 10: Transmissive and reflective oximetry

Measurement accuracy

Generally pulse oximeters indicate an accuracy of 2%, but this accuracy can be affected by many factors, related to the placement, context and patients, highlighted in figure 11 (Al-Halawani et al., 2023; Jung et al., 2022; Nitzan et al., 2014).

TAKEAWAYS

- Blood oxygen saturation is measured using light absorption qualities of hemoglobin and deoxyhemoglobin.
- Transmissive and reflective pulse oximetry are two measurement types, of which transmissive is the most common.

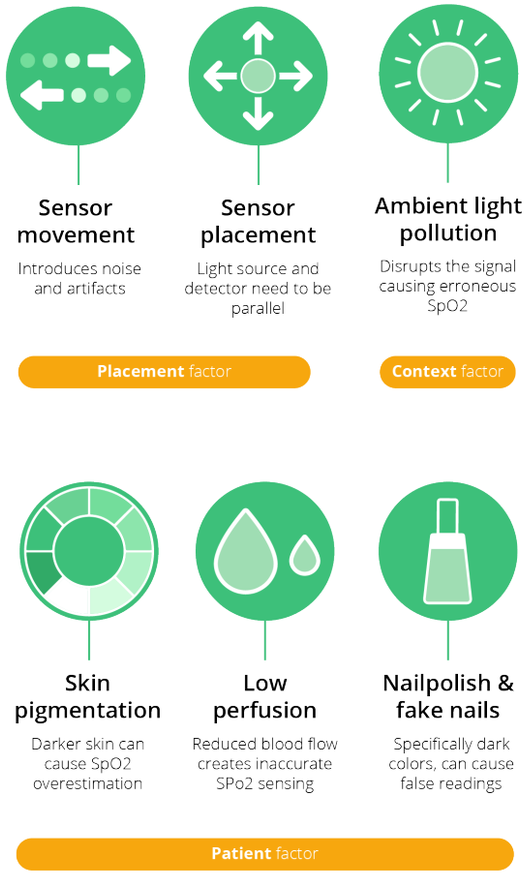


Fig. 11: Placement, context and patient factors influencing measurement accuracy.

3

CIRCULAR DESIGN STRATEGIES AND THEIR APPLICATION TO PULSE OXIMETRY

The circular economy challenges the conventional “take-make-waste” model by focusing on three key principles: eliminating waste and pollution, keeping products and materials in use, and regenerating natural systems. To guide circular innovation, the Value Hill model introduces ten life-extending strategies aimed at preserving product and material value for as long as possible.

Applying these principles in healthcare requires navigating safety regulations, financial constraints, and logistical challenges. Some pulse oximeter manufacturers have begun incorporating circular strategies, primarily targeting single-use sensors. Meanwhile, emerging innovations and new business models frame the future of sustainable pulse oximetry.

This chapter explores the fundamentals of circular design, introduces the 10R strategies and examines both current and future circular initiatives in the pulse oximeter market.

Methodology
The information presented in this chapter was gathered through a literature review, using search terms such as “circular economy,” “10R strategy,” and “circularity in healthcare.” Additionally, market research was conducted to identify how circular strategies are currently being integrated into pulse oximeter design.

Research question

1.1 What is the current market landscape of pulse oximeters and what circular strategies have been applied?

3.1 / CIRCULARITY

Our current way of living, grounded in the “take-make-waste” principle, is starting to reveal big societal, economic and environmental challenges (Towards a circular economy, 2013). Increased societal inequality, critical material scarcity and biodiversity loss are just a few among the many problems arising (Lucas et al., 2018).

To address these issues and to make human activity more resilient, and alternative to the linear economy was proposed, the circular economy. The circular economy challenges the “take-make-waste” model by reimaging business models to work in harmony with the ecological system. Nobre en Tavares (2021) have defined the circular economy as follows:

“Circular Economy is an economic system that targets zero waste and pollution throughout materials lifecycles, from environment extraction to industrial transformation, and to final consumers, applying to all involved ecosystems. Upon its lifetime end, materials return to either an industrial process or, in case of a treated organic residual, safely back to the environment as in a natural regenerating cycle. It operates creating value at the macro, meso and micro levels and exploits to the fullest the sustainability nested concept. Used energy sources are clean and renewable. Resources use and consumption are efficient. Government agencies and responsible consumers play an active role ensuring correct system long-term operation.”

In short, the circular economy relies on three principles: eliminating waste and pollution, circulating products and materials and regenerating nature (Circular Economy Introduction, z.d.).

The shift from linear to circular asks for creative redesigns of product, services and systems as well as the business models they are placed in. Therefore the transition requires active collaboration between different parties in order to make changes sustainable, economically viable and implementable.

TAKEAWAYS

- The goal of the circular economy is to eliminating waste and pollution, circulating products and materials and regenerating nature.

3.2 / VALUE HILL

A circular design and strategy tool central to the ESCH-R project is the Value Hill (Achterberg et al., 2016)(see figure 12). It aims to inspire circular design by demonstrating lifecycle pathways to retain a products value for as long as possible, by incorporating life-extending strategies (Lieder & Rashid, 2016). These life extending strategies are characterized as the 10 R’s. In order to retain as much value as possible, the R-strategies highest on the value ladder should be considered first. To demonstrate, reusing (R3) a product has more sustainable benefit than recycling (R8) a product. A combination of the strategies through the product design and product lifecycle are often required to eliminate the most waste and pollution. The next page elaborates on the definition of the individual R-strategies.

The Value Hill tool focuses on the circulation of products and materials, also called the technological cycle (technosphere). Ellen McArthur’s butterfly diagram expands on this idea by incorporating the biological cycle (biosphere), in which biodegradable materials are returned to the earth to regenerate (Nayak, 2022).

TAKEAWAYS

- R-strategies highest on the hill should be considered first.
- A combination of R-strategies is required to create the biggest sustainable impact.

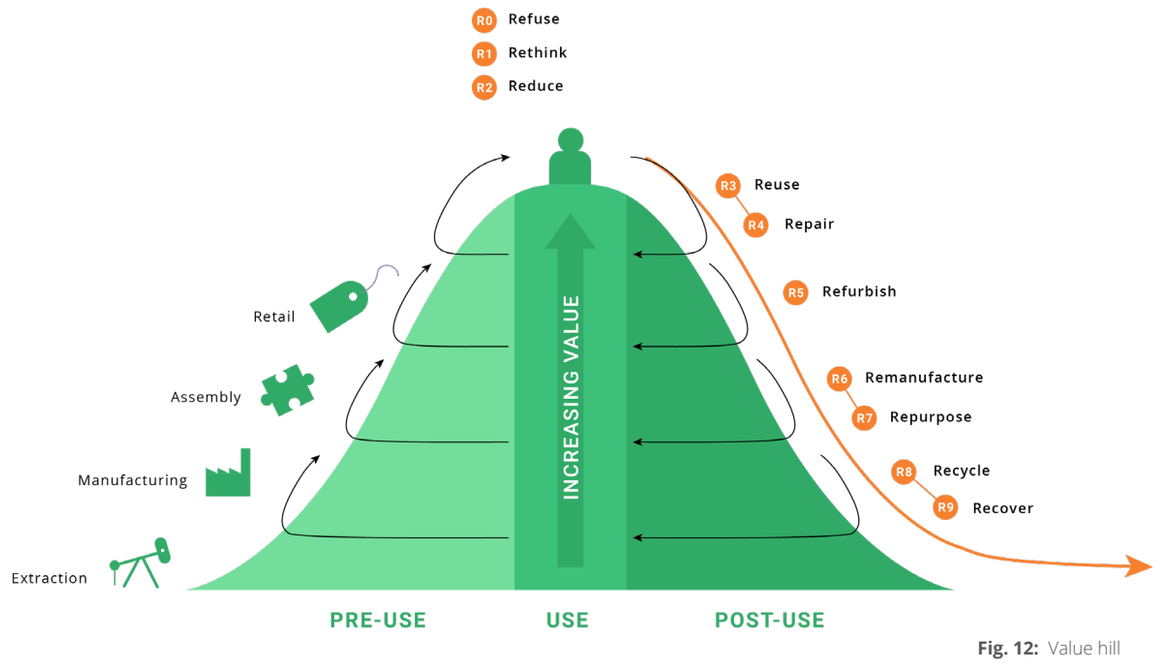


Fig. 12: Value hill

0	REFUSE	Making a product redundant by abandoning its function or by offering the same function with a radically different product.
1	RETHINK	Make product use more intensive (e.g. through sharing products).
2	REDUCE	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.
3	REUSE	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function.
4	REPAIR	Repair and maintenance of defective products so it can be used with its original function.
5	REFURBISH	Restore an old product and bring it up to date.
6	REMANUFACTURE	Use parts of discarded products in a new product with the same function.
7	REPURPOSE	Use discarded product or its parts in a new product with a different function.
8	RECYCLE	Process materials to obtain the same (high grade) or lower (low grade) quality.
9	RECOVER	Incineration of materials with energy recovery.

Fig. 13: 9R strategies as defined by Potting et al. (2017)

3.3 / CIRCULAR CHALLENGES IN HEALTHCARE

Adopting circular strategies in healthcare comes with specific challenges related to safety, regulations, financial and logistical constraints. These factors play a major role in shaping how sustainable solutions can be applied in the medical field.

Safety concerns

Preventing infections and contamination is the top priority in patient care. Circular strategies, like reusing (R3) or refurbishing (R5) products, might be seen as a risk to patient safety. This concern has driven the growing use of single-use materials in hospitals, even though their increased safety is not always scientifically proven but is often assumed (Bhutta, 2021; Davies et al., 2024). Because of this, infection prevention and perceived safety are crucial considerations when designing circular solutions for healthcare (Hoveling et al., 2024).

Regulatory challenges

Healthcare products must meet strict regulations, which can limit the use of circular strategies. For instance, medical devices must use medical-grade plastics, and mechanically recycled plastics do not meet these standards. Chemically recycled plastics can be labelled as medical grade, but their availability is low, and their environmental benefits remain unclear (Garcia-Gutierrez et al., 2023; Pianegonda, 2022). These regulatory limits make it harder to incorporate sustainable materials into product design.

Financial and logistical barriers

Financial constraints are another significant challenge. The current system of selling large quantities of single-use devices is profitable for manufacturers, while reusable devices, though often cheaper for hospitals, may not generate the same profits. Additionally, managing the end-of-life phase for low-value devices is rarely cost-effective and is made more difficult by logistical issues. Setting up collection and separation systems can be complex and costly. However, exploring existing centralized collection processes in hospitals could help find opportunities to improve end-of-life recycling and processing (Hoveling et al., 2024).

In summary, (perceived) safety risks, strict regulations (such as limits on recycled materials), financial challenges, and logistical issues in collection and separation are key barriers to applying circular strategies in healthcare. Addressing these challenges is essential to designing sustainable medical products that meet the sector's specific needs.

TAKEAWAYS

- To enable adoption, the pulse oximeter redesign must minimize (perceived) safety risks.
- Use of recycled materials for a pulse oximeter manufacturing is not yet feasible, but might be in the future.
- Existing centralized collection processes should be utilized for effective end-of-life strategy implementation.

3.4 / EXISTING CIRCULAR STRATEGIES IN THE PULSE OXIMETER MARKET

Philips' competitors in the pulse oximeter market, Masimo, Medtronic and Stryker, have set up sustainability programs to lower the environmental footprint of the devices and save costs for hospitals. These strategies focus on single-use remanufacturing (R6) and recycling (R8).

Single-use remanufacturing

Stryker and Medtronic, are two medical device manufacturers who have set up single-use pulse oximeter remanufacturing programs. Remanufacturing of single-use medical devices has been legalised in the Netherlands since January 2025, but has been legal in the United States and other countries for much longer (Health, 2024; Ministerie van Volksgezondheid, z.d.). The Stryker remanufacturing product journey is visualised in figure 14 (Reprocessing Overview Pulse Oximeter, z.d.).

Medtronic only remanufactures their (Nellcor) sensors once, whereafter they are recycled. Stryker remanufactures up to four times.

The main motivation for remanufacturing single-use devices for hospitals is the reduced costs, as the price of reprocessed devices is on average 60% of the original price (Duncker et al., 2020; Sacher et al., 2024). A lifecycle analysis conducted on remanufactured electrophysiology (EP) catheters, show that remanufacturing is also beneficial from a sustainability perspective (Essex & Thording, 2021). The impact of a remanufactured single-use EP catheter is about 50% of the impact of a new single-use catheter. Whether this is the same for pulse oximeters is hard to estimate.

Manufacturer opposition
Manufacturers of single-use pulse oximeters are critical of remanufacturing programs. While remanufacturers claim to maintain high-quality standards, some tests reveal issues such as reduced accuracy or improper cleaning (Bridges et al., 2010). This quality degradation can lead to reputation damage for the original manufacturers.

Another major concern for manufacturers is the loss of profits. By refurbishing and reselling single-use devices, remanufacturers reduce the demand for new products, directly impacting the original manufacturers' sales. In response, some manufacturers have redesigned their devices to make remanufacturing more difficult. For instance, Masimo replaced their PVC-lined cables with foam-covered ones, making them harder to clean.

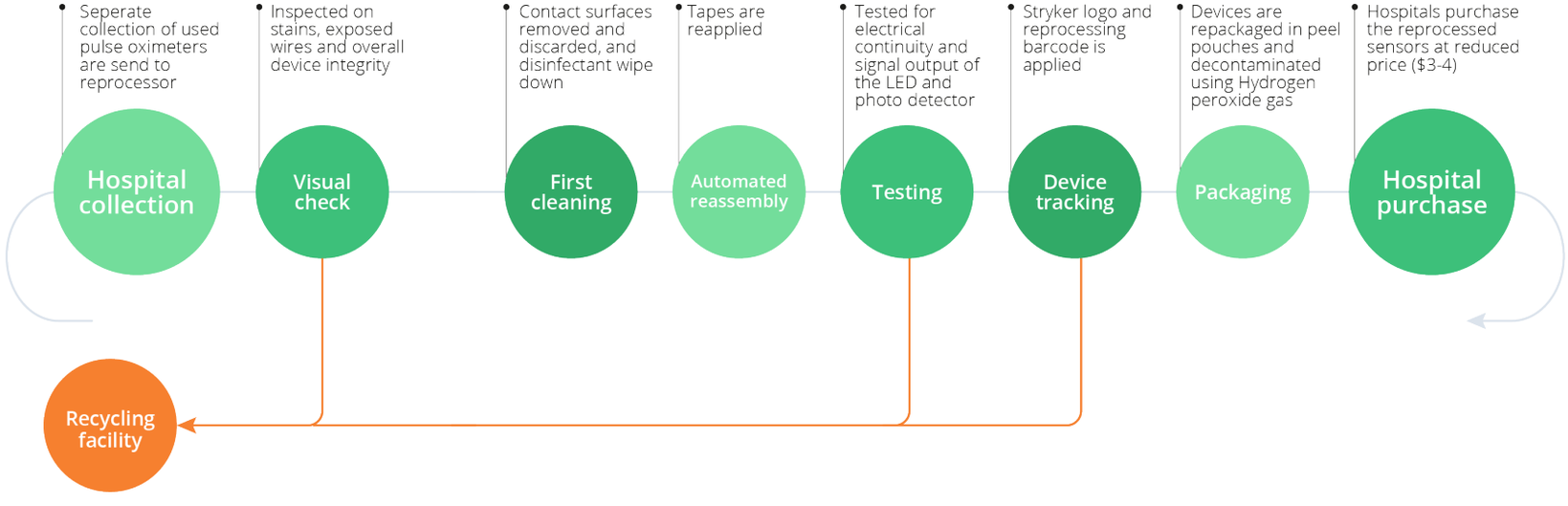


Fig. 14: Stryker remanufacturing process

Single-use recycling

Masimo and Medtronic have set up recycling programs for their single-use pulse oximeters, visualized in figure 15 (Sensor Recycling Program, z.d.). The targeted output of the recycling process is copper and other metals, other materials are incinerated for energy. This recycling system is open-loop, meaning that the recycled material output is not used in the production of new sensors, but instead is used in other industries (Vogtländer, 2022).

Through this program, hospitals can achieve cost savings as Masimo and Medtronic offer free waste collection services and provide discount credits for future sensor purchases.

Though good attempt are made to lower the environmental impact of pulse oximeters, it is notable that these strategies only focus on single-use devices, instead of targeting R-strategies higher up on the Value Hill.

TAKEAWAYS

- Circular strategies in the market all focus on the single-use pulse oximeters. R6 and R8.
- Remanufacturing of single-use sensors by external parties is actively opposed by device manufacturers.

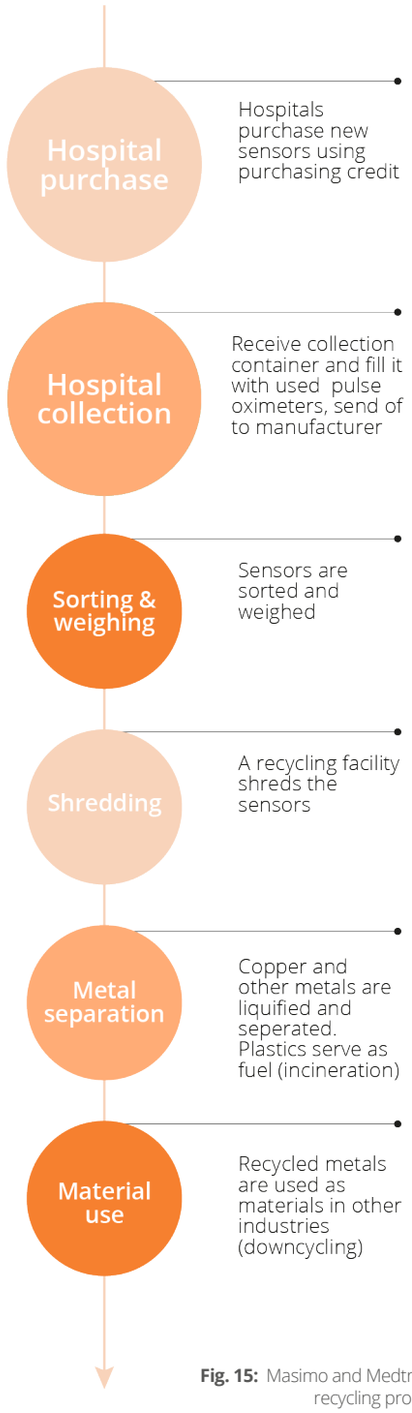


Fig. 15: Masimo and Medtronic recycling process

3.5 / FUTURE CIRCULAR STRATEGIES IN THE PULSE OXIMETER MARKET

In addition to the current strategies in the pulse oximetry market, new circular approaches are being explored for future implementation. These include business model innovations like pay-per-use and product-as-a-service, as well as cleaning an maintenance scenarios for patient monitoring sensors. Redesigning pulse oximeters to accommodate these services will be key to advancing circular practices.

Business model innovation

The Ellen MacArthur Foundation, highlights that circular business models are essential for accelerating the transition to a circular economy (Towards the Circular Economy Vol. 1, 2013) (Kirchherr et al., 2017). Unlike the traditional sales model, which transfers product ownership to the customer, circular models aim to keep ownership for longer, allowing companies to influence a product's lifecycle. Examples include pay-per-use (PPU), where a customer pays for each use of the product, and product-as-a-service (PaaS), where the customer pays for access to the product's functionality. Both models keep product ownership with the company, promoting sustainability by reducing waste, overproduction, and encouraging longevity and responsible disposal (Bocken et al., 2018).

Adopting these models requires a new understanding of how products are used, delivered, and maintained (Stretton & Daphne, 2023). More product data needs to be accessible throughout the lifecycle for both businesses and customers, which must be considered during product design.

Within the medical device industry these models are also gaining traction, Philips is already testing 'Monitoring as a service' in the U.S. (Five Reasons Why Healthcare Providers Are Adopting As-a-Service Models in Patient Monitoring, 2023; Guzzo et al., 2020).

Centralized cleaning and maintenance scenarios

As part of the "Digital Health in the Circular Economy" research consortium, Philips is exploring future approaches to cleaning and maintaining electrocardiogram lead sets. The aim of these approaches is to reduce the environmental impact of these devices. To allow expanded scope for these developments to pulse oximeters, design should allow this practice.

TAKEAWAYS

- Product redesign needs to allow business model innovation through data storage.
- Product redesign needs to allow centralized cleaning an maintenance scenarios.

4

SUSTAINABILITY ASSESSMENT OF PULSE OXIMETERS

The journey of a pulse oximeter differs significantly between single-use and reusable sensors, with varying applications of circular strategies such as reduce (R2), reuse (R3), and recover (R9). A comparison of these sensors within the EMC ICU context reveals a striking sustainability advantage for reusable pulse oximeters over single-use alternatives, reinforcing the need for hospitals to transition toward reusable models. The sensor longevity can be further improved by addressing common failure points, such as dirt buildup and cable damage. Achieving this requires a redesign of the product architecture to enhance durability and repairability.

This chapter explores how circular strategies are currently applied in pulse oximetry, quantifies their environmental impact, and identifies key redesign opportunities through product failure analysis and disassembly studies. The analysis is conducted independently from Philips and focuses on Masimo sensors in the EMC context.

Methodology
The research involved product journey mapping to analyze the current lifecycle of pulse oximeters. A Life Cycle Assessment (LCA) was conducted using the Idemat2023 database within the OpenLCA software. Common failure points were identified through an analysis of the Manufacturer and User Facility Device Experience (MAUDE) database, supplemented by an examination of broken pulse oximeters from EMC. Additionally, the ease of disassembly was assessed using the Disassembly Mapping methodology.

Research questions

1.2 What is the environmental impact of reusable and single-use pulse oximeter in the context of Erasmus Medical Center, how do they compare, and how can it be improved?

1.3 What points of failure limit the current pulse oximeter's lifespan and how can this be improved?

1.4 With what ease can the current pulse oximeters be disassembled, and how can this be improved to open up opportunities for end-of-life strategies?

4.1 / IMPLEMENTED R-STATEGIES IN PULSE OXIMETER LIFECYCLE

Product journey mapping is a tool to get insight into the entire lifecycle of a product in order to rethink it using circular strategies (Product Journey Mapping, z.d.). Figure 16 and 17 show simplified versions of the product journey of the single-use and reusable pulse oximeters. Highlighted are the R-strategies currently implemented in the product journeys.

Single-use sensor lifecycle

Figure 16 shows the lifecycle of a single-use pulse oximeter. The lifecycle is completely linear, from raw material extraction to incineration.

Within the lifecycle two R-strategies are highlighted. Firstly, the Masimo single-use sensor is optimized for minimal material use, part of the 'reduce' strategy (R2) (Masimo - RD SET Sensors, z.d.). With these sensors only weighting approximately 7 grams, they are a great improvement on older variations of single-use sensors, which could weight up to 40 grams.

Secondly, the sensors are discarded in general waste (non-hazardous) whereafter they are incinerated for recovering energy (R9).

The duration of the use phase for these single-use sensors varies by context. While manufacturers typically recommend discarding the sensor after half a day, hospitals such as the EMC extend their use for a single patient for up to a week, significantly reducing the environmental impact of the single-use sensor.

As discussed in Chapter 3.4, remanufacturing (R6) and recycling (R8) programs for these sensors are available but have not been implemented at the EMC.

Reusable sensor lifecycle

In the reusable product journey R3, reuse, is implemented. This strategy is fairly high up on the Value Hill, showing good recirculation of product value. The reuse system consists of product use, product cleaning according to protocol (Appendix A), whereafter the sensor is ready for use again.

Similar to the single-use sensors, energy is recovered at end-of-life through incineration (R9).

A big jump in circular strategies can be observed from R3 to R9. Even for the higher value reusable sensors, no end-of-life strategies are implemented to preserve the value of the product or material after its life in use, aside from a slight energy recovery through incineration. Opportunities for future implementation of higher value preserving circular strategies should be explored. This will become even more important in the future, with higher risk of material scarcity fuelled by geopolitical tensions (Critical Raw Materials, z.d.).

TAKEAWAYS

- After the product's life in use, no strategies are currently in place to preserve its material or product value, aside from incineration for energy recovery (R9). This presents a clear opportunity for circular improvement.

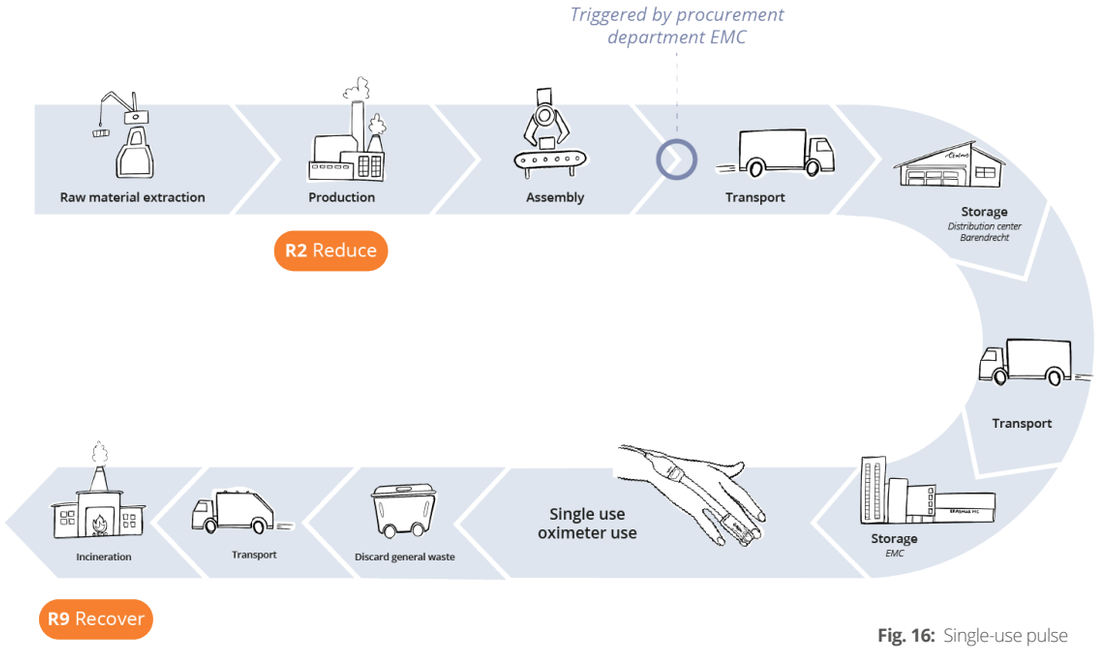


Fig. 16: Single-use pulse oximeter lifecycle

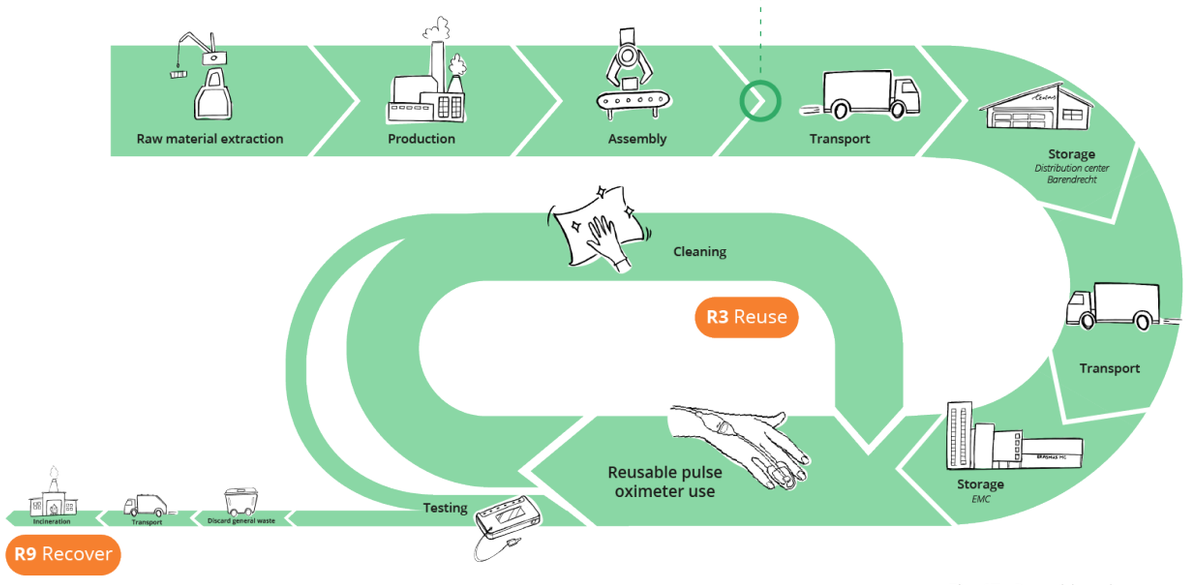


Fig. 17: Reusable pulse oximeter lifecycle

4.2 / LIFE CYCLE ASSESSMENT

In order to define effective circular design strategies, it is important to determine the current impact factors of the pulse oximeter and to compare the single-use and reusable version. The Life Cycle Assessment (LCA) is a widely accepted tool that allows quantification of environmental interventions and guide design decisions. Using the previously introduced product journey map (figure 16, 17), a fast-track LCA was set up for the use of pulse oximeters in the EMC.

One prior LCA, comparing single-use and reusable pulse oximeters, was performed by Juliana Duffy in 2023 (Duffy et al., 2023). This paper was used to evaluate my own LCA, but could not be used as direct input for my decision making. The reason for this is multitude, but most important is the vastly different context the LCA was set in, being the Massachusetts General Hospital. The kind and amount of sensors used, as well as the cleaning frequency and procedure greatly vary from the Dutch context, which has major impact on the final result of the LCA.

LCA setup

The impact of the single-use and reusable pulse oximeter was compared using the following functional unit:

"Providing continuous pulse oximetry measurements for all patients on the Intensive Care Unit of the EMC, for one year".

A functional unit quantifies the function of a product and makes sure the single and reusable pulse oximeter are compared on equal basis (Arzoumanidis et al., 2019). The Intensive Care Unit was chosen, as this department consumes the biggest amount of single-use sensors (Chapter 5.2).

The fast-track LCA was performed in OpenLCA using the Idemat2023 database. EMC 2023 procurement and department data was used as input as well as material determination of the two most commonly used pulse oximeters (for continues monitoring), the reusable Masimo sleeve (RD SET DBI) and single-use adhesive sensor (RD SET Adt).

The most important educated assumptions informing the fast-track LCA were as follows:

- 60 reusable sensors are required to supply the entire ICU, one per bed (50) and 10 extra sensors in storage.
- 5000 single-use sensors are required to supply the entire ICU. The purchased amount in 2023 was 4500 sensors, which supplied 90% of the ward.
- The reusable pulse oximeter is only cleaned at patient discharge, using ¼ of a microfiber cloth and water. This is conform the cleaning protocol of the hospital, for non-isolated patients (Appendix A).
- The reusable product lifespan was set at 1 year. The manufacturer indicates 2 year lifespan, but this is shortened due to product misuse (Duffy et al., 2023). This is an estimation as no EMC data or insight is available about the lifespan of the sensors in their context.
- The single-use pulse oximeters are used for up to a week on the EMC ICU, afterwards they are replaced with a new one.

For a detailed description of all fast-track LCA data, view Appendix B.

LCA results

Figure 18 shows the difference in climate change impact, expressed in CO_2 equivalent, between reusable sensors and single-use sensors for the EMC ICU department over a time period of one year. A clear difference can be observed in favor of the reusable sensors. One year of continuous monitoring using the single-use sensors would result in 179 kg CO_2 eq emissions, where the reusable sensors would only cause 34 kg CO_2 eq emissions.

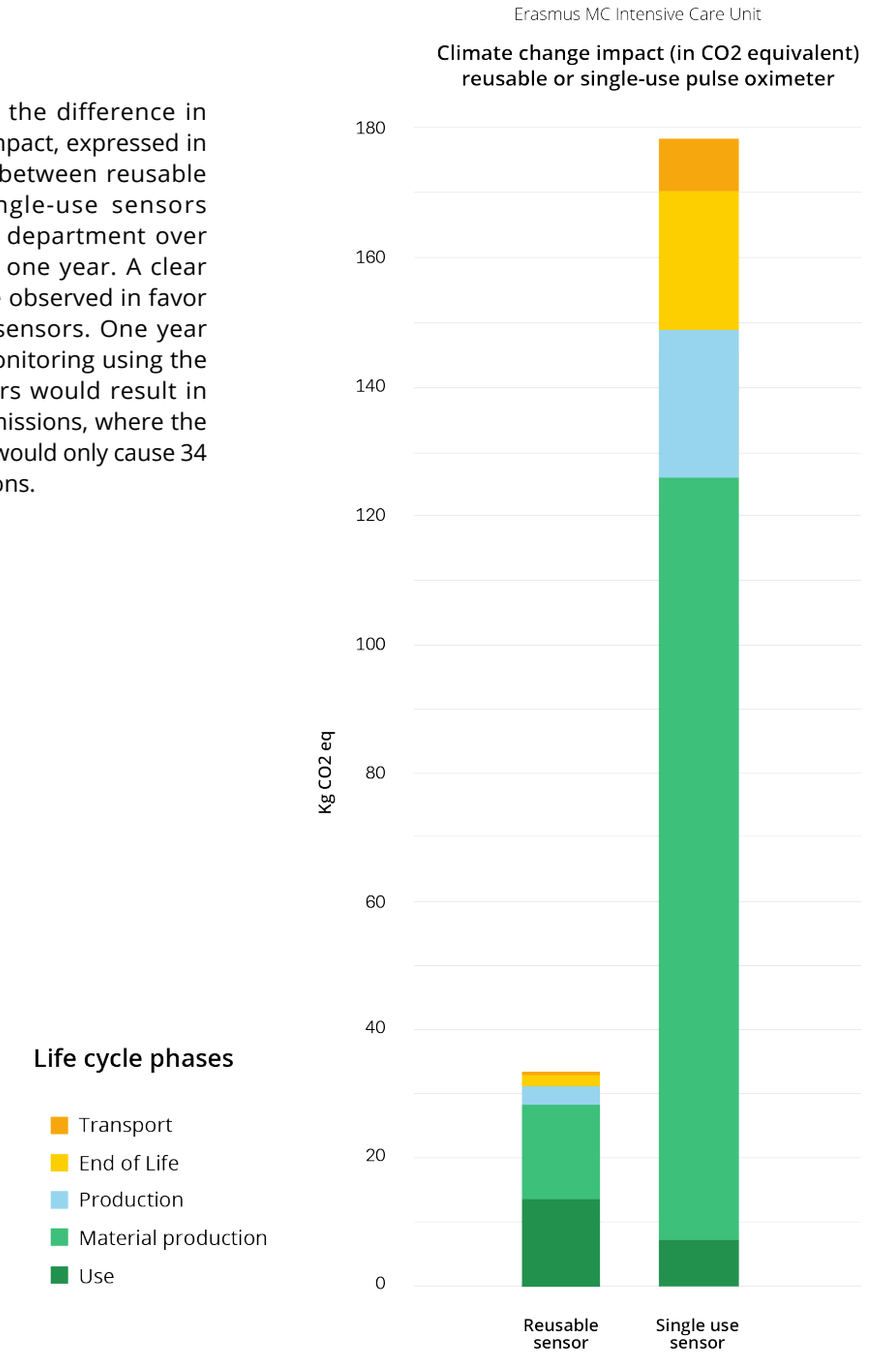


Fig. 18: Climate impact comparison single-use vs reusable sensor. Impact of sensor use for one year on the ICU department of EMC.

Figure 19 shows on how many ICU patients the reusable sensor needs to monitor until it becomes more sustainable than single-use sensors. The break-even point is reached after 11 uses. The estimated average number of uses before a reusable sensor reaches end-of-life in the ICU is 54, comfortably exceeding this threshold. In terms of cost, the financial break-even point is at 15 uses. This means that by the time the reusable sensor becomes more economical, it has already outperformed the single-use option environmentally.

The LCA results illustrate that transitioning from single-use to reusable pulse oximeters, in as many cases as possible, would cause a great reduction in environmental footprint for the EMC.

Erasmus MC Intensive Care Unit

Break-even point reusable and single use pulse oximeter

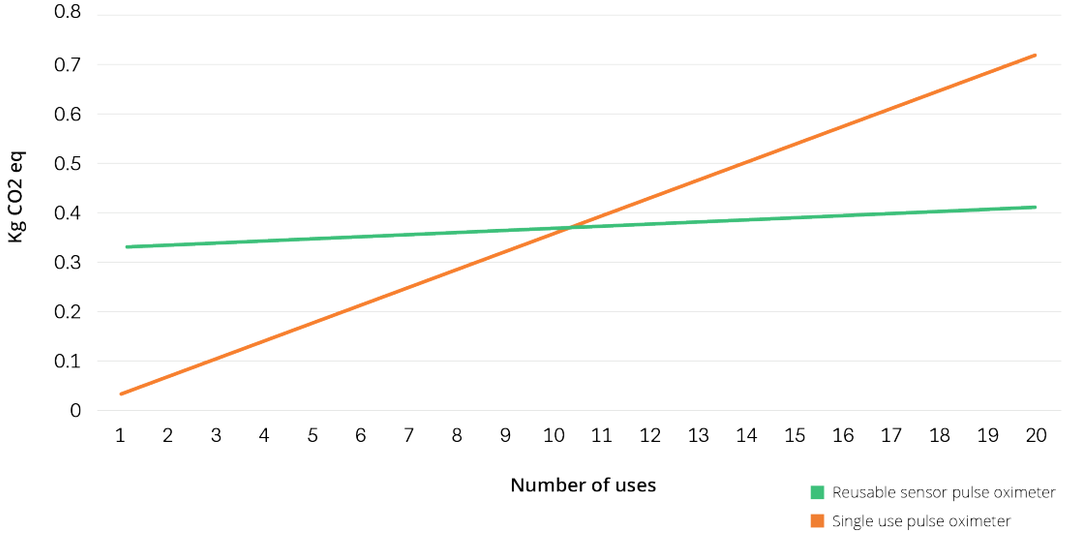


Fig. 19: Break-even point of single-use and reusable oximeters. kgCO2, kilograms of carbon dioxide.

Now that we have proven the environmental advantage of reusable sensors, let's examine this sensor in more detail. Figure 20 shows the reusable finger sleeve sensor's impact per lifecycle stage. The biggest impact factor is the raw material (44%), on which silicone rubber and copper have a big contribution. The assumption of the 1 year lifespan of the sensor impacts this impact factor significantly. Desiging for duribility, in order to extend the lifespan of the sensor would be effective to further lower the reusable sensors impact.

The material determination of the sensors was complicated due to the complex integration of the electronics within the sensors. Therefore, electronic materials were simplified to a copper weight estimation. However, it is known that within these elecronic components, there are more critical materials present aside from copper. Preserving these materials at end-of-life, through recycling (R8) would be valuable.

Closely following the raw material category is the use phase (41%), this phase is built up of lifecycle impact of cleaning wipes, used to clean the sensor after every patient use, and the electricity impact. Improving the cleaning efficiency and lowering the energy use of the sensor would further improve the sensors environmental impact. However, it should be noted, that both these impact factors are already relatively low, as the sensor is cleaned with water instead of alcohol and the sensor only consumes 40 mW. Significantly lowering these impacts may therefore be complex (Appendix B).

TAKEAWAYS

- Transitioning towards reusable pulse oximeter in place of single-use will result in major impact reductions.
- Extending product lifespan and recycling critical materials are effective strategies to improve sustainability in a reusable pulse oximeter redesign.

Climate change impact reusable pulse oximeter, per lifecycle stage

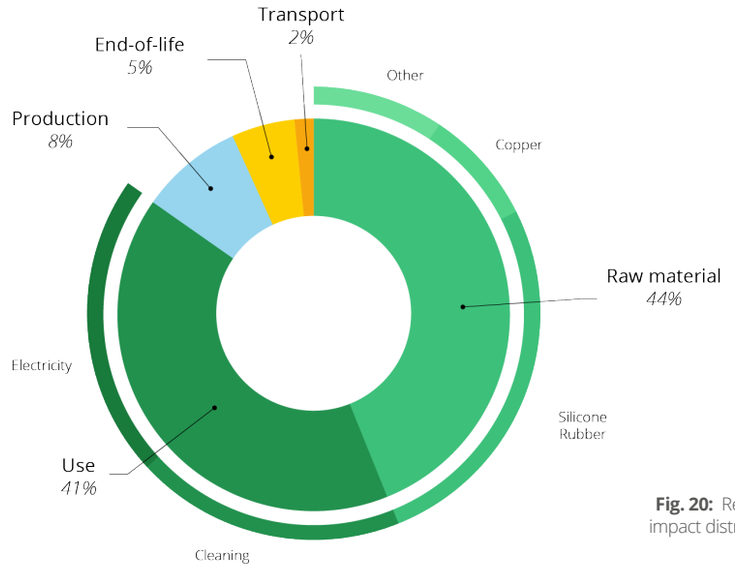


Fig. 20: Reusable oximeters impact distribution across life cycle stages.

4.3 / SENSOR DURABILITY

The LCA concluded that an increased lifespan of the reusable pulse oximeter would significantly decrease the overall climate change impact of the reusable pulse oximeter. In order to design for increased lifespan, the product degradation and breakage of both variations of reusable pulse oximeters was studied.

The Manufacturer and User Facility Device Experience Database (MAUDE), maintained by the FDA, was used to analyze adverse events and device malfunctions (Manufacturer and User Facility Device Experience (MAUDE) Database, z.d.). Reports on Philips pulse oximeters (2021-2024) and Masimo pulse oximeters (2023-2024) were evaluated. Since the MAUDE database only includes American reports, where single-use pulse oximeters are prevalent, there were limited reusable device reports available.

To supplement this research with insights from the Dutch healthcare context, 15 broken reusable pulse oximeters were examined at the Medical Technology department of the EMC. Combining findings from both sources, the primary causes of product degradation were identified and ranked by frequency.

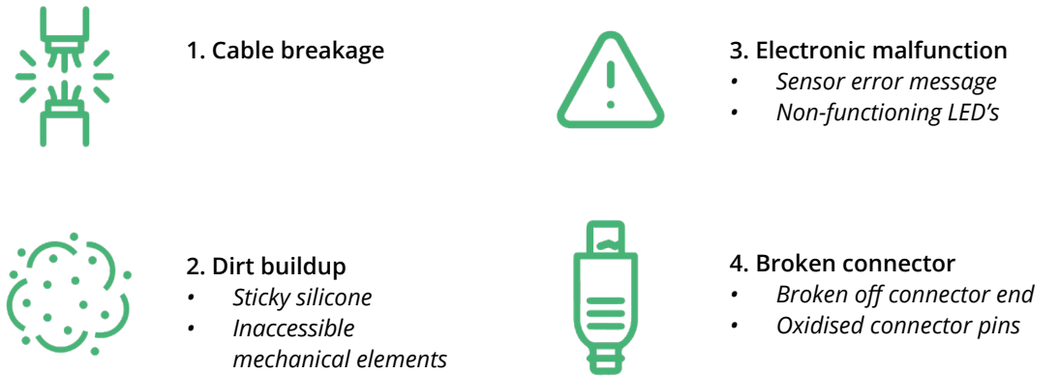


Fig. 21: Main causes for sensor degradation and breakage

Cable breakage

Cable breakage, identified as the most common cause of product failure, is supported by findings in the literature (Crede et al., 2013). Breakage primarily occurs at the connection point between the wire and the device, a critical area where stress accumulates due to the transition from solid to flexible materials (figure 22). Additionally, observations revealed that reusable sensors are often stored in a tangled and disorganized manner, which may worsen stress on this vulnerable connection point.

Fig. 22: Cable breakage at the EMC

Dirt buildup

Dirt buildup on the connectors was another frequently observed issue, potentially contributing to product failure over time or serving as the primary reason for discarding the sensor. Accumulated dirt was found in the product's ridges, which are difficult to clean, and in inaccessible areas around the moving parts when the device was disassembled. These design features should be minimized or eliminated in future product redesigns to improve durability and ease of maintenance.

Fig. 23: Visible dirt buildup after disassembly

TAKEAWAYS

- Increased robustness or repairability of the cable would increase sensor durability.
- Eliminating stress during storage can increase product lifespan.
- Eliminating areas prone to dirt buildup should be considered in product redesign.

4.4 / SENSOR DISASSEMBLY

In the 10R strategy, maintaining product value for as long as possible is essential. For R4-R9 (beyond reuse), ease of disassembly is crucial. For example, repair (R4) requires disassembly to access and replace parts. Optimizing disassembly can make these strategies feasible (Soh et al., 2014). To evaluate disassembly ease, disassembly maps were created (see figure 25). This method combines multiple disassembly strategies, and was created to guide the design process (De Fazio et al., 2021).

The target components for disassembly are the cable and electronics (components 14 and 3), marked by the failure indicator icon. As the cable is the primary cause of product failure (chapter 4.3), repairing it (R4) would effectively extend the sensor's lifespan. The electronics hold value for end-of-life recycling (R8) due to the presence of critical materials like copper, which are profitable to recycle (Critical Raw Materials, z.d.). Both reusable sensors exhibited the same issues, so only one is shown for illustration (see Appendix C for further details).
The disassembly map reveals that components 14 and 3 are located at the bottom, requiring the removal of most other parts, making disassembly complex and time-consuming. This reduces the profitability of critical material recycling. Additionally, the design prevents cable repair, as removing the cable permanently damages other parts, indicated by the non-reusable connector penalty. For a more comprehensive explanation of the setup of a disassembly map, see Appendix C.

Disassembly map findings

TAKEAWAYS

- Product redesign should aim for low disassembly depth of electronics.
- Product redesign should avoid part damage when removing the cable.

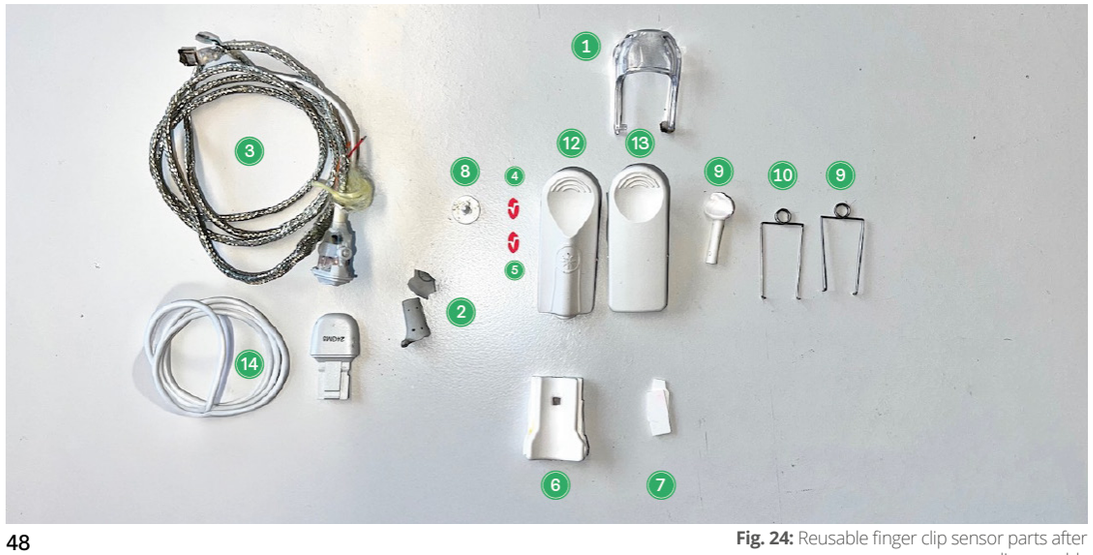
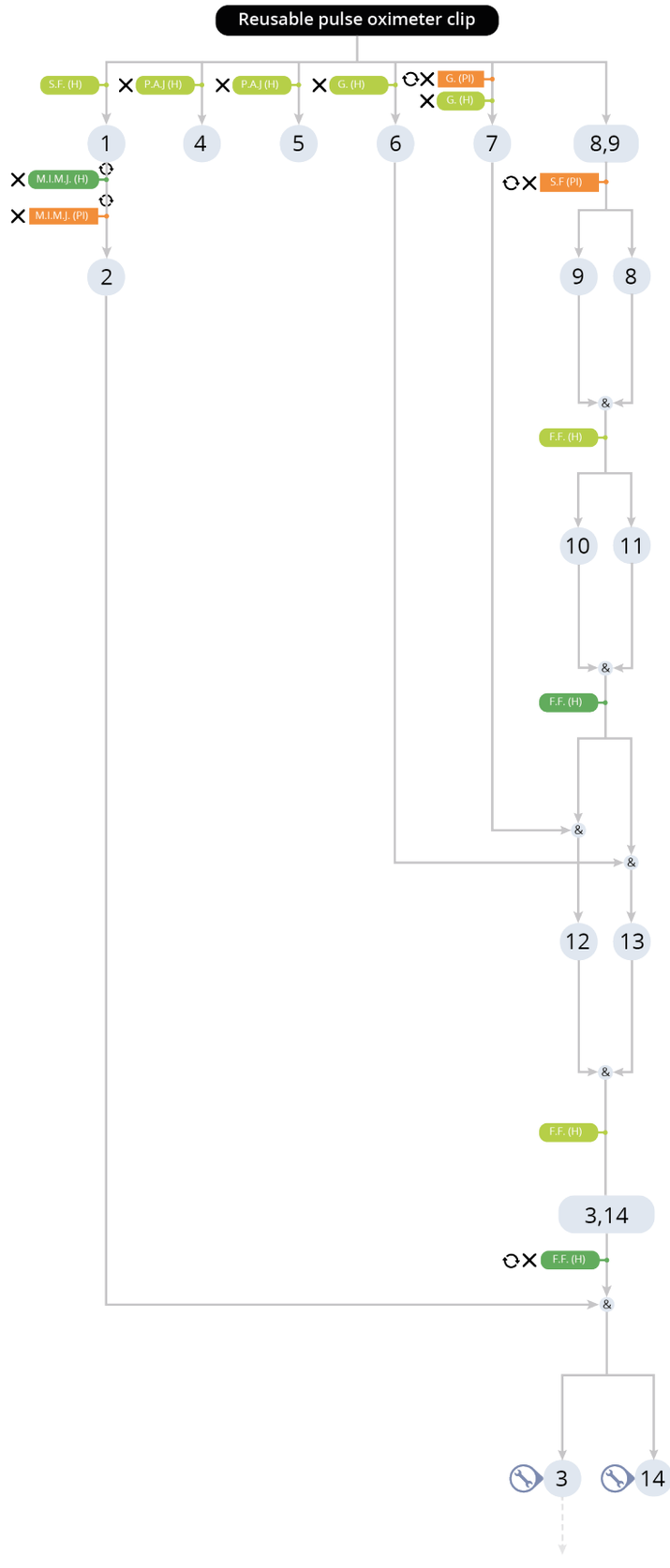


Fig. 24: Reusable finger clip sensor parts after disassembly

Fig. 25: Disassembly map reusable pulse oximeter finger clip



Target components

= Failure indicator

Penalties

= Product manipulation

= Non-reusable connector

Type of tool

(H) = Hand
(PI) = Pliers

Connectors

S.F. = Snap Fit
F.F. = Friction Fit
M.I.M.J. = Multi-part injection molding joint
(P.A.J.) = Peelable adhesive joint
G. = Glue

Disassembly action

Force intensity	Fastener type	Tool	Action block representation
Force < 5N	Snap fit	Hand	
		Spudger	
	Friction fit	Hand	
		Spudger	
5N < Force < 20N	Snap fit	Hand	
		Spudger	
	Friction fit	Hand	
		Spudger	

5

MAPPING THE SYSTEM

The lifecycle of reusable pulse oximeters involves several key phases: purchasing, logistics, reuse, failure, and waste handling, each with its own stakeholders. The Medical Technology (MT) department plays a crucial role in extending device lifespan by testing sensors. However, limited data on product usage and lifespan, along with a lack of traceability, restricts their impact.

Usage patterns vary significantly between departments, with the ICU being the largest contributor to single-use sensor waste. Barriers to reusable adoption exist at both system and product levels, including, lack of awareness on single-use disposal quantities, the incomplete equipment exchanges between departments, inconsistent cleaning responsibilities, low-perfusion patients, sensor instability and patient comfort.

This chapter explores the pulse oximeter life cycle in more detail, focussing on product journey stages within the hospital. It analyzes department-specific usage and identifying key obstacles to adopting reusable sensors.

Methodology
Semi-structured explorative interviews were conducted with key stakeholders in the pulse oximeter product journey, including a Medical Technology advisor, Logistics manager, Purchasing staff member, and healthcare professionals from the Pulmonary Clinic, ICU, OR, and ER. Additionally, an observational study was performed at the Pulmonary Clinic, where a nurse was shadowed for a full day.

To visualize research findings, mapping techniques such as product journey and user journey mapping were applied. These insights were further validated with healthcare staff through a co-understanding meeting, ensuring alignment with real-world practices.

Research questions
1.5 What journey do pulse oximeters currently make through ther entire lifecycle and what barriers and opportunities unveil themselves for the implementation of circular strategies?

1.6 What product and system features form barriers for reusable pulse oximeter use?

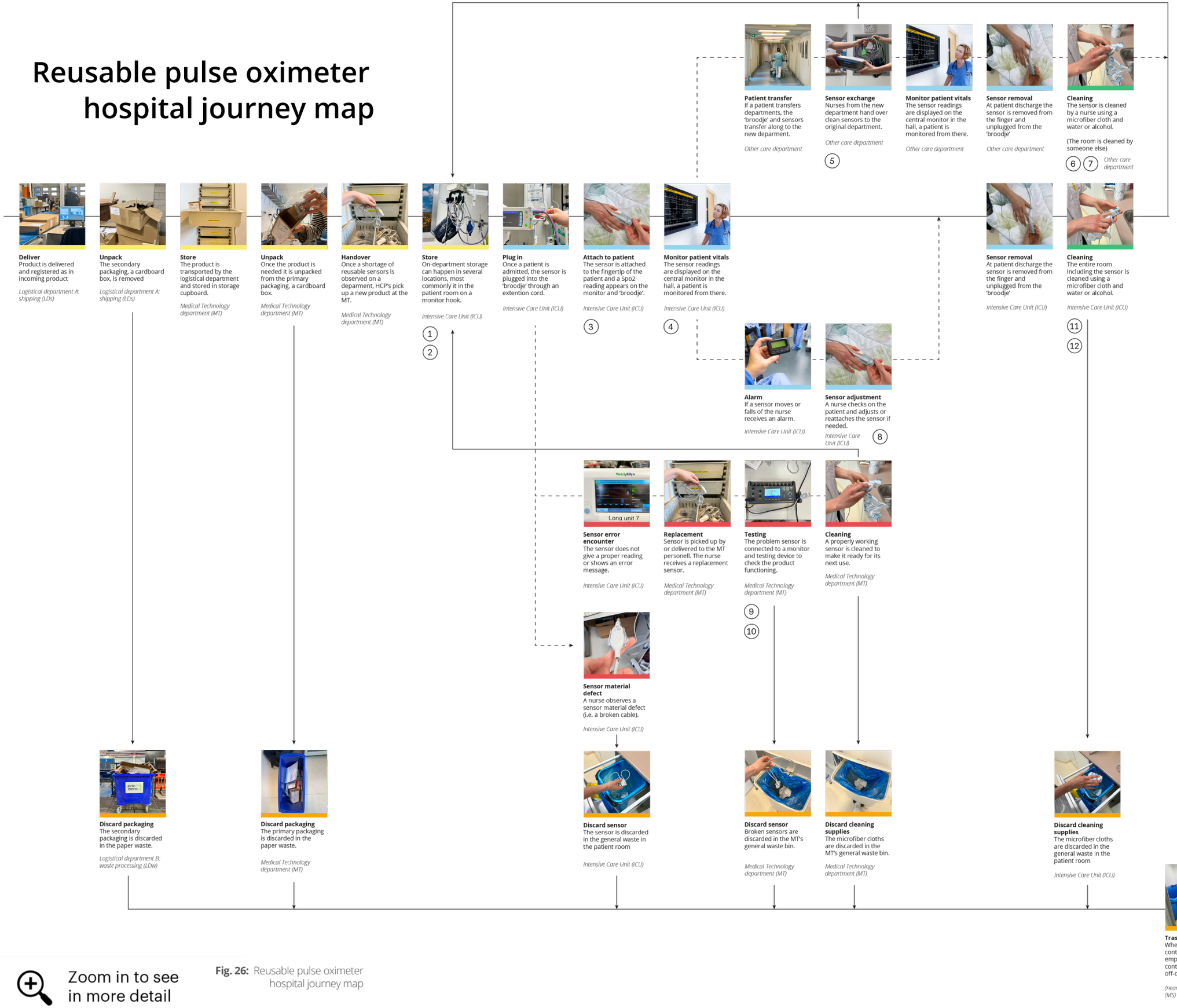
5.1 / PRODUCT JOURNEY MAP

Chapter 4.1 introduced simplified product journey maps for both single-use and reusable pulse oximeters. To identify specific opportunities for circularity within the hospital system and to see what barriers exist to transition to a fully reusable pulse oximeter system, the journey of the reusable pulse oximeter in the ICU context for continuous monitoring was examined in greater detail. This expanded journey map outlines every product interaction, from the sensor's arrival at the hospital to its departure, including its physical location for every interaction, and is visualized on the next page in figure 26.

Insights related to each product journey step are marked with circled numbers, corresponding to the explanations on the right side of the page. Key insights will be explored further in chapter 5.2.

APRIL 2025

Reusable pulse oximeter hospital journey map



Zoom in to see in more detail

Fig. 26: Reusable pulse oximeter hospital journey map

Legend

- Standard journey track
- Possible alternative journey track
- Logistics journey steps
- Patient care journey steps
- Sensor reuse journey steps
- Sensor failure journey steps
- Waste handling journey steps

Insights

1
The reusables sensor is not always present in the patient room, leading to unreliable availability (read 5.2.4)

2
The single use is stored in the storage room, lowering the threshold to use the reusable sensor

3
Some patients refuse the sensor due to discomfort. This complicates the nurse's job (read 5.2.5)

4
Trend based SpO2 changes are more important in HCP decision making than absolute SpO2 measurement values.

5
This exchange is often incomplete or skipped entirely, leading to equipment shortages. (read 5.2.4)

6
If nurses are responsible, equipment cleaning is often skipped (read 5.2.4) .

7
Once the sensors are cleaned they are hung neatly back on the hook.

8
In case of isolated patients, this checkup requires dressing up in PPE, which are discarded afterwards

9
More than half of the sensors are found to be properly working, therefore this step is an essential product life extending step (read 5.1.4)

10
The MT creates a seperated waste stream of broken sensors (read 5.1.4)

11
The amount of wipes used varies greatly per patient room, depending on the contamination of the room.

12
The sensor cleaning protocol is set up by the infection prevention team, and is vastly different from the protocol prescribed by the manufacturer (read 5.2.4)

The product journey map is divided into five phases: logistic, patient care, sensor reuse, sensor failure and waste handling steps. The product purchasing phase was not included in the map, as there is no physical interaction with the product, though this phase triggers the start of the product journey and is therefore of great importance.

Before diving into various patient care scenarios throughout the hospital, it is important to fully understand the journey steps and stakeholder needs surrounding this patient care phase, because this knowledge provides context for interpreting those variations accurately. Consequently, these phases will be explained first.

Product purchasing phase

The first journey phase to detail is the sensor purchasing. The process of selecting what pulse oximeter to purchase for the hospital is a subcomponent of the full monitoring system purchase. This monitoring system also includes the 'broodjes', bedside monitors, central monitors and other vital sensing devices. As this is a purchase surpassing the €143.000 limit, this purchase is done through a European Tender procedure (European Medicines Agency, 2024). In this process a hospital sets up a 'quotation guideline', to which any company can respond with an offer. The step by step process is visualised in figure 27.

The selection of a pulse oximeter is secondary to the main monitoring system. Still some guidelines are set up for making a selection of pulse oximeters. The most important selection criteria for the EMC procurement department is the accuracy of the measurements. This is determined on the basis of academic papers comparing the devices of different brands. Secondly, feedback from product use trials in the hospital, i.e. regarding usability can be deciding factors.

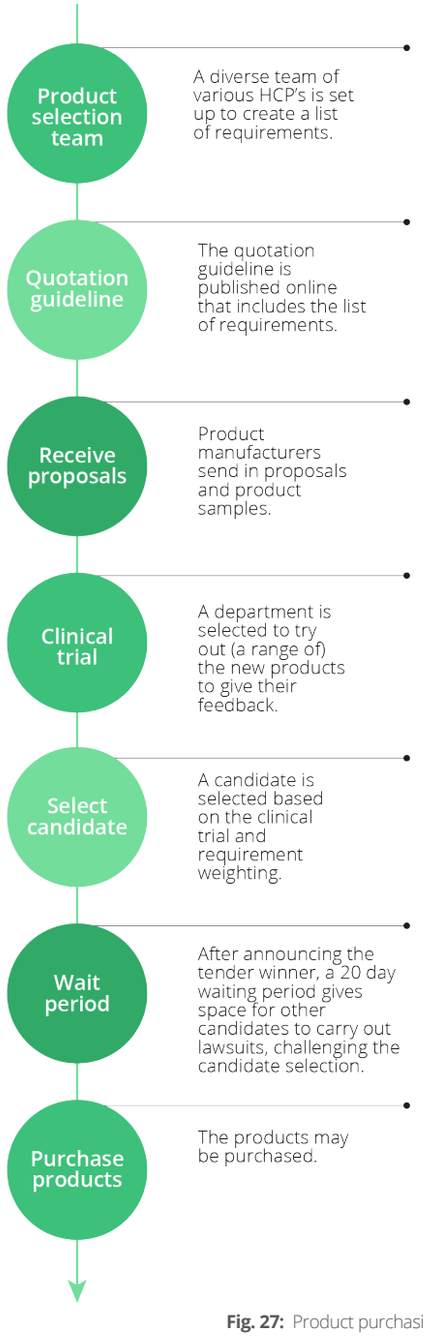


Fig. 27: Product purchasing process

Logistic phase

The EMC has a sophisticated logistics team, responsible for incoming product logistics as well as waste management. When reusable pulse oximeters are purchased, they are transported to the Medical Technology department where they are stored. When in use the reusable pulse oximeters are often stored in the patient rooms, with extras in the decentral storage. This lowers the barrier of reaching for the reusable sensor.

Sensor reuse phase

Cleaning of reusable sensors is an essential step in the reuse cycle. According to hospital protocol, the reusable sensor should be cleaned between every patient (Appendix A). Depending on exposure to bodily fluids or patient isolation status, cleaning involves using either water or a 70% alcohol solution applied with a single-use microfiber cloth. The protocol does not specify the exact cleaning duration or detailed procedural steps. Pulse oximeters are labelled as non-sterile, and are therefore not subject to extensive sterilization procedures.

The cleaning process of cleaning the pulse oximeter takes approximately 60 seconds, informed by observations. Only about 25% of this time (15 seconds) is spend on the cleaning of the reusable pulse oximeter. The other 75% is spent on cleaning the adapter cable, which is also used in case of single-use pulse oximeter use. Therefore, the cleaning of the pulse oximeter is not expected to add a big workload to the cleaning process.

Responsibility for cleaning varies across departments. Some rely on dedicated cleaning staff to sanitize rooms and equipment after patient discharge, while others require nurses to handle the cleaning themselves.

The EMC's protocol is different from the protocol supplied by the manufacturer. The infection prevention department of the hospital can define their own cleaning protocol based on their own research and expertise.

Sensor failure phase

Whenever a nurse faces a technical problem with medical equipment, this is reported to the Medical Technology department (MT). This department is responsible for the servicing and upkeep of medical equipment, to guarantee quality and safety. Proceedings can sometimes involve repair and replacement of components and following test procedures. This last one applies to the reusable pulse oximeter.

Upon arrival at the MT, the sensor is connected to a monitor and tested using the Fluke ProSim 8 (Fluke biomedical, z.d.)(figure 26). This device simulates patient vital signs. If the monitor reading matches the Fluke ProSim 8's set oxygen saturation within a 2% deviation, the sensor is deemed functional and returned to the care department's storage. If the sensor gives an incorrect reading, or no reading, the device is discarded as general waste and new devices are ordered.

Surprisingly, MT testing reveals that the majority of sensors are still in working condition. However, a challenge arises when a device arrives at the MT, there is no way to determine how long it has been in use or whether it is still under warranty. This lack of tracking makes it difficult to diagnose common failure patterns and assess product longevity, limiting opportunities for targeted improvements.

Although medical technicians express a strong interest in repairing pulse oximeters when possible, the current design does not allow for

part replacements or repairs. Nevertheless, MT plays a crucial role in extending product lifespans by identifying functional devices that might otherwise be discarded prematurely.

The medical equipment department is an interesting stakeholder in the reusable pulse oximeter circulation, as they cause many broken reusable pulse oximeters to be collected in one central spot (figure 28). In chapter 3.3 separate collection was expressed as a barrier for circular strategy implementation. But since this logistical system is already largely in place, this forms opportunities for end-of-life strategies.

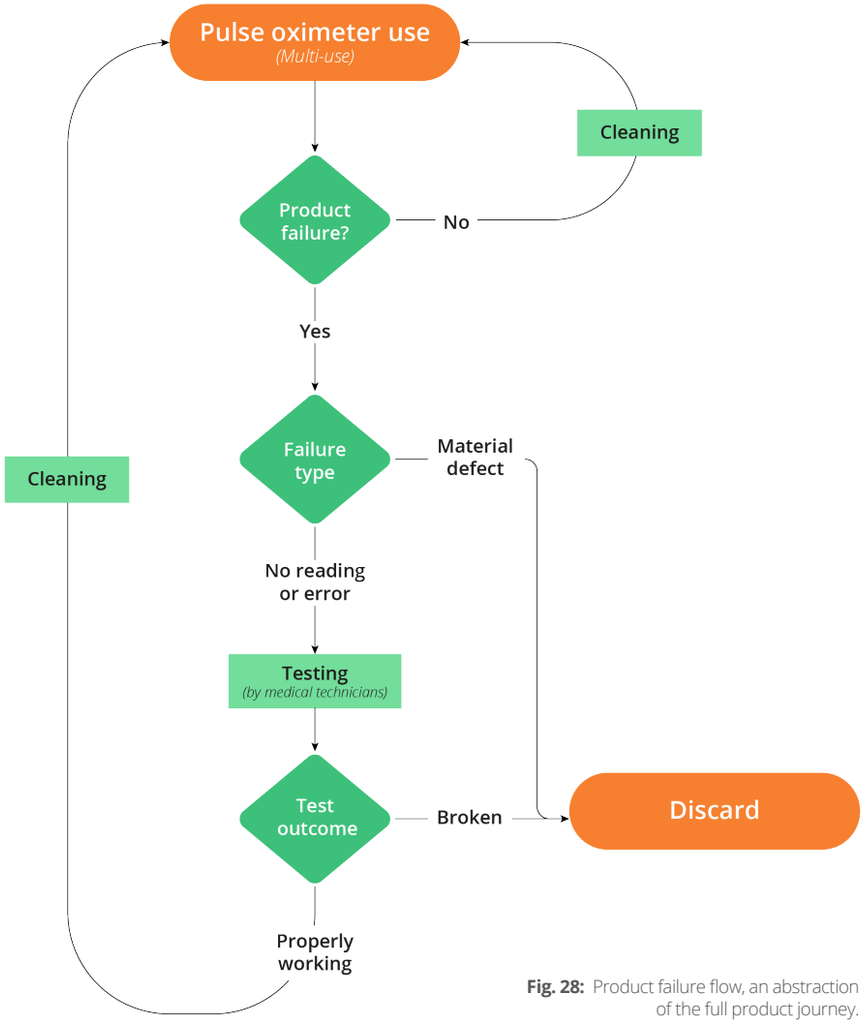


Fig. 28: Product failure flow, an abstraction of the full product journey.

Waste handling phase

The last step of the product journey within the hospital is the waste management. The sensors are discarded in the general waste at the MT department of the patient room. The waste bags are collected in big containers in the waste rooms called 'milieu station'. These containers are transported through logistical halls to the waste management locations. General waste is compacted in a waste compactor and transported to external waste management facilities. Lowering the amount of waste, by eliminating single-use pulse oximeters, saves the hospital money as the waste processing costs €0.22 per kilo and additional personnel costs. This would also free up capacity of the waste management staff to focus on other sustainable initiatives like separation of more waste streams.

TAKEAWAYS

- Accuracy and product usability are determining factors for pulse oximeter purchasing.
- Reusable pulse oximeters are commonly stored in the patient room, to lower the threshold for using them.
- The need to clean the reusable pulse oximeter does not form significant a barrier in choosing the sensor.
- Responsibility for pulse oximeter cleaning can be on nurses or dedicated cleaning staff.
- Protocols can be created and altered according to hospital requirements.
- Lack of data on product lifespan prevents diagnosing common failure patterns and limits opportunities for improvements.
- The existing centralized collection system can create opportunities for end-of-life strategies.
- Decreasing waste quantities saves the hospital money, adding to benefits for reusable sensors.

5.2 / PRODUCT USE PHASE

During the product use phase, the pulse oximeter serves its primary function of monitoring patient vital signs. This phase is simplified in the product journey to its core steps: plugging in the device, attaching the sensor to the patient, and monitoring vital signs. However, the pulse oximeter sensor is used across various hospital departments, each with a unique context.

To understand the barriers to reusable sensor use at the EMC, several departments were evaluated.

These departments were chosen based on their high (absolute) volume of single-use sensor purchases in the hospital's procurement records (figure 29).

The following hospital departments have been mapped:

- Pulmonary Clinic (PC)
- Emergency Room (ER)
- Operating Room (OR)
- Intensive Care Unit (ICU)

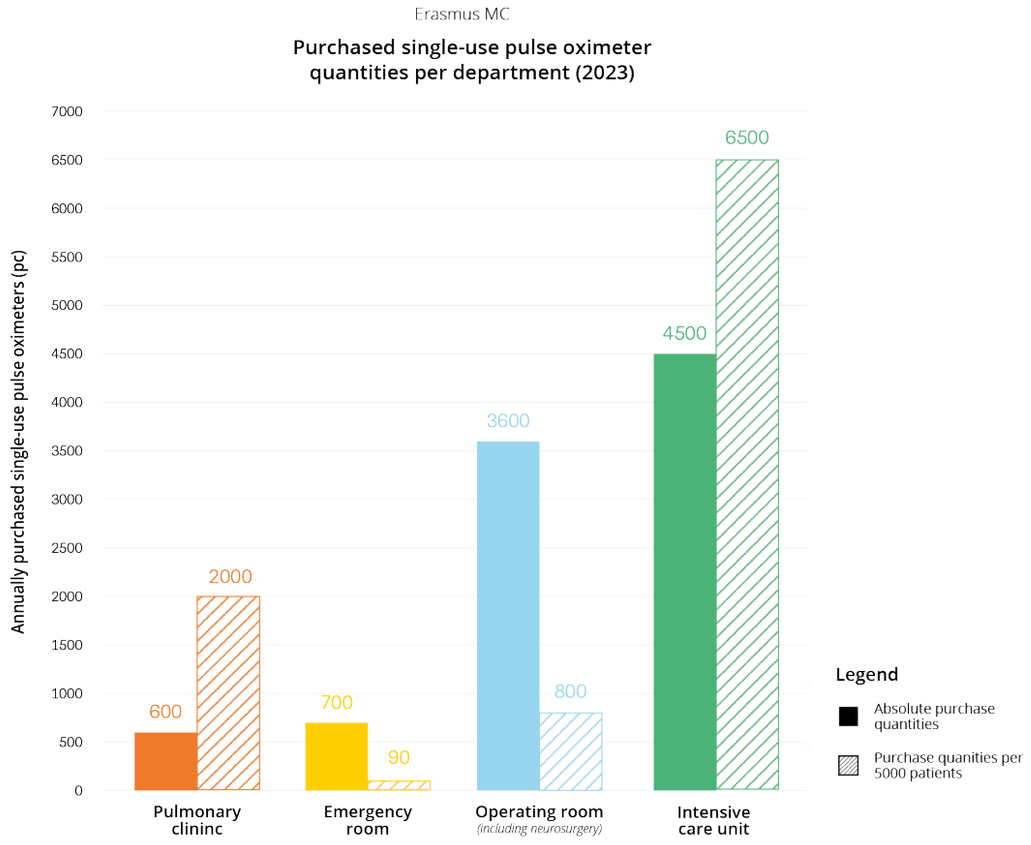


Fig. 29: Purchasing quanities of single-use pulse oximeter per department (2023)

Together these departments are responsible for 97% of the single-use adult pulse oximeters purchased in 2023. The ICU (46%) and OR (37%) have the biggest purchasing quantities. However, per 5000 patients, the OR uses significantly less pulse oximeters than the ICU.

To illustrate how pulse oximeters are used across different hospital departments, insights were translated into interaction maps. These maps also serve as a tool to clearly communicate research findings to hospital staff. In total, five maps were created, two for the pulmonary clinic and one for each of the other three departments. This report presents and discusses three of these maps, as they capture all essential information needed to understand the key findings. The remaining maps can be found in Appendix C.

Figure 30 provides a reading guide for the maps, which are structured as follows:

1. The product use scenario (1a), connected to the movement map (1b) gives factual information about the interaction steps and where these take place.
2. The product experience section compliments the use scenario by giving insight into the experience of the patient and nurse and highlighting pain points within the interaction.
3. The department data section informs on the contribution of the department on the total disposable use and gives an indication of department size and monitoring type.

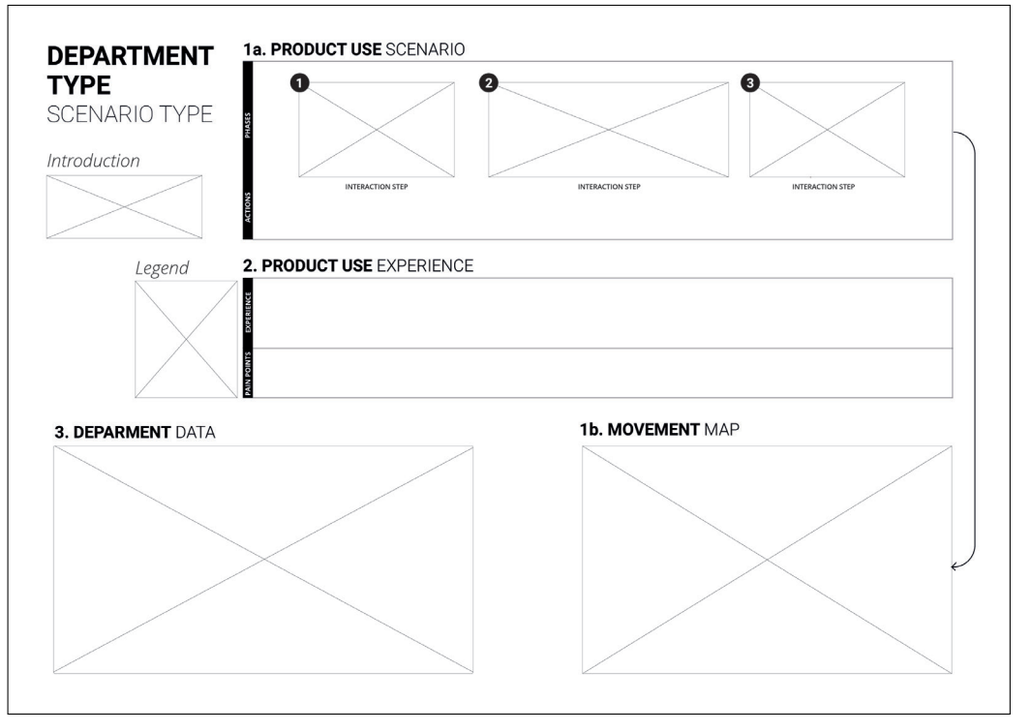


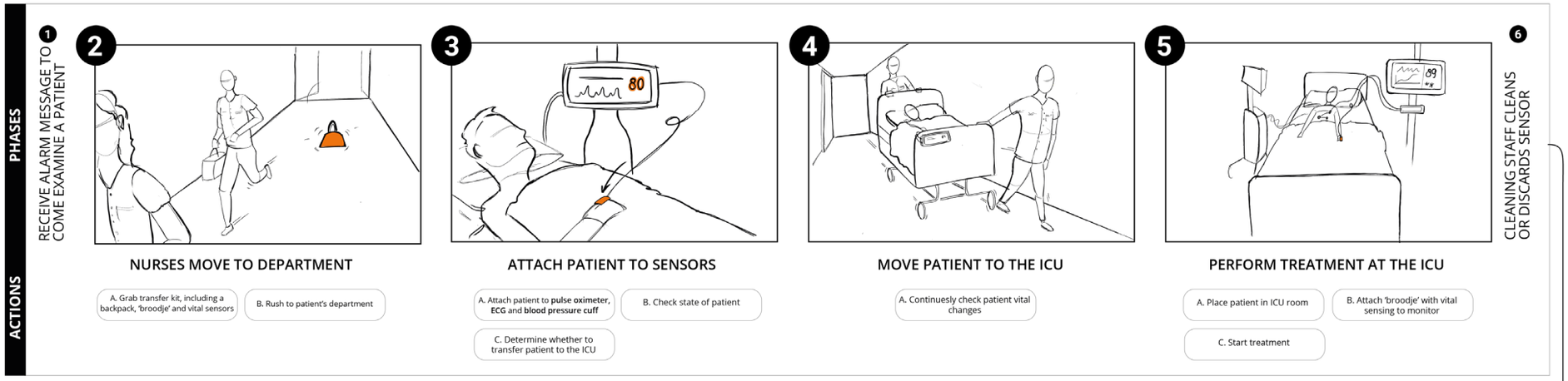
Fig. 30: Reading guide, interaction maps

Zoom in to see in more detail

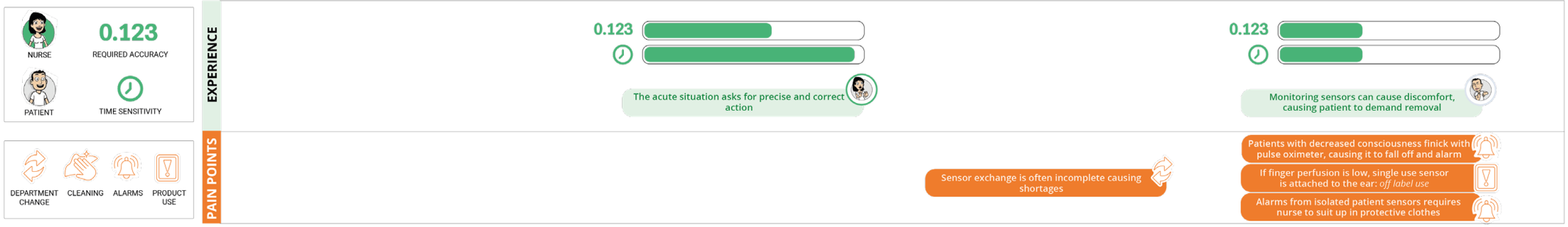
INTENSIVE CARE UNIT
PATIENT PICKUP

ICU patients are always transfered from other departments if patient is in need of more intensive care. This (often) time sensitive transfer is visualised here.

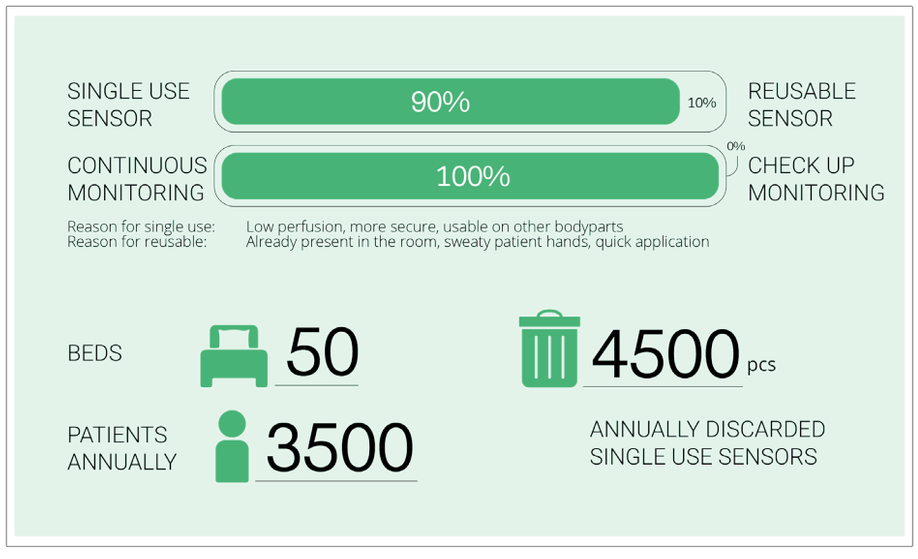
1a. **PRODUCT USE** SCENARIO



2. **PRODUCT USE** EXPERIENCE



3. **INTENSIVE CARE UNIT** DATA



1b. **MOVEMENT** MAP

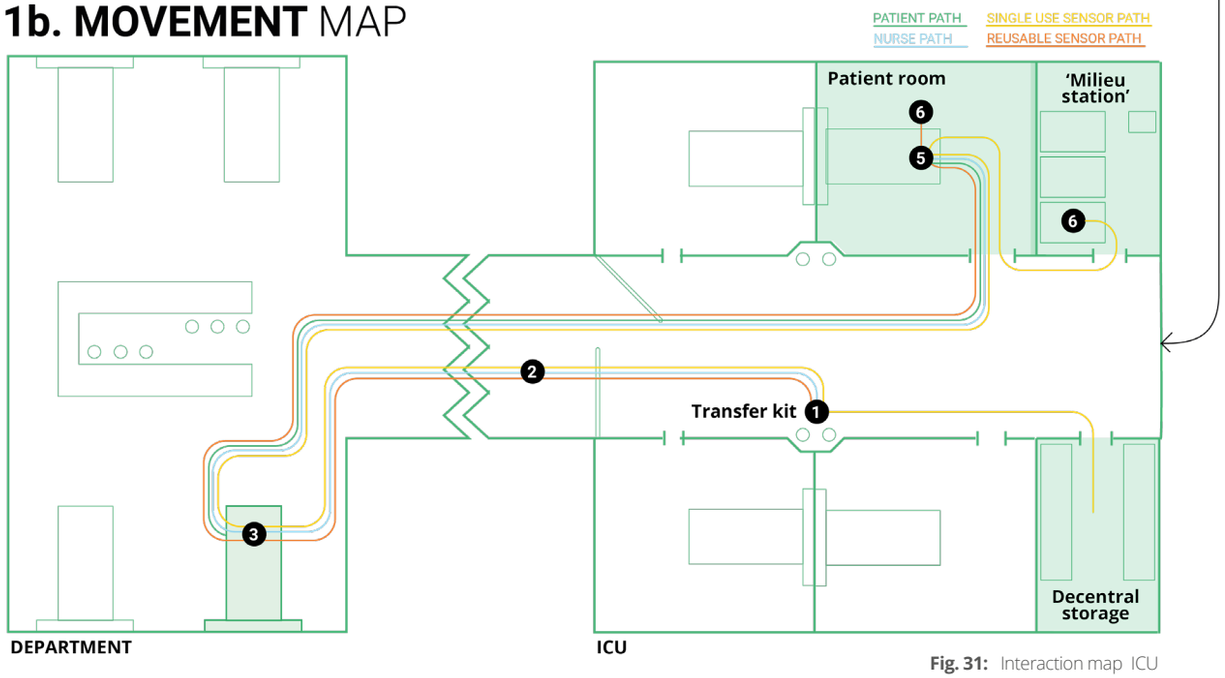


Fig. 31: Interaction map ICU

Zoom in to see in more detail

OPERATING ROOM
FULL PATIENT STAY

Most patients undergoing an operation are sceduled in advanced. They are transfered from their department to the OR shortly before intervention, undergo the operation and recover. This process is visualised here.

1a. **PRODUCT USE** SCENARIO

PHASES

1 MOVE SCEDULED PATIENT TO 'HOLDING'

2 ATTACH PATIENT TO SENSORS

3 TRANSPORT PATIENT WITH SENSORS TO OPERATION ROOM

4 PERFORM OPERATION

5 TRANSPORT PATIETN TO 'VERKOEVER'

6 RECOVER ON THE 'VERKOEVER'

7 NURSE CLEANS SENSORS AFTER PATIENT TRANSFER

ACTIONS

- A. Attach patient to **pulse oximeter, ECG** and **blood pressure cuff**
- B. Check if monitoring values are represenatative
- A. Continuesly check patient vital changes
- A. Patient recovers
- B. Remove sensors from patient
- C. Transfer patient to department

2. **PRODUCT USE** EXPERIENCE

NURSE — 0.123 REQUIRED ACCURACY

PATIENT — TIME SENSITIVITY

DEPARTMENT CHANGE · CLEANING · ALARMS · PRODUCT USE

EXPERIENCE

0.123 | 0.123 | 0.123

Constant accurate readings result in confident anesthetist actions

PAIN POINTS

- Knowing the nurse has to clean the sensor after the operation may result in single use choice
- A nurse's sensor preference can become a new standard for nurse students
- Department sensor exchanges cause reusable shortages, requiring disposable use
- Moving the patient during operation can cause the sensor to fall off

3. **OPERATION ROOM** DATA

SINGLE USE SENSOR 10% | 90% REUSABLE SENSOR

CONTINUOUS MONITORING 100% | 0% CHECK UP MONITORING

Reason for single use: Can't find reusable, low perfusion, no risk of pressure sores (long operation)
Reason for reusable: Standard, staff encouragement

BEDS 26

PATIENTS ANNUALLY 25000

2000 pcs ANNUALLY DISCARDED SINGLE USE SENSORS

1b. **MOVEMENT** MAP

PATIENT PATH · SINGLE USE SENSOR PATH
NURSE PATH · REUSABLE SENSOR PATH

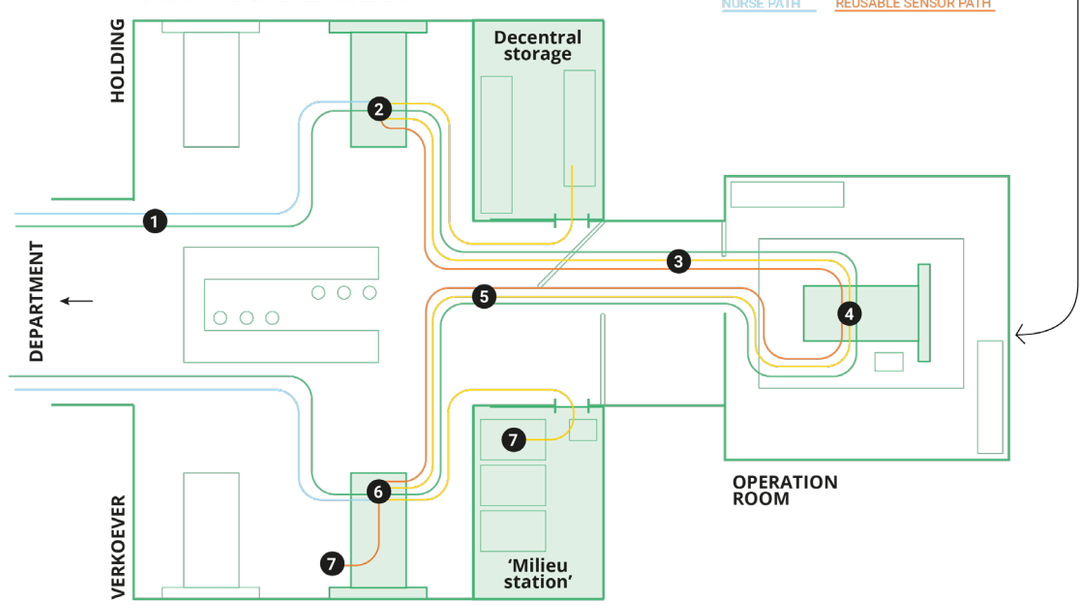


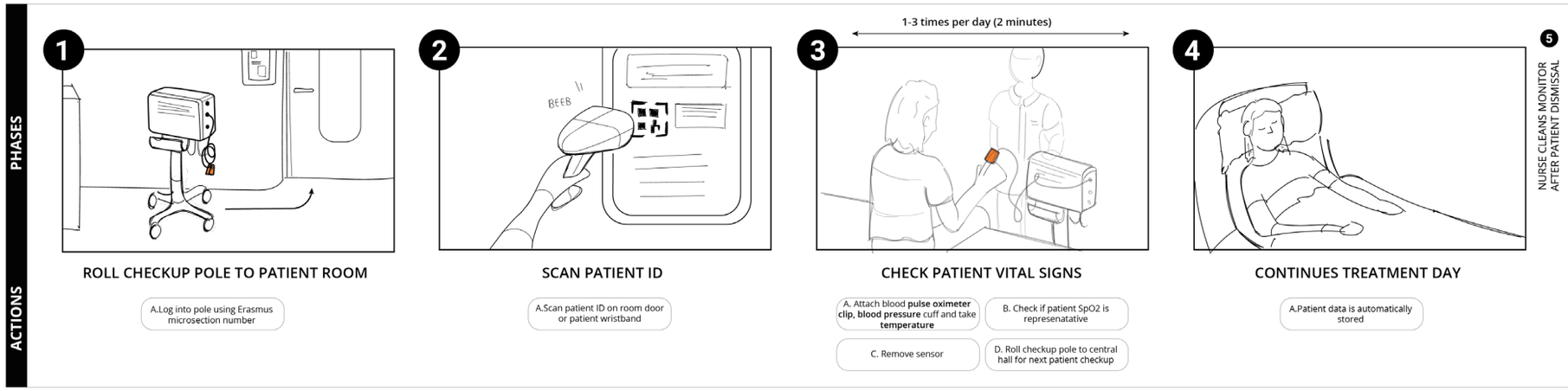
Fig. 32: Interaction map OR

Zoom in to see in more detail

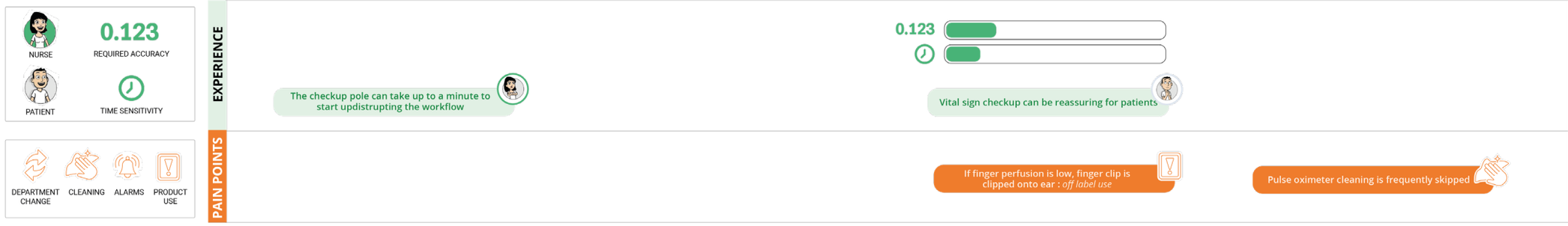
PULMONARY CLINIC
INTERMITTED MONITORING

95% of pulmonary clinic patients gets monitored through intermitted monitoring, getting checked 1 to 3 times daily. This process is visualised here.

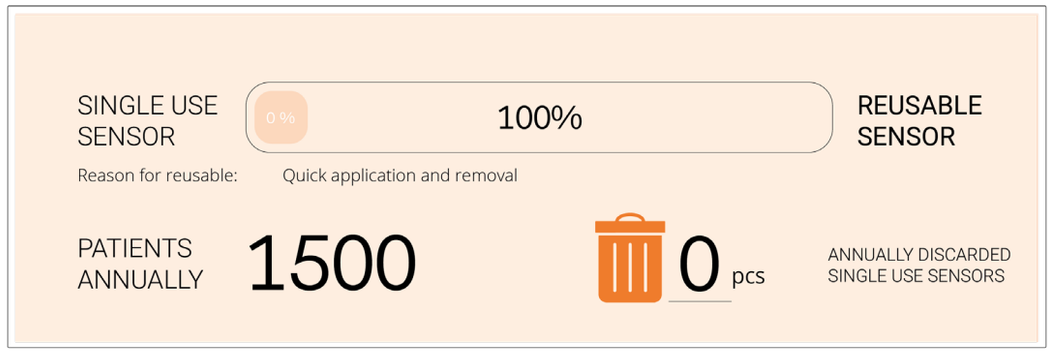
1a. **PRODUCT USE** SCENARIO



2. **PRODUCT USE** EXPERIENCE



3. **PULMONARY CLINIC** INTERMITTED MONITORING DATA



1b. **MOVEMENT** MAP

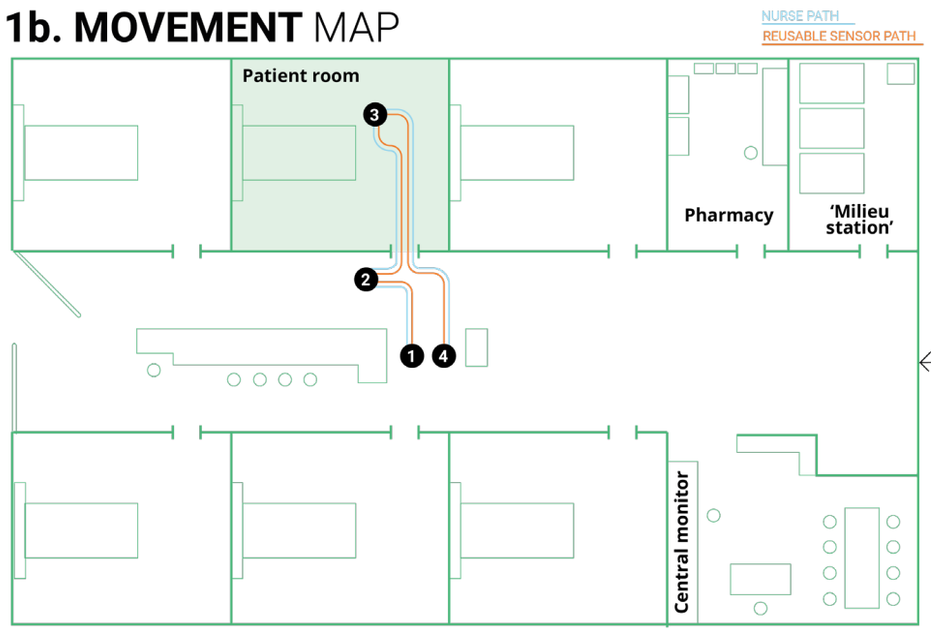


Fig. 33: Interaction map PC

Systemic barriers for reusable pulse oximeter use

By studying the different departmental scenarios and the product journey map, a range of barriers to reusable pulse oximeter use was identified. These barriers can be categorized into systemic and product-level challenges.

Continuous vs intermitted monitoring
The biggest influence on the decision to use an single-use pulse oximeter as opposed to a reusable pulse version, is the type of monitoring performed. As previously explained (Chapter 2.2), there are two types of monitoring; intermitted and continuous monitoring. Intermitted monitoring checkups, as can be seen in the pulmonary clinic map, are always performed using a reusable pulse oximeter, therefore not contributing to single-use disposal quantities. The reusable monitor is faster to apply than the single-use sensor and does not have many downsides when used for this short period of time (20-60 seconds). In contrast, continuous monitoring is performed with both single-use as reusable pulse oximeters. The reason for single-use sensors in some continuous monitoring settings, is explained further in 'Product level barriers of reusable pulse oximeter use'.

As all of the single-use disposal is a consequence of continuous monitoring, intermitted monitoring scenarios can be left out the problem scope.

Unawareness of single-use disposal quantities
Patient care departments for this study were selected based on procurement data that highlighted the quantities of single-use pulse oximeters they utilized annually. Staff members in these departments expressed surprise when confronted with the sheer volume of devices their teams consumed, revealing a significant gap between their perceptions and the actual usage data.

> **"2,000 per year?* Oh, I didn't expect that—I thought it would be much less."**
> – ER team manager
> **2000 sensors include neonate sensors*

This unawareness suggests a disconnect that can hinder efforts to address product and system issues. Staff are less likely to take action to initiate change when the scale and origin of the problem is not fully understood. Raising awareness may serve as a first step toward encouraging initiatives to transition to reusable pulse oximeter use.

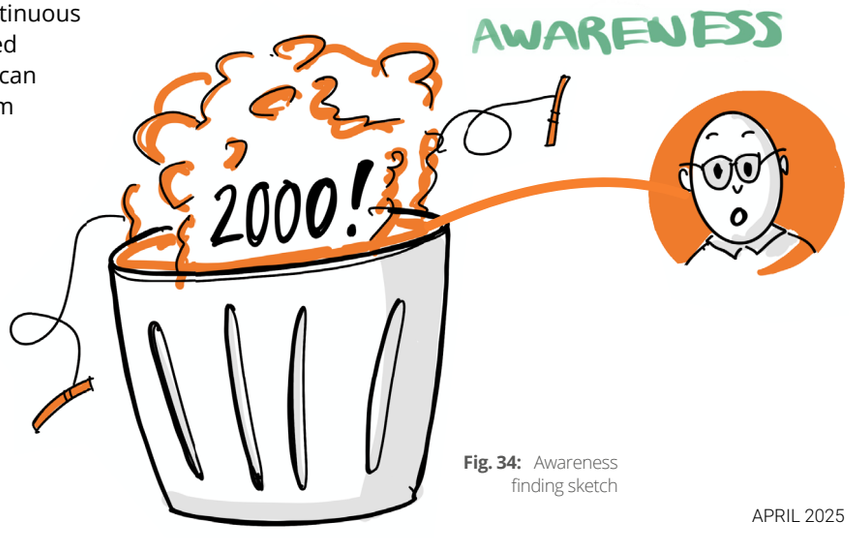


Fig. 34: Awareness finding sketch

Department transfers and equipment exchange
An important consideration when analyzing department scenarios is that departments do not stand alone. Patients frequently move between departments, especially the ER, ICU, and OR, bringing medical devices along. As a result, a reusable sensor starting in the ICU can end up in another department. This interaction reveals a key pain point: the protocol for equipment exchange during department transfers.

According to the protocol, nurses from both departments must exchange sensors and other equipment to maintain balanced quantities. However, during rushed transfers, this exchange is often incomplete or overlooked. This leads to some departments accumulating excess pulse oximeters while others face shortages.

The uncertainty about the availability of reusable sensors when needed may drive nurses to prefer single-use sensors, which are always stocked and readily accessible. Additionally, the lack of product location traceability makes it difficult to identify departments with surplus or shortages. This can result in unnecessary sensor purchases, leading to wasted resources and increased costs.

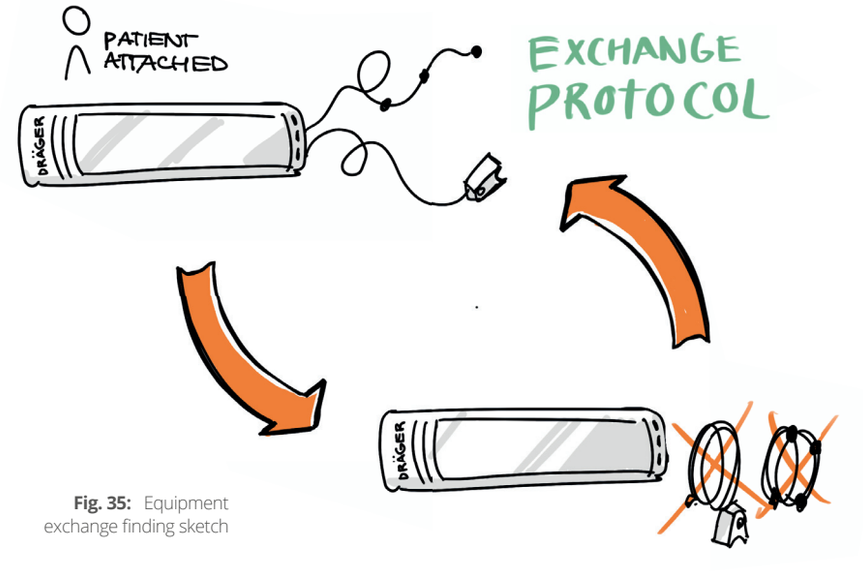


Fig. 35: Equipment exchange finding sketch

Inconsistent cleaning responsibilities
The interaction maps reveal that cleaning responsibilities for pulse oximeter sensors vary across hospital departments. In the ICU, cleaning staff are responsible for sanitizing the room and all equipment after patient discharge. In the PC and OR, while cleaning staff sanitize the room, the equipment is the responsibility of the nursing staff. In the ER, cleaning staff clean the rooms, but most equipment is transferred with the patient to another department, shifting the cleaning responsibility accordingly.

This inconsistency in cleaning responsibilities presents a barrier to the adoption of reusable pulse oximeters. For cleaning staff, cleaning is a primary responsibility, ensuring that ICU equipment is thoroughly cleaned between patients according to protocol. In contrast, in the PC and OR, equipment is only cleaned if it appears visibly dirty and if nurses have the time to do so. This irregular cleaning practice increases the risk of contamination and decreases confidence in the hygiene of reusable devices.

The perception of whether this lack of consistent cleaning is problematic varies across hospital staff. The infection prevention team, responsible for establishing cleaning protocols, views thorough cleaning as essential and believes protocols should be followed strictly. In contrast, many nurses do not perceive incomplete cleaning as a significant risk to infection control or patient care quality:

> **"I can't imagine that any colleague would concern themselves with that."**
> (about cleaning during a patient's stay)
> – ICU nurse

This misalignment of perceptions between departments and professional roles further complicates the reliable implementation of reusable pulse oximeters. Without standardized cleaning procedures and clearer responsibilities, there is a risk that reusable sensors will not be consistently cleaned, undermining their safety and usability. Aligning these differing perspectives and establishing clear protocols is crucial to overcoming this systemic barrier.

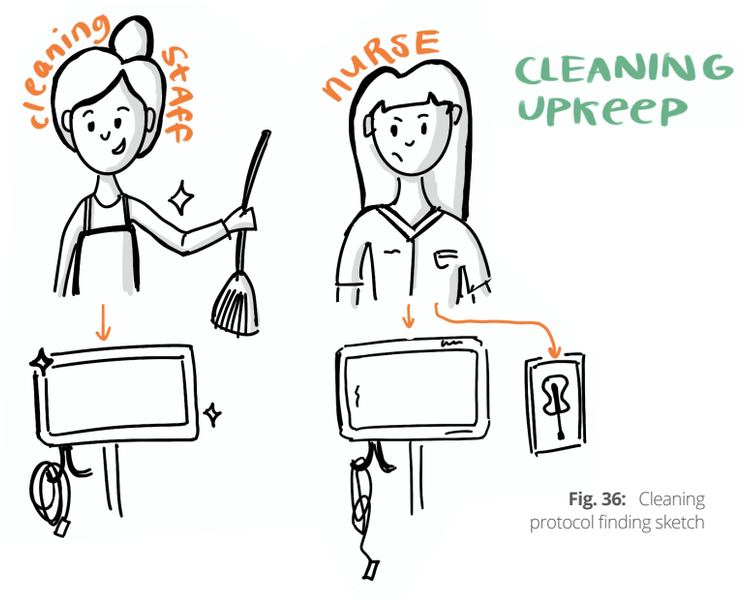


Fig. 36: Cleaning protocol finding sketch

Product level barriers for reusable pulse oximeter use

Low-perfusion
Many critically ill patients experience low perfusion, reducing blood flow to extremities like fingertips. This condition is particularly common in the ICU, where approximately 40% of patients are affected. In these cases, the only available reusable option an the ear clip sensor. However, due to its limited availability, tendency to fall off, and potential to cause pressure sores, nurses rarely choose this option. As a result, when low perfusion is present, a single-use pulse oximeter is typically used and repositioned on other body parts.

However, this practice carries risk. Even though the measurements received from the repositioned single-use pulse oximeter are experienced as reliable by nurses, research suggests otherwise

> **If fingers are not suitable, alternative locations must be used. It doesn't matter where, as long as infrared light can pass through. These can include various areas like the ear, nose, or lip."**
> – ICU nurse

(Seeley et al., 2015). Off-label probe placements, in the lower ranges of oxygen saturation, result in substantially overestimates oxygen saturation. While in higher oxygen saturation ranges, the oxygen saturation is underestimated. Off-label sensor placement is therefore likely to fail to alert staff of patients who are desaturated and in need of intervention most (Hlavin et al., 2024).

Paradoxically, purchasing decisions for pulse oximeters are heavily influenced by the scientific accuracy of the selected sensors. However, the frequent off-label use of these sensors undermines their reported accuracy. Addressing this misalignment through better education on the risks of off-label use and increasing the stock of reusable ear clip sensors could promote safer practices and greater adoption of reusable alternatives.

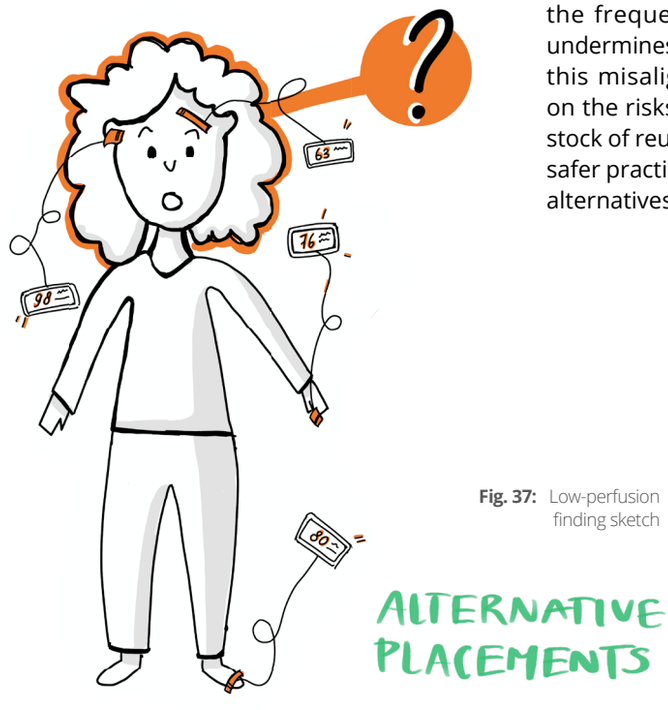


Fig. 37: Low-perfusion finding sketch

Sensor instability and alarm fatigue
When a pulse oximeter falls off or fails to provide a reading, nurses receive an alarm notification. Frequent unnecessary alarms contribute to alarm fatigue, a phenomenon where repeated false alarms desensitize medical staff, reducing their trust in alarm systems (Lansdowne et al., 2016). Responding to these alarms also disrupts nurses' workflows, further straining their already high workloads (Lewandowska et al., 2020).

Due to its heavier design, the reusable pulse oximeter is more prone to falling off or shifting compared to the single-use version. This increased likelihood of displacement leads to more nuisance alarms and encourages nurses to favor single-use sensors for their reliability.
In addition to sensor displacement, motion artifacts pose another challenge. Motion artifacts are inaccuracies in sensor readings caused by slight movements between the sensor and the patient's skin (Sinex, 1999). These artifacts can cause frequent inaccurate readings and delay the detection of hypoxia. The reusable device, for the same reason as fall off occurrence, has a higher frequency of motion artifact.

Reduced trust in reusable sensors often prompts nurses to verify measurements through blood gas assessments, where blood is drawn and analyzed in a laboratory. Each blood gas test produces approximately 99 g CO_2 equivalent emissions, significantly higher than the 36 g CO_2 equivalent emissions associated with a single-use sensor (McAlister et al., 2020).

In conclusion, improving the stability of the reusable sensor is crucial to enhancing usability, reducing alarm fatigue, and maintaining its environmental benefits.

Patient comfort
Patient comfort is a significant product-level barrier to adopting reusable pulse oximeters, particularly for patients requiring continuous monitoring.

One primary issue, especially with the reusable finger sleeve sensor, is its silicone rubber material, which fully encases the finger. This design traps heat and moisture, causing sweating and discomfort during prolonged use. Additionally, the rigid structure may be too tight for patients with larger fingers, leading to pinching and pressure points.

Another concern is the weight and bulkiness of the reusable sensor, which limits hand mobility. This makes it less comfortable than the small, lightweight single-use sensor, particularly for patients monitored over long periods. As a result, healthcare staff often prefer the single-use option to maintain patient comfort.

Addressing these comfort issues through design improvements could enhance patient experience and encourage greater adoption of reusable sensors.

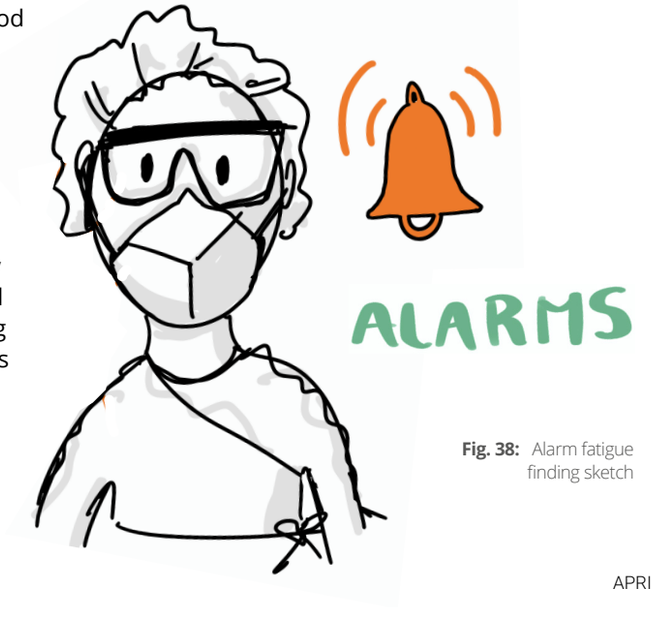


Fig. 38: Alarm fatigue finding sketch

TAKEAWAYS

Systemic barriers for reusable pulse oximeter use include:
- Continuous monitoring.
- Unawareness of single-use disposal quantities.
- Department transfers and equipment exchange.
- Inconsistent cleaning responsibilities.

Product level barriers include:
- Low perfusion patient groups.
- Sensor instability and alarm fatigue.
- Patient comfort.

6

PROBLEM DEFINITION AND DESIGN DIRECTION

A timeline of interventions for sustainable pulse oximetry has been identified, with the redesign of the fingertip pulse oximeter as the primary focus of this project. The aim is to reduce hospital dependence on single-use sensors by enhancing sensor stability, patient comfort, and traceability while supporting circular design through extended product lifespan and circular business models.

This chapter concludes the research phase of this project, and introduces the design phase.

6.1 / DESIGN INTERVENTIONS

The current market landscape and future sustainable developments within the pulse oximeter industry have been identified, along with an assessment of the sustainability of existing pulse oximeters at both the product and system levels.

Based on this analysis, nine recommended changes and interventions have been outlined and can be represented on a timeline (Figure 39).

Interventions 'Now'

The interventions positioned in the 'Now' timeline block focus on addressing the identified systemic barriers to reusable pulse oximeter use. By overcoming or improving these barriers within the current context, the EMC can reduce the environmental impact of pulse oximetry without relying on product redesigns or external parties.

In addition to reducing environmental impact, addressing these systemic issues, specifically 'Educating about off-label use' and 'Changing the cleaning protocol', will also enhance the quality of patient care provided by the EMC.

Figure 40 on the next page explains the four interventions for 'now'. A few solution directions are proposed, but the final solutions should be defined in partnership with HCP's.

Fig. 39: Changes and interventions to implement now, in the future of within the far future.

Patient safety

Awareness about

Off-Label Use

Single use pulse oximeters are commonly used on off-label locations. This can serverely lower the measurement accuracy, putting patient safety at risk.

Solution directions
- Educational training for nurses.
- Purchase additional reusable low-perfuction pulse oximeters.

Awareness

Awareness about

Single Use Disposal

Department leads are unaware about the high quantities of single use pulse oximeters that are purchased and disposed of yearly. This unawareness can lead to a lack of action.

Solution directions
- Communicate purchasing data to department green teams.

Protocol

Improving the

Equipment Exchange

During patient department transfers, equipment should also be exchanged. This exchange is often incomplete, leading to reusable pulse oximeter shortages in one department and surplus in another.

Solution directions
- End of the month equipment redistribution

Protocol

Improving the

Cleaning Procedure

When nurses are responsible, pulse oximeter cleaning in between every patient use is frequently skipped. If the sensor is not visibily dirty nurses don't view the lack of cleaning as a risk.

The infection prevention department wants cleaning protocols to be properly executed to lower infection risks.

Solution directions
- Make dedicated cleaning staff responsible for equipment cleaning after patient discharge, on more departments

Fig. 40: Interventions 'now'

Interventions 'Future'

The interventions positioned in the 'Future' timeline are changes and interventions, that should be ready to implement within 10 years. 'Introduce circular business models' and 'Implement centralized cleaning and maintenance cycles' refer to the identified, ongoing developments (chapter 3.5) that will evolve in the coming years. The other two are recommended changes, based on identified barriers and opportunities.

Ongoing development

Adopt a

Circular Business Model

In order to combine profitability and sustainability Philips should adapt their business model from linear to circular, further advancing in product-as-a-service and pay-per-use among others.

Ongoing development

Implement the

Centralized Cleaning and Maintenance cycles

Philips should further evolve their sensor reprocessing cycles. Where the sensors are cleaned and maintained within the hospital or by an external party, lowering the cleaning burden on nurses and ensuring proper product functioning.

End-of-life

Maintain value through

Repair and Recycling

A seperate collection flow of reusable pulse oximeters should retain more product value of the sensors at end-of-life through repair and recycling.

Product Redesign

Create a

Fingertip Sensor Redesign

Improve the current reusable finger tip pulse oximeter, tailored for continuous monitoring. By tackling the product and system level barriers, this redesign should replace the single-use pulse oximeter, lowering the environmental footprint and increasing usability.

Read 6.2 for more details.

Fig. 41: Interventions 'Future'

Interventions ‘Far future’

The intervention positioned in the “Far future” timeline is a change expected to be ready for implementation within 25 years. At the product level, a key barrier identified is the lack of reusable low-perfusion pulse oximeters with satisfactory usability. This challenge is particularly significant in the ICU, where a large patient group requires these specialized sensors.

Due to the technical complexity of developing low-perfusion sensors, the research, design, and testing phases require a longer timeframe. As a result, this intervention is designated for the far future.

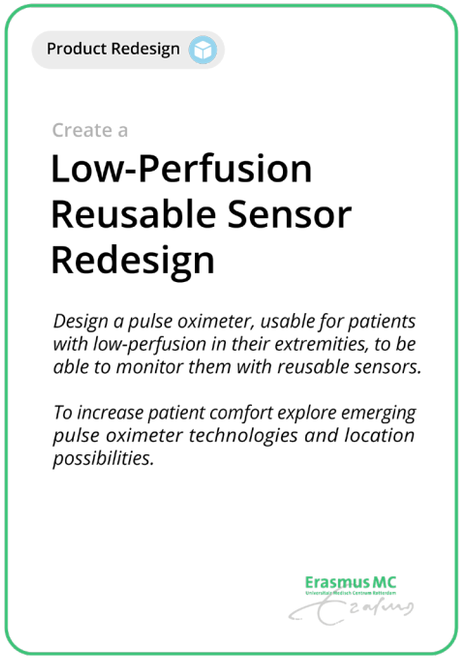


Fig. 42: Intervention ‘Far future’

6.2 / DESIGN DIRECTION

The main design direction for this project is to create a future-ready reusable fingertip sensor (within 10 years) to replace single-use pulse oximeter sensors in as many scenarios as possible, thereby reducing the environmental impact of pulse oximetry. This will be achieved by addressing key product-level barriers, such as improving sensor stability, reducing nuisance alarms, and increasing patient comfort, and tackling the systemic barrier of product loss during department transfers by enhancing product traceability throughout the hospital.

To support the circular design principle of keeping materials and products in use for as long as possible (Chapter 3.1), the sensor redesign will prioritize extending product lifespan by preventing or enabling the repair of common sensor degradation issues (Chapter 4.3).

Additionally, the redesign will accommodate future changes and interventions. This includes adapting the product to be able to adopt to circular business models and the implementation of centralized cleaning and maintenance cycles by enabling lifecycle data storage (Chapter 3.5). The design will also consider the recyclability of valuable materials to further reduce waste.

It is important to recognize that hospital departments are interconnected, as sensors circulate across various clinical contexts. Therefore, the sensor design must be versatile enough to function effectively across multiple departments.

A secondary focus of the project will address the ‘Now’ interventions. Rather than developing specific solutions for current issues, the aim is to raise awareness among healthcare professionals (HCPs) from different disciplines. By fostering understanding and engagement, these professionals can take action on the identified challenges and continue the work beyond the conclusion of this graduation project.

The Design Goal

“Design a next generation fingertip pulse oximeter sensor that reduces reliance on single-use devices by improving sensor stability, patient comfort, and traceability across hospital departments, and supporting circular design through extended product lifespan, material recycling and enabling circular business models.”

7

‘NOW’ INTERVENTIONS

Based on the four key now-interventions framed in chapter 6, a multi-stakeholder co-creation session was set up. The session aimed to share research findings, gather diverse perspectives, and collaboratively explore solution directions. For three of the now-interventions, the most promising solution directions wer identified. Inconsistent cleaning could be improved by shifting cleaning tasks to trained facility staff. Market research into a safer low-perfusion sensors could limit the amount of off-label use of the single-use pulse oximeter. Lastly, shortages in sensor stock due to incomplete equipment exchange in patient transfers could be solved through a monthly sensor redistribution by care assistants.

Methodology

To ideate these solution directions an infection prevention staff member, procurement staff member, and care department lead were invited to participate in a multi-stakeholder co-creation session. This session was guided by materials, being the simplified interaction maps, problem cards and solution direction cards. Additionally the single-use and reusable pulse oximeters were present to inspire conversation. The session was recorded and analysed to summarize the key findings.

Research questions

2.1 How can we implement multi-stakeholder co-creation in the hospital setting?

2.2 What interventions could lower the systemic barriers for reusable pulse oximeter use in the current hospital system?

7.1 / CO-CREATION SETUP

Chapter 6 identified four key interventions to support the adoption of reusable pulse oximeters: ‘Improving the cleaning procedure’, ‘Limiting off-label use’, ‘Improving equipment exchange’ and ‘Creating awareness about single-use disposal’. To begin addressing these systemic barriers, a co-creation session was held with relevant hospital stakeholders.

The session aimed to share research findings, gather diverse perspectives, and collaboratively explore solution directions. Beyond generating insights, it also aimed to create ownership and encourage continued action beyond the scope of this graduation project.

Co-creation with diverse hospital stakeholders is especially crucial in the EMC, as the hospital operates highly decentralized. Many departments function autonomously, limiting information exchange between them. This session aimed to bridge those silos by facilitating collaboration across departmental boundaries.

The problems

Three of the four identified interventions were discussed during the co-creation session. The fourth, ‘Creating awareness about single-use disposal quantities,’ was excluded, as a hospital dashboard is already being developed to track disposable product usage. The remaining interventions, detailed in Chapter 5.2, are summarized below:

Improving equipment exchange: Inconsistent sensor exchanges during patient transfers lead to supply imbalances, uncertainty about availability, and increased reliance on single-use alternatives.

Limiting off-label use: Frequent off-label use of single-use sensors in low-perfusion ICU patients, such as placement on the ear or nose, compromises clinical safety.

Improving the cleaning procedure: Varying cleaning responsibilities and differing views on hygiene standards across departments risk improper cleaning and compromise the safety of reusable sensors.

The participants

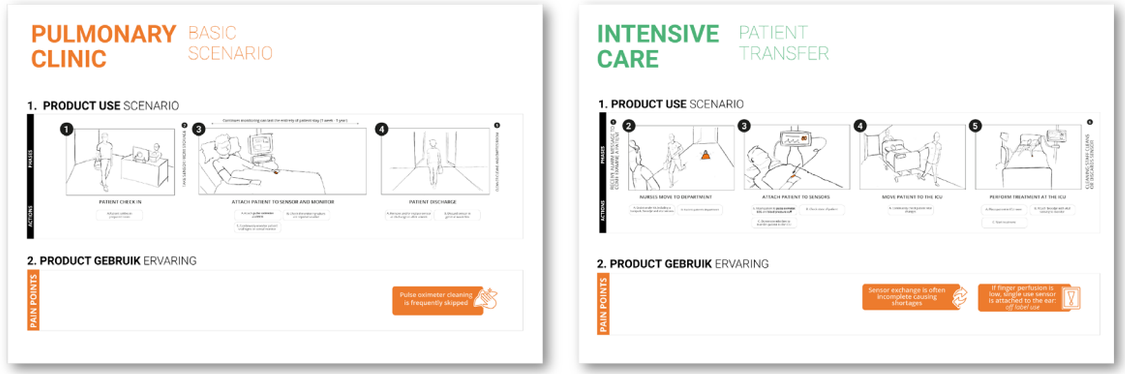
The most relevant stakeholders, nurses, infection prevention staff, procurement staff, and care department leads, were each invited to the session. Due to unforeseen circumstances, the nurse was unable to attend. However, the infection prevention representative, with prior nursing experience, was able to partially represent the nursing perspective.

Materials and setup

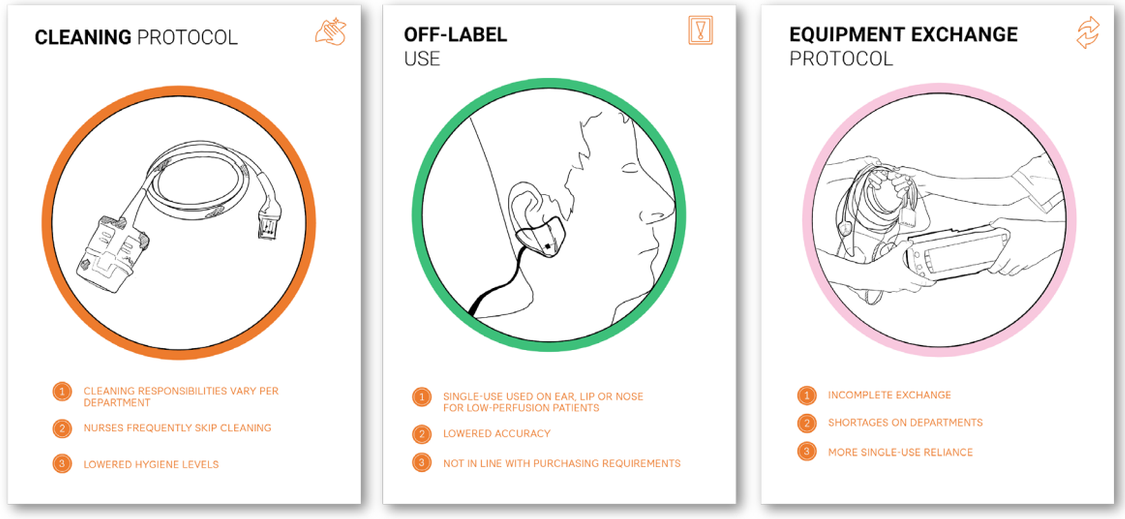
Figure 43 displays the materials used during the session, including pulse oximeters for reference. The session began with a brief introduction and a round of personal introductions, followed by a presentation of the key barriers using simplified interaction maps. This ensured all participants had a shared understanding, regardless of their prior familiarity with the product.

Each barrier was then discussed in two steps: participants first shared their experiences and views on the issue, then brainstormed solutions using solution directional cards. This process was repeated for all three barriers before concluding the session.

Introducing the context and problems



Understanding the problems



Solving the problems

Fig. 43: Co-creation interaction materials used

7.2 / CO-CREATION FINDINGS

Improving the cleaning procedure

Infection prevention staff see poor cleaning compliance as a major issue and have been trying to improve it for years:

"We've been trying for almost three years to get people to clean sensors after use."
– Infection prevention staff member

The issue isn't necessarily a lack of time, but rather a lack of priority. However, nurses are aware the sensors get dirty, which discourages them from using the reusable option at all:

"If you asked nurses to stick their finger in it, I think they'd say: 'Hmm, I'd rather not.'"
– Infection prevention staff member

The procurement staff was surprised by the lack of cleaning:

"Not following the cleaning protocol basically undermines everything."

"We have spotless beds but dirty sensors that could spread infections?"
– Procurement staff member

Solution direction
A promising idea is to assign cleaning duties for sensors (and other equipment) to facility staff instead of nurses, just like what is currently done in the ICU. While it may not be perfect, it would likely improve cleaning consistency and quality. To make this work, facility staff would need proper training on how to clean medical devices. Expanding their responsibilities would increase costs, which should be taken into consideration.

Limiting off-label use

The use of sensors on off-label locations is recognized by staff, but how frequently this occurs, and whether it is a significant problem, remains unclear. Further research is needed to understand the scale of the issue. Additionally, varying perceptions exist about the risks of off-label use. To align understanding, scientific literature on the risks of off-label placements was shared with participants after the co-creation session.

It was also noted that manufacturers are becoming increasingly strict in discouraging and regulating off-label use, which could make this issue more pressing in the near future.

Solution direction
Due to the high risk of pressure ulcers with the currently available low-perfusion ear clip sensors, their use is not actively encouraged. A possible solution could result from market research into reusable sensors specifically designed for accurate measurements at more central body locations, such as the ear, without the downsides of current ear clip designs. It is also recommended to communicate this need to manufacturers like Masimo and Philips, as awareness of this demand could accelerate product development in this area.

Improving equipment exchange

The barrier was clearly recognized by all participants. It was described as if a "black hole" exists in the hospital, where sensors and other equipment seem to disappear once transferred between departments, rarely to be seen again.

"You'd think there's a surplus somewhere, but that surplus is nowhere to be found."
– ICU lead

To cope with shortages, ICU staff often resort to ordering additional sensors. While this temporarily solves the issue, it has both financial and environmental drawbacks.

Solution directions
Raising awareness on the wards
Awareness campaigns, such as lessons, e-learnings, or playful reminders, were mentioned as common protocol reenforcing tools. Yet, participants highlighted their short-lived impact.

"Nurses are constantly being made aware of new topics, and the previous one quickly fades."
– Infection prevention staff member

A more effective approach might be positive motivation, like attaching tags to sensors that say: "We haven't had to order new sensors in 25 days—keep it up!" However, such interventions would need evaluation to ensure they don't inadvertently increase single-use consumption or suffer from short-lived impact like previous mentioned awareness efforts.

Monthly redistribution of equipment
The most promising solution discussed was the implementation of a monthly redistribution of the sensors across departments. Care assistants were suggested as potential coordinators. An existing WhatsApp group could be expanded to include care assistants from all departments, enabling better communication and coordination. For this system to work, it must first be clear how many sensors each department typically needs and where both stock and surplus are stored.

"If we really want this together, it's achievable."
– ICU lead

The findings from the co-creation session were shared with participants afterward to help key insights stick and provide clear action points to follow up on.

One key point for future sessions: having a nurse present would add important value. In this session, nurses were often discussed, but not directly involved in the conversation.

Overall, the session was well-received. There was valuable exchange of knowledge and experiences across roles, and participants actively contributed to brainstorming realistic solutions. I hope this session planted a seed for improving the system for reusable pulse oximeter use.

TAKEAWAYS

- Monthly sensor redistribution by care assistants could reduce shortages and prevent unnecessary orders.
- Market research into a safer low-perfusion sensor is needed to reduce inaccurate off-label placements.
- Shifting cleaning tasks to trained facility staff may improve hygiene consistency.
- Discussing the identified system barriers through co-creation with multiple stakeholders generated valuable exchange of knowledge and realistic solution posibilities.

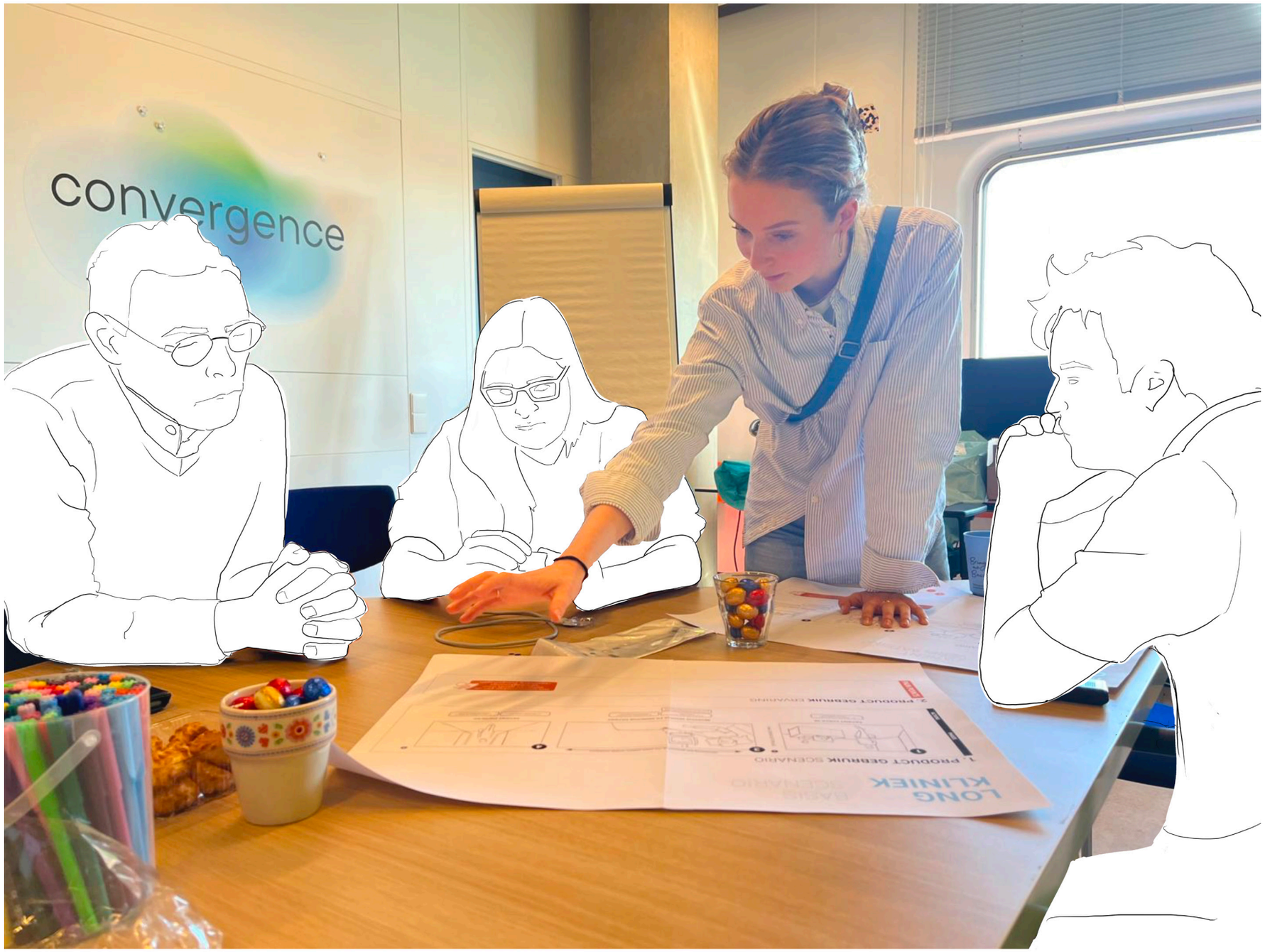


Fig. 44: Co-creation session impression

8

PHILIPS NOVA

This chapter presents the final design of the Philips Nova, a hybrid pulse oximeter combining a single-use patch for enhanced sensor stability with a reusable base for improved sustainability. Integrated with the Philips Connect system, the sensor is traceable throughout the hospital via a ‘broodje’ adapter, which tracks usage and location data in the cloud. While its climate impact does not surpass that of fully reusable devices, it significantly reduces the footprint of single-use alternatives by incorporating circular strategies such as reduce, reuse, repair, recycle, and recover.

The aim of this conceptual product design and accompanying system redesign is to inspire medical devide manufacturers on the implementation of circular strategies within pulse oximeter design and start conversations around the different ways of approaching circular healthcare.

This chapter presents the final product and system redesign. A more detailed explanation of the design decisions can be found in chapter 9.

Methodology
The design process involved ideation and prototyping, both individually and through collaborative sessions with designers (Appendix E). Requirements and feedback were gathered through HCP user testing. Literature research on the Internet of Things was conducted to support traceability integration.

Research questions
3.1 How can product level barriers be overcome in a sensor redesign?

3.2 How can we make the product traceable through the hospital and over its lifetime?

3.3 How can we extend product lifespan by improving its durability?

3.4 How can end-of-life strategies maintain product/material value after its life in use?

8.1 / INTRODUCING THE PHILIPS NOVA

The Philips Nova marks a new chapter in pulse oximeter innovation, combining usability and sustainability through its hybrid design. This sensor features a reusable sensor base paired with a single-use patch, minimizing waste while optimizing ease of use.

Built with life-extending R-strategies in mind, the Nova is designed for reuse, enables cable repair to prolong product life, and facilitates critical material recycling at end-of-life.

Beyond its technical innovations, the Philips Nova opens new opportunities for circular business models. Through product traceability and lifecycle tracking, it enables better resource management and supports Philips' shift toward a more sustainable, service-based approach.

Grounded in the hospital environment, the Nova seamlessly integrates into existing workflows, enhancing usability without disrupting clinical routines.

By combining cutting-edge technology with sustainable practices, the Philips Nova reflects Philips' commitment to minimizing climate impact while improving health and well-being through meaningful innovation.

TAKEAWAYS

- The Philips Nova tackles product and system barriers through its stable hybrid design and traceability.
- The Philips Nova adopts circularity through integrating reuse, repair and recycling strategies.

Fig. 45: The Philips Nova prototype, worn

8.2 / INTENDED USE

Figure 46 shows the intended use steps of the Philips Nova. The use steps are familiar to HCP's as it closely resembles the application of the RD set Adt, current single-use sensor. As with the single-use sensor, the backing of the single-use patch is removed, the patch is properly aligned on the fingertip and the wings are folded over to secure the patch in place.

The steps that follow are specific to the Nova sensor. The detector module is than clicked onto the bottom of the finger, the infrared (IR) module is folded over to the top and snapped into place. As a last step the cable end is plugged into the adapter cable and the protective latch cover is closed.

This design ensures a secure attachment of the reusable sensor components to the fingertip, allowing greater patient mobility while reducing false alarms. Additionally, it avoids fully enclosing the finger, preventing heat and moisture buildup for enhanced patient comfort.

TAKEAWAYS

- The single-use patch interaction closely resembles the current singe-use sensor application.
- The additional user steps include two snap fit connections.

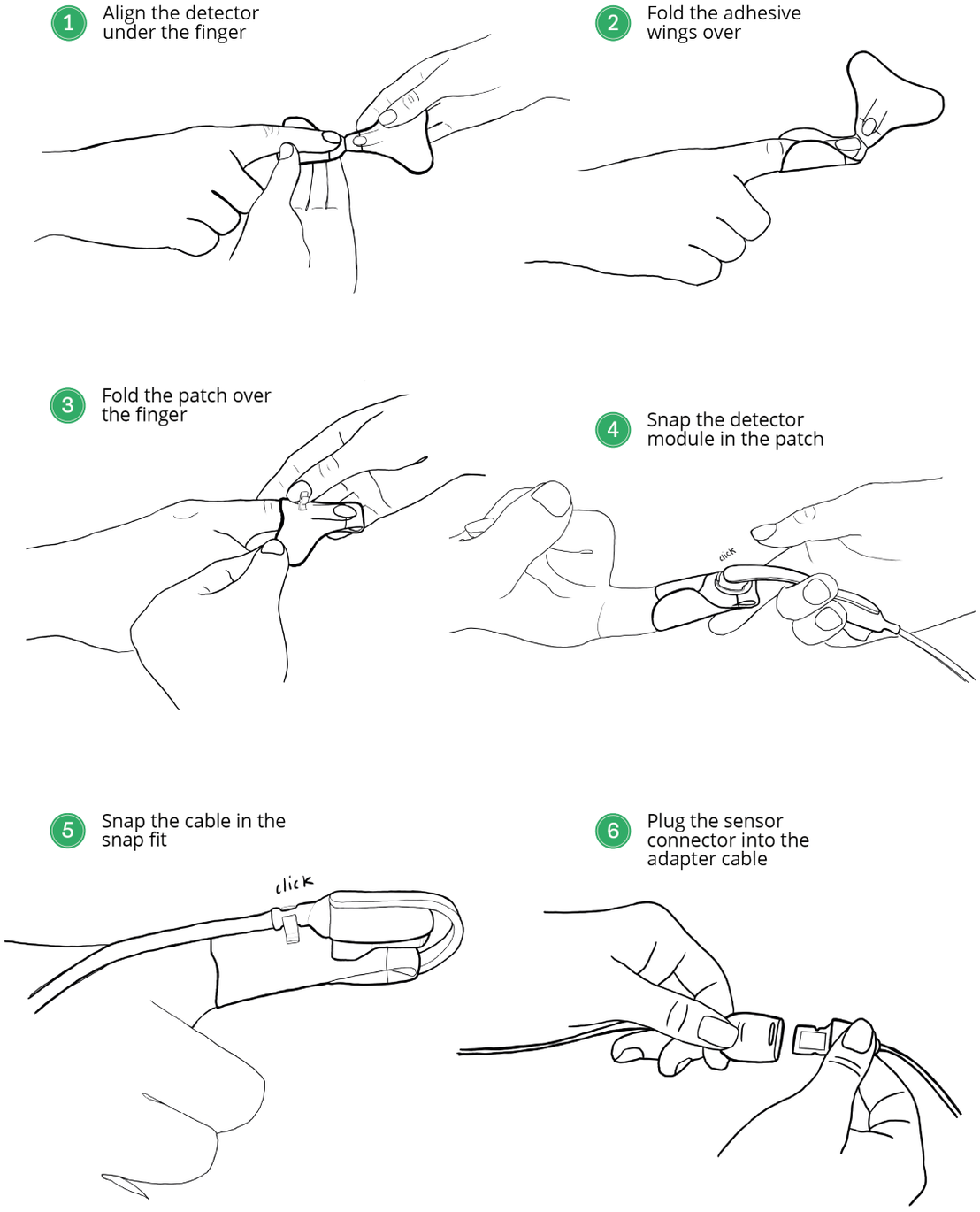


Fig. 46: Philips Nova sensor use

8.3 / PRODUCT ARCHITECTURE

Figure 47 and 48 show the basic components of the Philips Nova. Two main parts can be identified, the reusable base and the single-use patch.

The reusable base consists of three sub elements, the infrared (IR) module, detector module and cable module. These elements house all the electronic components required to measure pulse and oxygen saturation levels. Most of the electronic components are housed in the Infrared module, to lower the material volume on the bottom of the fingertip. This design improves dexterity and ease of hand use.

The single-use patch is built up of a polyethylene sticker element, with two snap fit attachments, the cable and detector module snap fits. These snap fits create a stable fit on the finger, while allowing size freedom and skin ventilation.

The single-use and reusable elements are identifiable as such through the use of color. The sticker is fully white, a color associated with single-use products.

TAKEAWAYS

- The reusable base allows size freedom, skin ventilation and dexterity.
- The single-use patch is white to insinuate single-use.

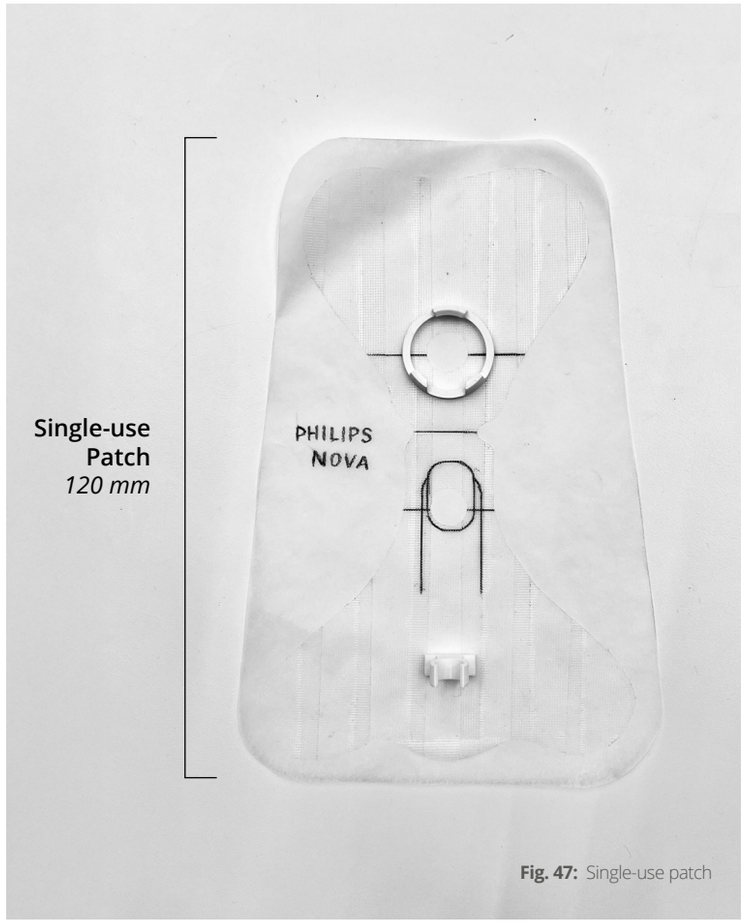


Fig. 47: Single-use patch

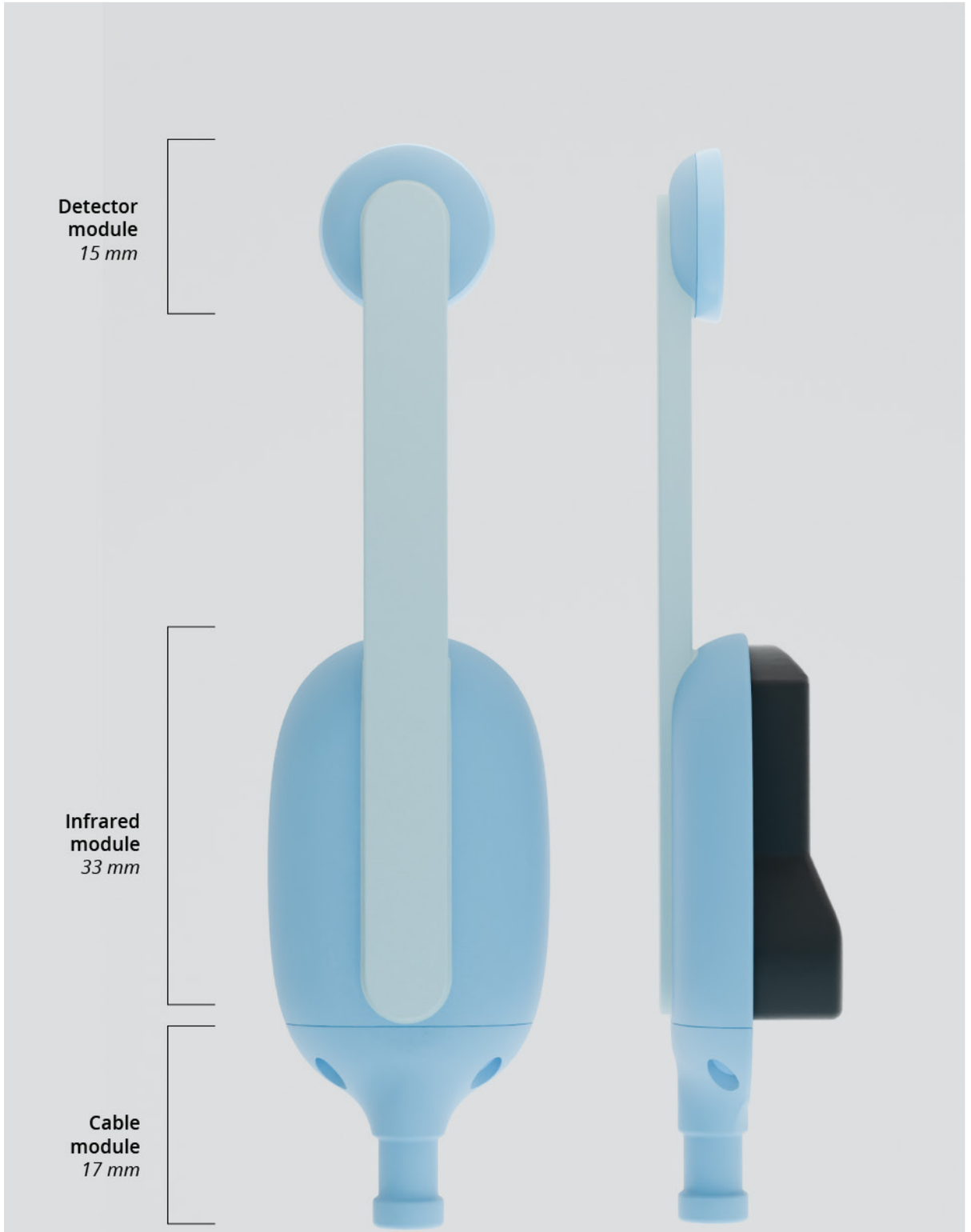


Fig. 48: Reusable base top and side view, indicating the modules

8.4 / SENSOR TRACEABILITY

The future use of medical equipment within circular business models relies on the use, storage, and sharing of product data (Stretton & Daphne, 2023). To support this transition, a conceptual product line within Philips is proposed, called Philips Connect. Philips Connect is designed to support the implementation of new circular business models, by providing Philips with valuable data, such as sensor usage time and frequency and maintenance records. It also offers added value to hospitals by allowing real-time localization of all products within the vital monitoring system.

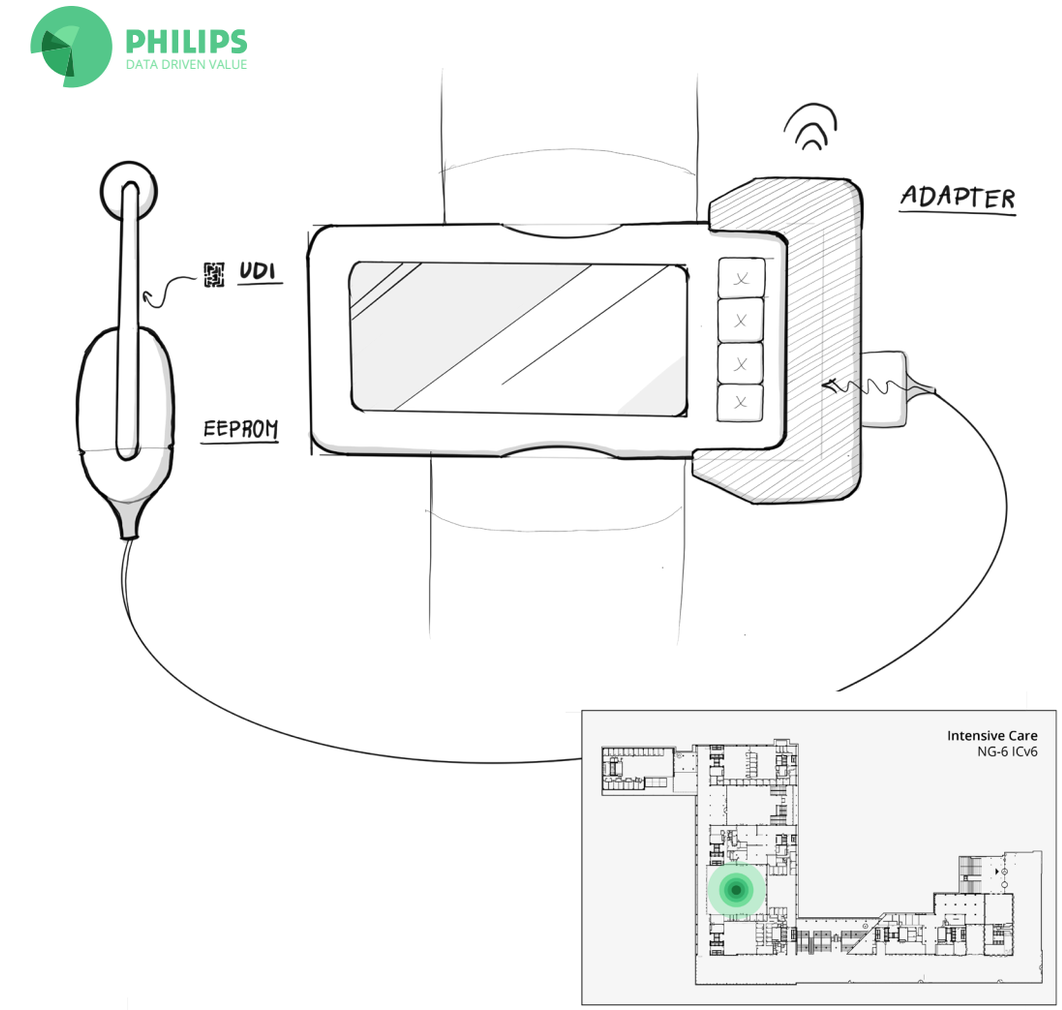
Philips Connect provides oversight of the distribution of 'broodjes' and sensors across hospital departments, making it possible to redistribute equipment and prevent shortages. The envisioned software could enable access to the live location of the 'broodje' and the last recorded usage location of the Philips Nova pulse oximeter. This traceability also simplifies the mandatory two-year maintenance process and helps reduce costs by preventing the loss of valuable equipment.

Sensor traceability relies on three key components working together. First, the Philips Connect portable monitor adapter registers sensor usage data, stores it in the cloud, and includes location tracking technology. Second, the Philips Nova is equipped with a memory chip (EEPROM) that stores a unique sensor ID, allowing the adapter to accurately log data to the correct device. Third, a Unique Device Identifier (UDI) QR code is printed on each device, linking directly to the Philips Connect software page, where hospitals can register additional details such as maintenance cycles.

This traceability system is designed not just for the pulse oximeter sensor but for all components of the vital monitoring system, including the 'broodjes' and other vital sensors. This scalability reduces investment costs while increasing overall value.

TAKEAWAYS

- The conceptial Philips Connect software and product range allows the implementation of circular business models and the live-location tracking of 'broodjes' and last usage location of sensors.
- The system is build up of an adapter, EEPROM and UDI.
- The traceability system is scalable to include all vital monitoring equipment.



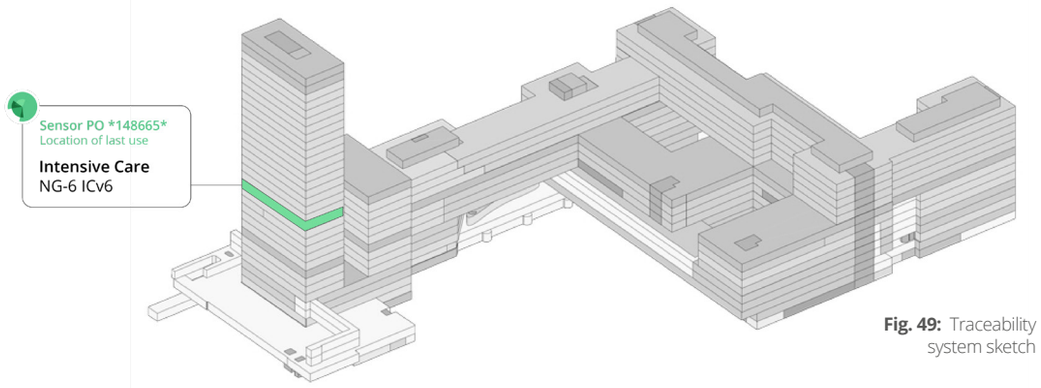


Fig. 49: Traceability system sketch

8.5 / IMPLEMENTED R-STRATEGIES

Figure 50 shows the simplified version of the product journey map for the Philips Nova. The analysis of original product journey maps (chapter 4.1) and identification of opportunities for the implementation of more life-extending R-strategies brought about, this proposed product journey map.

As the Philips Nova is a hybrid product, consisting of a reusable and single-use component, this distinction (regarding end-of-life) is made using different journey colors for the different components. Within the reusable base journey, many recirculations of products, parts and materials can be observed, reflecting the implementation of circularity. R'strategies implemented in this journey are: reduce (R2), reuse (R3), repair (R4) and recycle (R8) In contrast, the single-use component is still part of a linear lifecycle, incorporating the recover strategy (R9).

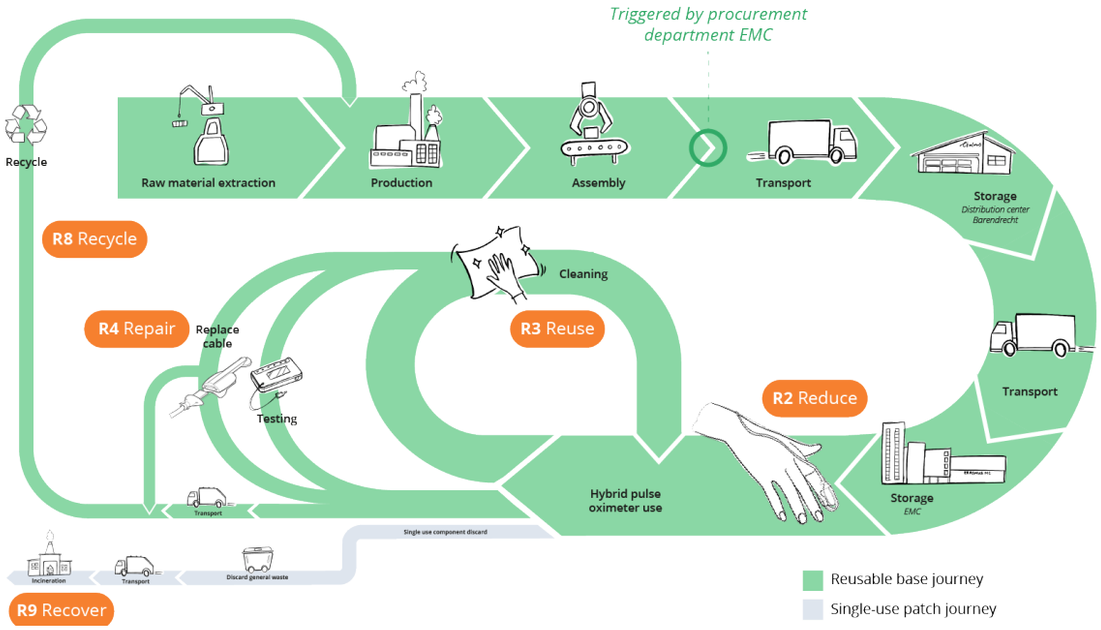


Fig. 50: Product journey map Philips Nova

Reduce (R2)

The reduce strategy is facilitated by the introduction of Philips Connect. As previously mentioned, this system helps prevent the loss of valuable equipment. Additionally, product traceability enables the identification of surplus and shortages across departments, preventing unnecessary purchases and ultimately reducing the total number of sensors needed to serve the hospital.

Whether the Philips Nova achieves a reduction in material use depends on the comparison. Compared to single-use sensors, material consumption is reduced, as most of the material is now concentrated in a reusable component. However, when compared to the current reusable sensor, the addition of a single-use patch increases overall material consumption.

Reuse (R3)

The reuse cycle of the reusable base fits into the same system as the current reusable sensor. Meaning that after every patient discharge the component will be cleaned using water and a microfiber wipe, by the nurse or cleaning staff. Afterwards the reusable sensor base is stored on the patient monitoring hook, ready for its next use.

As the skin contact of the reusable component is parted by the single-use patch, this might result in reduced contamination of the reusable base, lowering the risk of cross-contamination between patients. Whether this risk is reduced, needs to be proven through scientific study, however, the reduced perceived risk might already lower the barrier for transitioning towards this (partly) reusable device (chapter 3.3).

Repair (R4)

To extend the lifespan of the reusable base, the device has been designed for cable repair, addressing the most common point of failure in current devices (Chapter 4.3). Repairs would be carried out by the Medical Technology (MT) department, which is already responsible for testing pulse oximeters.

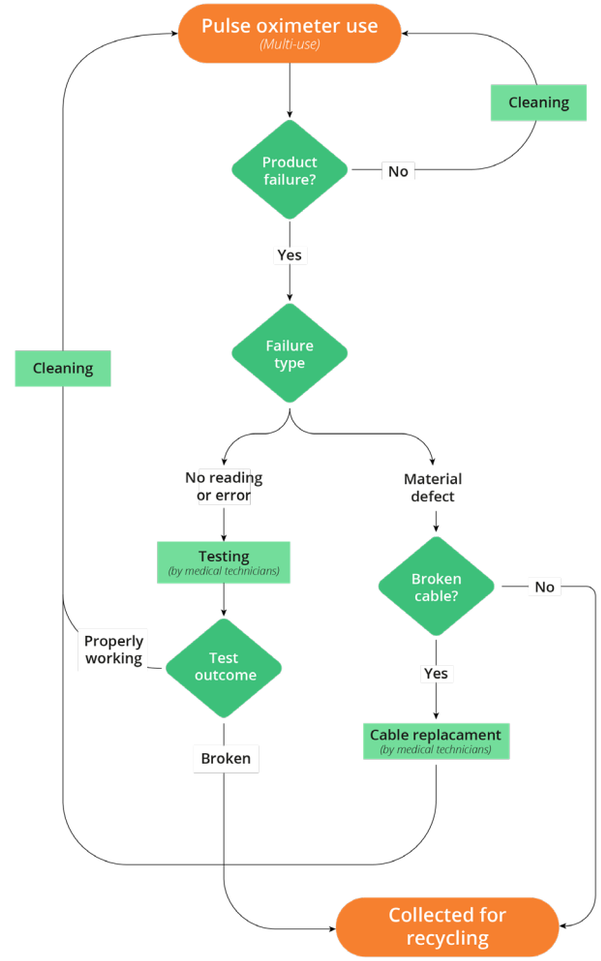


Fig. 51: Product failure flow

The cable replacement process is simple and familiar. The cable is secured with two small screws, removing these screws and unplugging the cable allows the MT department to replace it with a new cable element, available from Philips.

Integrating repair into the hospital workflow requires only a minor adjustment. Currently, pulse oximeters with material defects are discarded by nurses, while those with reading errors are sent to the MT department. Under the new process, devices with both electrical and material defects would be routed to the MT department, requiring only a small change in nurse workflow.

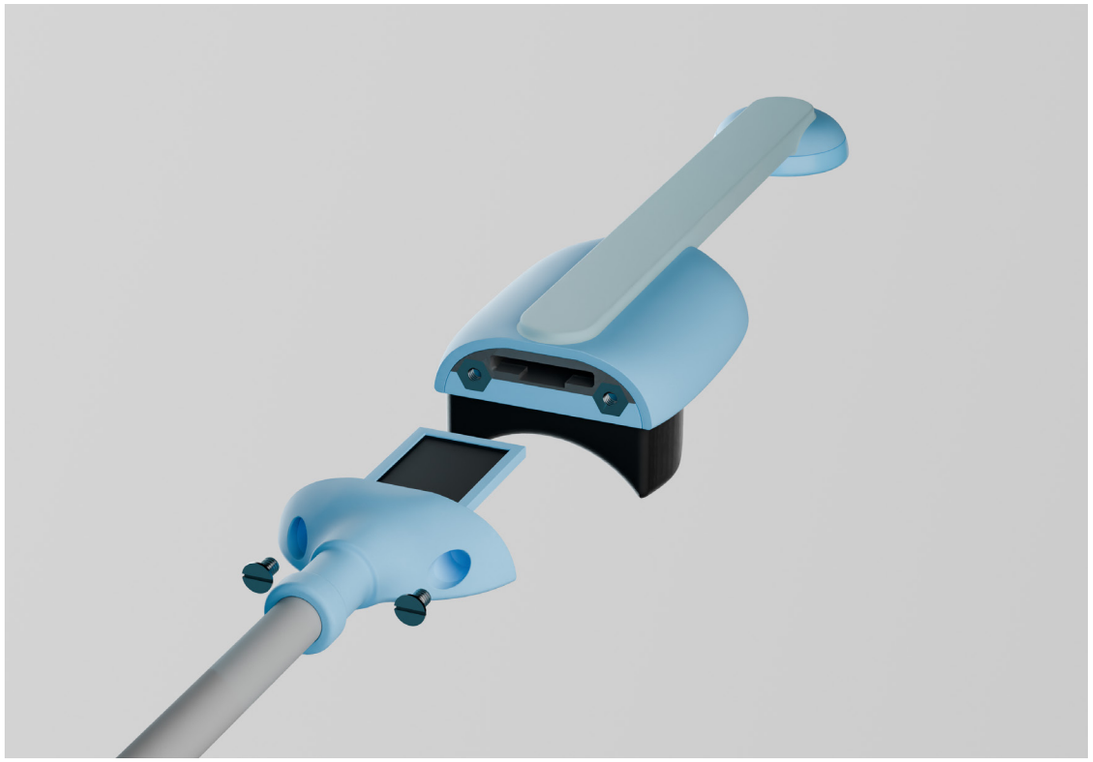


Fig. 52: Cable repair PLACEHOLDER

Recycle (R8)

Due to adjustments in pulse oximeter flow for product repair, all defective pulse oximeters and cable components are collected by the MT department. Rather than discarding these broken items, they are packed together for shipment to a recycler.

Under the procurement agreement between Philips and EMC, a dedicated recycler could be specified, enabling Philips to share manufacturing information with the recycler. This collaboration would enhance the retention of material value during the recycling process. Philips has expressed to be open to these kinds of collaborations.

The quantity of Philips Nova sensors within the Netherlands is too low to justify the establishment of a full disassembly and material recycling system at end-of-life. Therefore, the recycling efforts will focus on recovering the most valuable materials, particularly critical components such as copper, through product shredding and material seperation techniques (Loibl & Tercero Espinoza, 2021).

Recover (R9)

The implementation of separate waste collection containers for single-use patches is not widely supported by healthcare professionals. These systems can add to nurses' workload, lead to high logistical costs, and be difficult to scale for similar devices (Hoveling et al., 2024) (Chapter 3.3). As a result, like current single-use sensors and cleaning materials, the patches are disposed of as general hospital waste and incinerated for energy recovery (R9).

At the EMC, trials are underway to explore the feasibility of separate plastic waste streams for non-contaminated materials, enabling recycling. Since the single-use patch is made entirely of recyclable plastics, it could potentially be integrated into this waste stream in the future.

TAKEAWAYS

- Philips Connect allows product stock reductions (R2).
- All broken sensors are now tested and possibly repaired (R4) by the MT deparment.
- A recycling (R8) stream is set up for aquiring copper.
- Single-use patches are incinerated for energy recovery (R9).

8.6 / LIFE CYCLE ASSESSMENT PHILIPS NOVA

In order to evaluate the Philips Nova and compare it to the current pulse oximeters, the Philips Nova was assessed within the same scope as the original LCA (chapter 4.2). Figure 53 shows this impact. As the figure shows, one year of continuous monitoring using the Philips Nova results in 57 kg CO2 eq emissions. This is more impactful than the reusable pulse oximeter (34 kg), which was to be expected due to the addition of the single-use patch. However, this impact is still significantly less than the single-use pulse oximeter (179 kg).

As the Philips Nova overcomes many of the barriers related to reusable pulse oximeter use. Transitioning the hospital from the single-use towards the Philips Nova will be way more achievable than transitioning towards the current reusable sensor.

Due to the improved stability of the Philips Nova, the sensor is expected to lower the amount of nuisance alarms associated with reusable pulse oximeter movement. This will in turn lower the needed verification of the measurement data through blood gas assessment, further lowering the environmental footprint of patient care (this was not implemented in the LCA).

As the product is also built for repair, aiming to lengthen its lifespan, this could further lower the product impact. This extended lifespan is hard to estimate, and therefore not incorporated into the LCA.

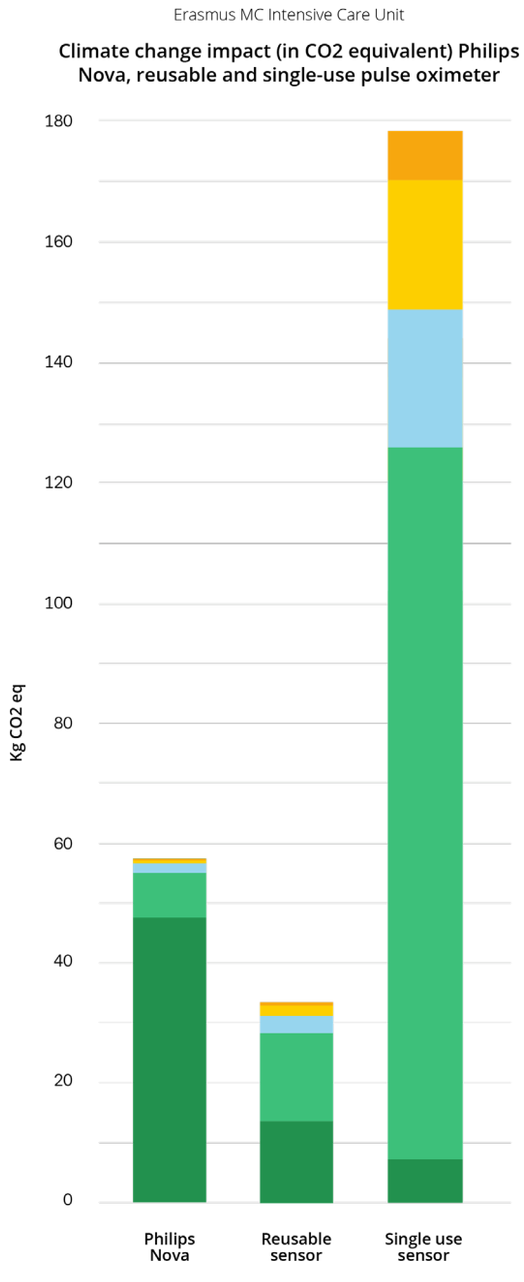


Fig. 53: Climate impact comparison Philips Nova vs single-use vs reusable sensor. Impact of sensor use for one year on the ICU department of EMC.

Transition vision

In the current hospital setting, single-use and reusable pulse oximeters are used alongside each other. With the introduction of the Philips Nova, a transition is envisioned where the Philips Nova and the reusable pulse oximeter will coexist, gradually phasing out the single-use sensors. Since the Philips Nova offers many of the same advantages as the single-use version, it enables a smooth transition. However, the reusable pulse oximeter will still be necessary in certain time-critical situations, as its rapid application time remains unmatched. This transition scenario is illustrated in figure 54.

If the ICU, where single-use sensors are currently used on approximately 90% of patients, were to fully replace the single-use sensors with the Philips Nova, it could result in an estimated annual reduction of 110 kg of CO_2-equivalent emissions for the EMC ICU. It's important to note that this figure is a rough estimate.

TAKEAWAYS

- The climate change impact of the Philips Nova competes with the reusable device.
- By replacing the single-use sensors with the Philips Nova, hospitals can significantly lower their impact.

Fig. 54: Combination of sensors used in the EMC , current vs future scenario

9

DESIGN DETAILING

This chapter dives deeper into the considerations made to get to the final design. Highlighting design decisions through the introduction of the requirements per chapter (for a full list, see Appendix F). Both the product features as well as the system integration will be further explained, including results from usability testing.

Methodology
Similarly to chapter 8, ideation and prototyping methods as well as literature were used to inform and develop this design. Additionaly user testing and interviews were conducted (Appendix H). A simulated clinical environment with a stand-in patient was used to reflect realistic usage. Participants watched an instructional video before testing the prototype. The study concluded with a survey-guided interview based on the validated 'Post-Study System Usability Questionnaire' (Lewis, 2007). Video recordings of product use were studied to gather results.

Research questions
3.1 How can product level barriers be overcome in a sensor redesign?

3.2 How can we make the product traceable through the hospital and over its lifetime?

3.3 How can we extend product lifespan by improving its durability?

3.4 How can end-of-life strategies maintain product/material value after its life in use?

3.5 How does the Philips Nova compare to the current single-use and reusable pulse oximeters in terms of usability?

9.1 / SYSTEM ADAPTATIONS

Req ID	Category	Requirement
S1.1	Product implementation	Awareness on new product use should be instructed to all nurses over email and posters.
S1.2	Logistics	The product logisics fits in the sophisticated logisitics system at Erasmus MC
S1.3	Logistics	Product is storable in non-sterile central storage unit and drawers.
S1.4	Logistics	Single-use components should be stored close to the patient's bed.
S1.5	Product failure	The product is testable using the FLUKE prosim 8.
S1.6	Waste handling	No additional waste seperations bins are needed in patient rooms.

Product journey map

Figure 55 shows the adapted detailed product journey map for the Philips Nova. As in the original product journey map, all five product journey phases are highlighted their individual color.

Logistics phase

Since the Philips Nova consists of both reusable and single-use components, an additional logistics pathway is required to manage both stock types. The reusable base follows the same logistical path as the current reusable sensor, while the single-use patch is stored on the central storage unit, located on the department hallway. Hereafter medical student stock up patient room drawers, mirroring to the current single-use sensor system. This logistics journey fits into the logistics workflow, not putting an extra burden on this system, or requiring change.

Sensor reuse phase

The reuse process for the Philips Nova's reusable base remains unchanged compared to the current reusable sensor.

Sensor failure phase

As explained in 8.5 'Repair', the MT department gets the extra responsibility of cable repair, which aligns with their expressed interest (5.1). Since this department experiences less workload pressure than healthcare professionals (HCPs), this added task does not create an operational burden.

Philips Connect offers a significant efficiency gain by enabling easy tracking and servicing of sensors and portable monitors ('broodjes') without having to search high and low for their placement in the hospital.

Waste handling phase

The disposal process for single-use patches and cleaning supplies follows the same waste management pathway as the current single-use product. However, an additional recycling process is introduced for the reusable base. As described in section 8.5, Recycle, the MT department is responsible for collecting and packaging the reusable bases for recycling. The incidentally additional outgoing mail is the responsibility of the logistics department.

Product use phase

The interaction with the Philips Nova is explained in 8.3 'Intended use'. The sensor is conveniently stored near the point of use: the single-use patches are kept in patient room drawers, while the reusable base is placed on the monitor hook, ensuring easy access during patient care.

Zoom in to see in more detail

Legend

- Standard journey track
- Possible alternative journey track
- Logistics journey steps
- Patient care journey steps
- Sensor reuse journey steps
- Sensor failure journey steps
- Waste handling journey steps

Deliver patches
Patcges are delivered and registered as in incoming product

Logistical department A: shipping (LDs)

Unpack
The secondary packaging, a cardboard box, is removed

Logistical department A: shipping (LDs)

Store
The product is transported by the logistical department and stored in the central storage unit.

Central storage unit (non-sterile)

Store in patient room
The patches are stocked up in the patient drawers by medical students.

Intensive Care Unit (ICU)

Remove backing
Once a measurement is needed the patch backing is removed.

Intensive Care Unit (ICU)

Attach to patient
The patch is aligned and stuck onto the patient finger

Intensive Care Unit (ICU)

Patient transfer
If a patient transfers departments, the 'broodje' and sensors transfer along to the new department.

Other care department

Sensor exchange
Nurses from the new department hand over clean sensors to the original department.

Other care department

Monitor patient vitals
The sensor readings are displayed on the central monitor in the hall, a patient is monitored from there.

Other care department

Sensor removal
At patient discharge the sensor is removed from the finger and unplugged from the 'broodje'

Other care department

Cleaning
The sensor is cleaned by a nurse using a microfiber cloth and water or alcohol.

(The room is cleaned by someone else)

Other care department

Deliver reusable base
Product is delivered and registered as in incoming product

Logistical department A: shipping (LDs)

Unpack
The secondary packaging, a cardboard box, is removed

Logistical department A: shipping (LDs)

Store
The product is transported by the logistical department and stored in storage cupboard.

Medical Technology department (MT)

Unpack
Once the product is needed it is unpacked from the primary packaging, a cardboard box.

Medical Technology department (MT)

Handover
Once a shortage of reusable sensors is observed on a deparment, HCP's pick up a new product at the MT.

Medical Technology department (MT)

Store
On-department storage can happen in several locations, most commonly it in the patient room on a monitor hook.

Intensive Care Unit (ICU)

Plug in
Once a patient is admitted, the sensor is plugged into the 'broodje' through an extention cord.

Intensive Care Unit (ICU)

Attach to patient
The sensor is attached to the patch on the fingertip of the patient

Intensive Care Unit (ICU)

Monitor patient vitals
The sensor readings are displayed on the central monitor in the hall, a patient is monitored from there.

Intensive Care Unit (ICU)

Sensor removal
At patient discharge the sensor is removed from the finger and unplugged from the 'broodje'

Intensive Care Unit (ICU)

Cleaning
The entire room including the sensor is cleaned using a microfiber cloth and water or alcohol.

Intensive Care Unit (ICU)

Alarm
If a sensor moves or falls of the nurse receives an alarm.

Intensive Care Unit (ICU)

Sensor adjustment
A nurse checks on the patient and adjusts or reattaches the sensor if needed.

Intensive Care Unit (ICU)

Sensor error encounter or material defect
The sensor does not give a proper reading, shows an error message or material defect

Intensive Care Unit (ICU)

Replacement
Sensor is picked up by or delivered to the MT personell. The nurse receives a replacement sensor.

Medical Technology department (MT)

Testing
The problem sensor is connected to a monitor and testing device to check the product functioning.

Medical Technology department (MT)

Cleaning
A properly working sensor is cleaned to make it ready for its next use.

Medical Technology department (MT)

Maintenance registration
The sensor's maintenance is logged, by scanning the device and registering the testing cycle in the online database.

Medical Technology department (MT)

Cable replacement
A non-properly working sensor receives a replacement cable

Intensive Care Unit (ICU)

Testing
The sensor with renewed cable is tested again

Medical Technology department (MT)

Cleaning
A properly working sensor is cleaned to make it ready for its next use.

Medical Technology department (MT)

Maintenance registration
The sensor's maintenance is logged, by scanning the device and registering the replaced cable in the online database.

Medical Technology department (MT)

Store broken sensor
Broken sensors and cables are stored at the MT department until a few are collected

Medical Technology department (MT)

Package for recycler
The sensors and cables are packaged in an envelope and adressed to a dedicated recycler

Medical Technology department (MT)

Package processing
The package is processed as outgoing package by the logistics department

Logistical department A: shipping (LDs)

Send to recycler
The package is send of to the recycler

Logistical department A: shipping (LDs)

Discard packaging
The secondary packaging is discarded in the paper waste.

Logistical department B: waste processing (LDw)

Discard packaging
The primary packaging is discarded in the paper waste.

Medical Technology department (MT)

Discard patch backing
The patch backing is discarded in the patient room general waste

Intensive Care Unit (ICU)

Discard cleaning supplies
The microfiber cloths are discarded in the MT's general waste bin.

Medical Technology department (MT)

Discard sensor patch
The sensor patches are discarded in the general waste in the patient room after use.

Intensive Care Unit (ICU)

Discard cleaning supplies
The microfiber cloths are discarded in the general waste in the patient room.

Intensive Care Unit (ICU)

Trash bin emptying
When the waste container is full, it is emptied in a bigger container off-department

(nearest) Milieu Station (MS)

Waste handling
Full milieu station containers are transported through the logistical hallway to the logistics department. Waste is compressed and shipped off by pre-zero.

Logistical department B: waste processing (LDw)

Fig. 55: Redesigned product journey map

Product awareness and education

To ensure a seamless transition to the Philips Nova, it is essential to raise awareness among healthcare professionals (HCPs). In clinical settings, knowledge about product use is often passed down from one generation of nurses to the next. However, this informal training process carries the risk of perpetuating incorrect usage. Therefore, providing thorough initial education on device use is critical to minimizing this risk.

When introducing a new device, hospitals typically send an introductory email and display informational posters in high-traffic areas such as break rooms, storage rooms, and pharmacies. Both of these communication strategies are recommended for the Philips Nova rollout.

The introductory email should explain:

1. **Reason for transitioning:** Creating a common understanding on the improved patient care and sustainable advantage. This explanation should also address employee concerns, observed during the clinical trial of the purchasing phase (5.5). By incorporating these elements in the communication, individuals will recognize the value of change, leading to affective commitment (K. I. Miller & Monge, 1986; V. Miller et al., 1994).

2. **Instruction for Use:** The IFU steps as explained in 8.3 ‘Intended use’ should familiarize the nursing staff with product handling.

The posters should communicate:

1. **Reusable vs. Single-Use Distinction**: The biggest risk of product misuse of the Philips Nova is the accidental disposal of the reusable base along with the single-use patch. Since hybrid products may be unfamiliar to nurses, this distinction should be clearly and repeatedly communicated.
2. **Instruction for Use:** Ensure that the key usage steps are easily accessible in the initial implementation phase. Providing clear, visible guidance will help reduce uncertainty, resulting in a more positive perception regarding the transition (Bordia et al., 2004).

By combining direct communication with visible reminders, hospital departments can effectively integrate the Philips Nova while minimizing errors and resistance to change.

TAKEAWAYS

- The Philips Nova product journey closely fits existing journeys, minimizing system adaptations.
- Email and posters are used to communicate the transition to the Philips Nova to minimizing errors and resistance to change.

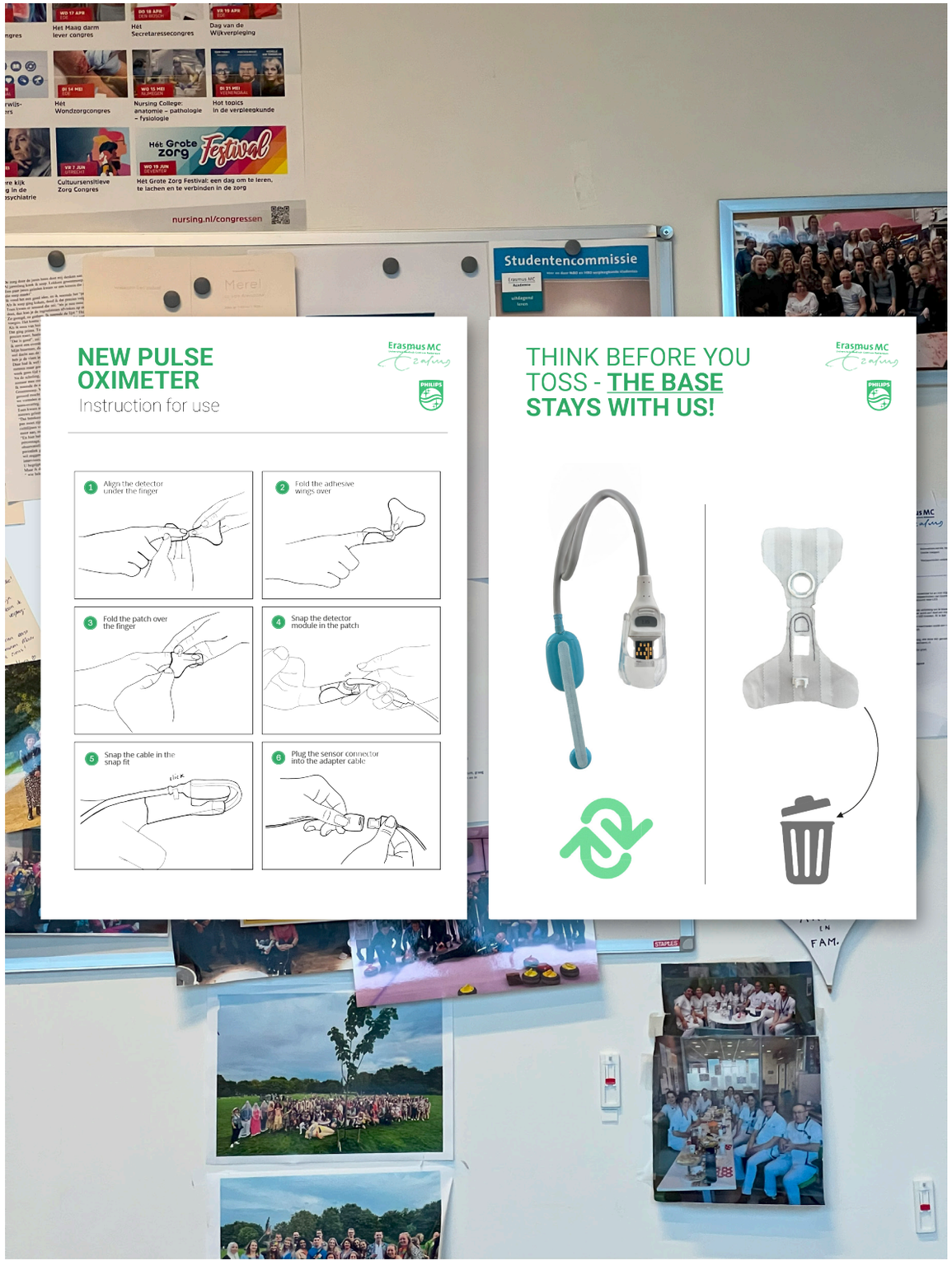


Fig. 56: Awareness posters on the pulmonary clinic department of EMC

9.2 / REUSABLE BASE

Req ID	Category	Requirement
R2.1	Price	The Reusable base costs €30 or less to manufacture
R2.2	Fit	The sensor must be used on the 3 middle fingers
R2.3	Fit	Sensor has to give access to the fysiological surgical sights
R2.4	Fit	Sensor allows finger sizes varying between 14 mm and 20 mm breadth (mm)
R2.5	Fit	The product has one adult size
R2.6	Fit	The material volume on the bottom side of the finger should be minimized.
R2.7	Fit	The detector and infrared light are aligned vertically on the top and buttom of the finger
R2.8	Fit	The contact surface between the product and the skin is flush
R2.9	Appearance	The reusable component cannot be white as the main color.
R2.10	Appearance	The top and bottom component are assymetrical to avoid confusion about orientation
R2.11	Appearance	The sensor design communicates technical sophistication, comfort and safety
R2.12	Appearance	Any material around the light source or detector has to be black
R2.13	Usability	The reusable component can be removed while leaving the sticker secured to the finger
R2.14	Usability	The adhesive side of the sticker may not touch the reusable component
R2.15	Usability	The reusable base can be attached to the patient with one hand
R2.16	Usability	The cable module can only be disassembled by MT staff, and does not come loose by accident
R2.17	Cleaning	Cleaning should take the same amount of time or shorter than 70 seconds
R2.18	Cleaning	The reusable base avoids dirt collecting ridges for the connection with the patch
R2.19	Cleaning	Sensor materials can withstand water, 250 ppm, 1000 ppm cholide solutions and 70% alcohol without breakdown

Securing mechanism

Secure attachment of the sensor to the finger is of great importance for this redesign, aiming to lower nuisance alarms and increase patient comfort. This secure attachment is facilitated through a combination of design features.

The connection between the reusable base and the single-use patch relies on two snap-fit mechanisms. The detector module is fully enclosed by 3 snap fits around the circumference of the circle, tightly pulling the detector to the skin surface. Two of these snap frame the sides of the wire connecting the detector and IR module, preventing any rotational movement.

The second snap-fit mechanism secures the IR module to the fingertip by locking around a notch in the cable transition. Since snap-fit mechanisms may weaken over time with repeated use, these elements are integrated into the single-use patch, ensuring durability within its intended short lifespan.

Fig. 57: Detector module snap fit design PLACEHOLDER

While this second snap-fit mechanism provides strong attachment, it does not restrict movement in all directions. To prevent unwanted rotational movement, a rounded finger cushion (Figure 58) is incorporated into the design. Made from flexible silicone rubber, this cushion adapts to the natural shape of the finger, also allowing the Philips Nova to accommodate a wide range of finger sizes comfortably (Req. R2.4).

The detector module's contact surface with the skin is also made out of silicone rubber. This material conforms to the fingertip's shape, enhancing comfort while also acting as a light shield to protect the detector from ambient light interference.

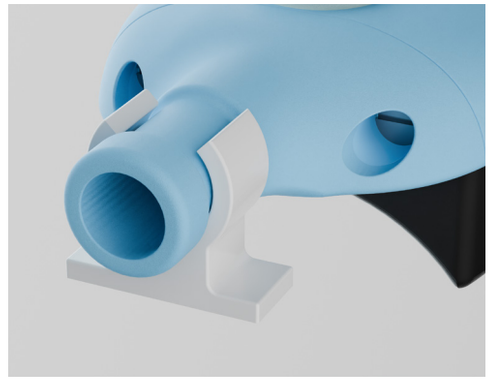


Fig. 58: IR module snap fit design PLACEHOLDER

Ideation and prototyping
During the initial ideation phase, various securing mechanisms were explored beyond the chosen hybrid product, including wrist-secured designs and mechanical pressure mechanisms (Figure 59, Appendix G). Ultimately, the hybrid concept was selected because it offered flexibility for different finger sizes without increasing product size or weight. Additionally, it maintained a minimal design, crucial for proper cleaning, while ensuring secure attachment without the discomfort or risk of artery compression associated with high-pressure mechanisms.

Once the hybrid concept direction was finalized, multiple connection methods between the patch and the reusable base were ideated, prototyped, and tested with healthcare professionals (Appendix H). The final design was chosen based on several key factors. First, the base and patch needed to be individually removable from the finger to prevent accidental disposal of the reusable base along with the patch (req R2.13). Second, the adhesive should not come into contact with the reusable base, as this would require additional cleaning (R2.14). Lastly, the reusable base was designed without internal ridges to prevent dirt accumulation, ensuring proper hygiene and ease of maintenance (req R2.18). These considerations ensured that the final design met both practical and hygienic requirements while maintaining ease of use.

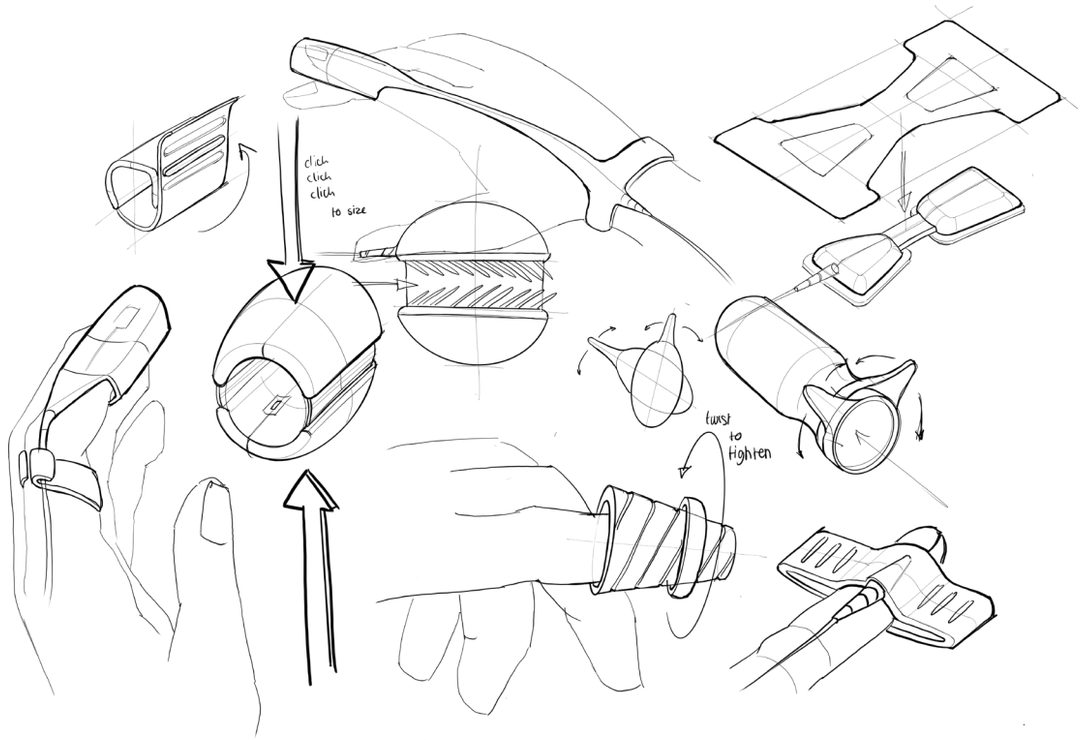


Fig. 59: Ideation sketches initial concept direction

Fig. 60: HCP's prototype testing hybrid iteration 1

Cable modularity

The cable module is secured to the infrared module using two mechanisms: a snap-fit and two screws.

The snap-fit mechanism is based on the existing Masimo cable attachment, where the male and female parts lock together through an internal snap-fit. This feature allows the cable to be temporarily secured for retesting at the MT department before committing to the more time-consuming screw attachment. By holding the cable in place, this mechanism enables quick verification of whether the cable replacement has restored proper sensor functionality, after which the screws can be used for a more permanent fixation.

The M1.4 screws, similar to those used in iPhone screen assembly, pass through the cable module and into the infrared module, which houses the female screw threads. While this assembly step may require some precision, the screws only need a few turns to secure the connection. Since cable replacement is expected to be an infrequent procedure, this design choice ensures durability without adding unnecessary complexity. Additionally, using standard screws and inserts helps reduce production costs.

Ideation

Figure 61 illustrates several alternative designs explored for the screw-in cable attachment, including a pin-release SIM card mechanism and a top-down screw thread mechanism. The final design was selected for its ability to remain secure over time, withstand significant pulling forces, maintain a compact form, and allow for repeated removal and reattachment without compromising durability.

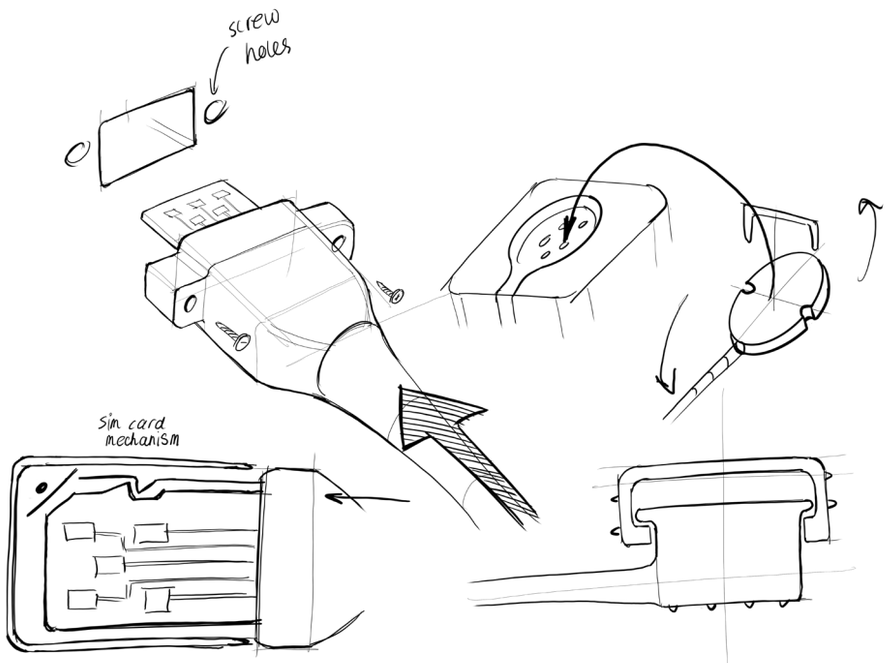


Fig. 61: Ideation sketches cable modularity

Form study

Once the core functionality of the device was established, a form exploration was conducted to define its overall design. The goal was to create a product that visually communicates safety, technical sophistication, and comfort, aligning with both healthcare professionals' (HCPs) expectations and patient needs.

From an HCP's perspective, safety and technical sophistication are critical factors in fostering trust in the product. A design that conveys technical refinement also enhances the perceived value of the reusable base, reducing the likelihood of accidental disposal by healthcare personnel.

In addition to professional trust, patient experience played a key role in the design process. A product that expresses comfort not only improves usability but also enhances overall patient satisfaction.

Figure 62 illustrates the various design iterations explored during this phase. The final shape was selected based on user feedback collected through a survey, this design ranked the highest in all categories. The chosen design features a rounded, continuous, and minimalist shape.

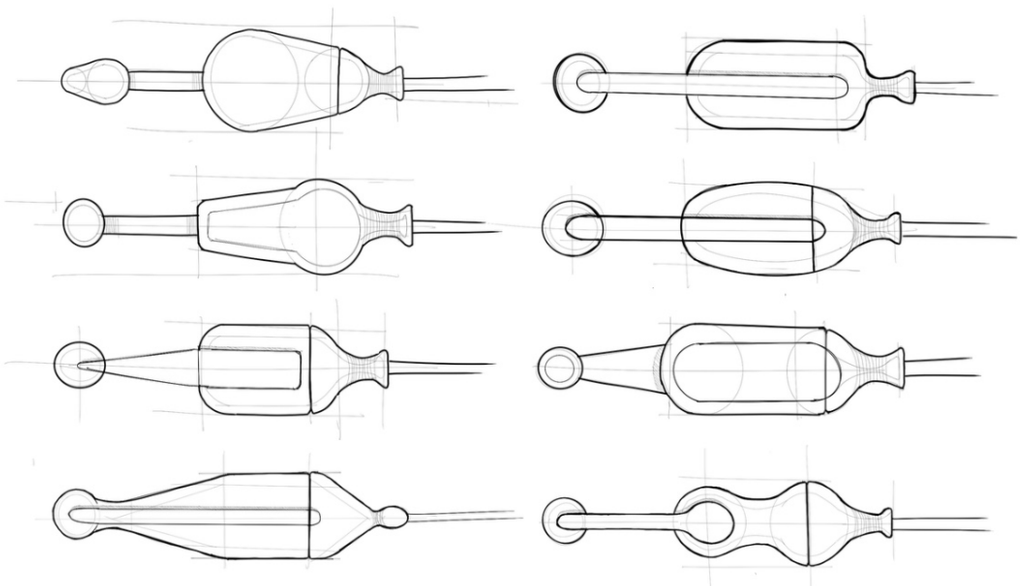


Fig. 62: Form study sketch

Production and Assembly

Figure 64 shows the material, production technique and assembly mechanisms for the reusable base. As this is a conceptual design, this is a first iteration production and assembly design. In next iterations, this design should be further detailed with the help of engineering experts.

A component assembly to highlight is the connection between the finger cushion (8) and the IR module base (5). Silicone rubber ring seals are frequently used in product designs to ensure water tightness. Similarly, the finger cushion's silicone rubber is compressed into the IR module base groove with the use of snap fits and a closure ring (6). This prevents water from entering the device, which could lead to bacteria growth.

The production and assembly of electronic components, like circuit boards were left out of scope. Similar to the reusable finger clip, these electronic components will be cast in PC plastic to ensure durability by preventing oxidation. The outer shape of this cast was modeled in the design.

Prototyping
The product assembly was prototyped using a 2:1 scale model (figure 63)

TAKEAWAYS

- The securing mechanism allows the reusable base and single-use patch to be removed individually, preventing accidental discards.
- Cable repair is facilitated through a screw in cable module.
- The product expresses safety, technical sophistication, and comfort.

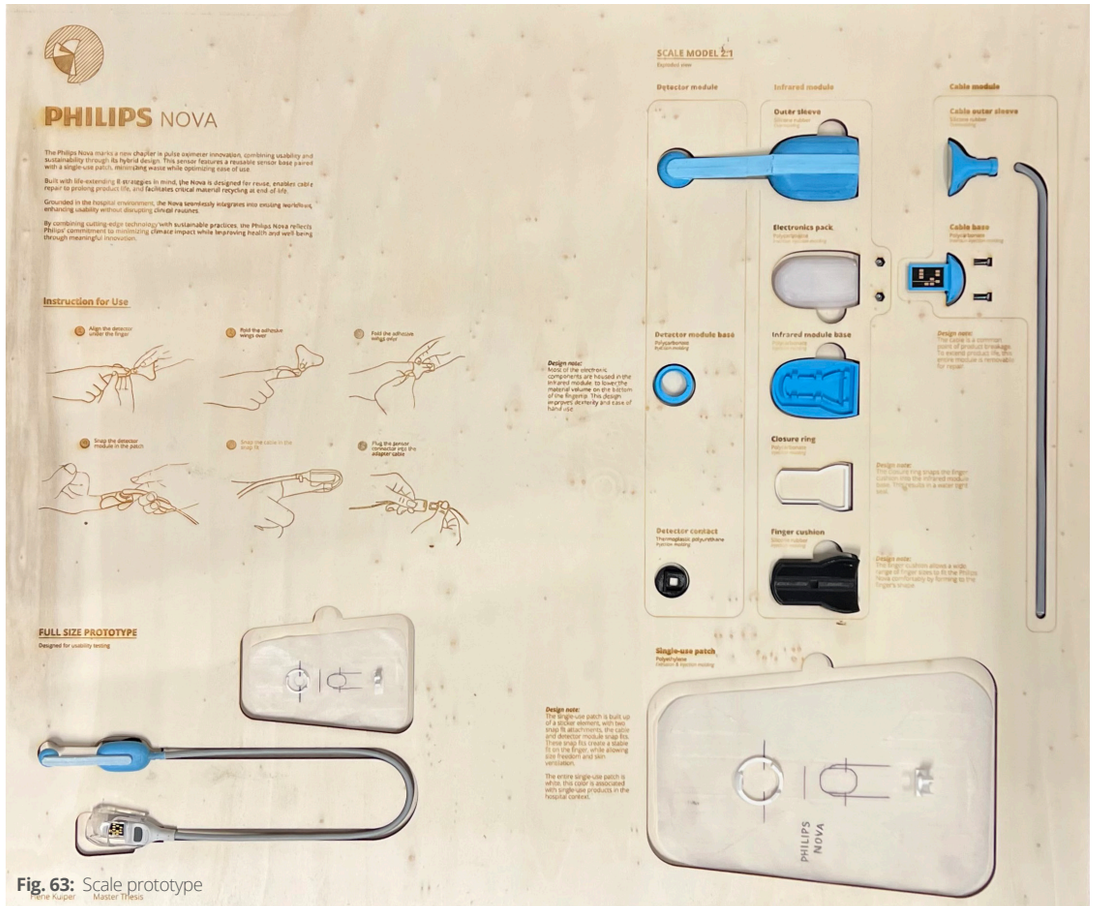


Fig. 63: Scale prototype
Fiene Kuiper Master Thesis

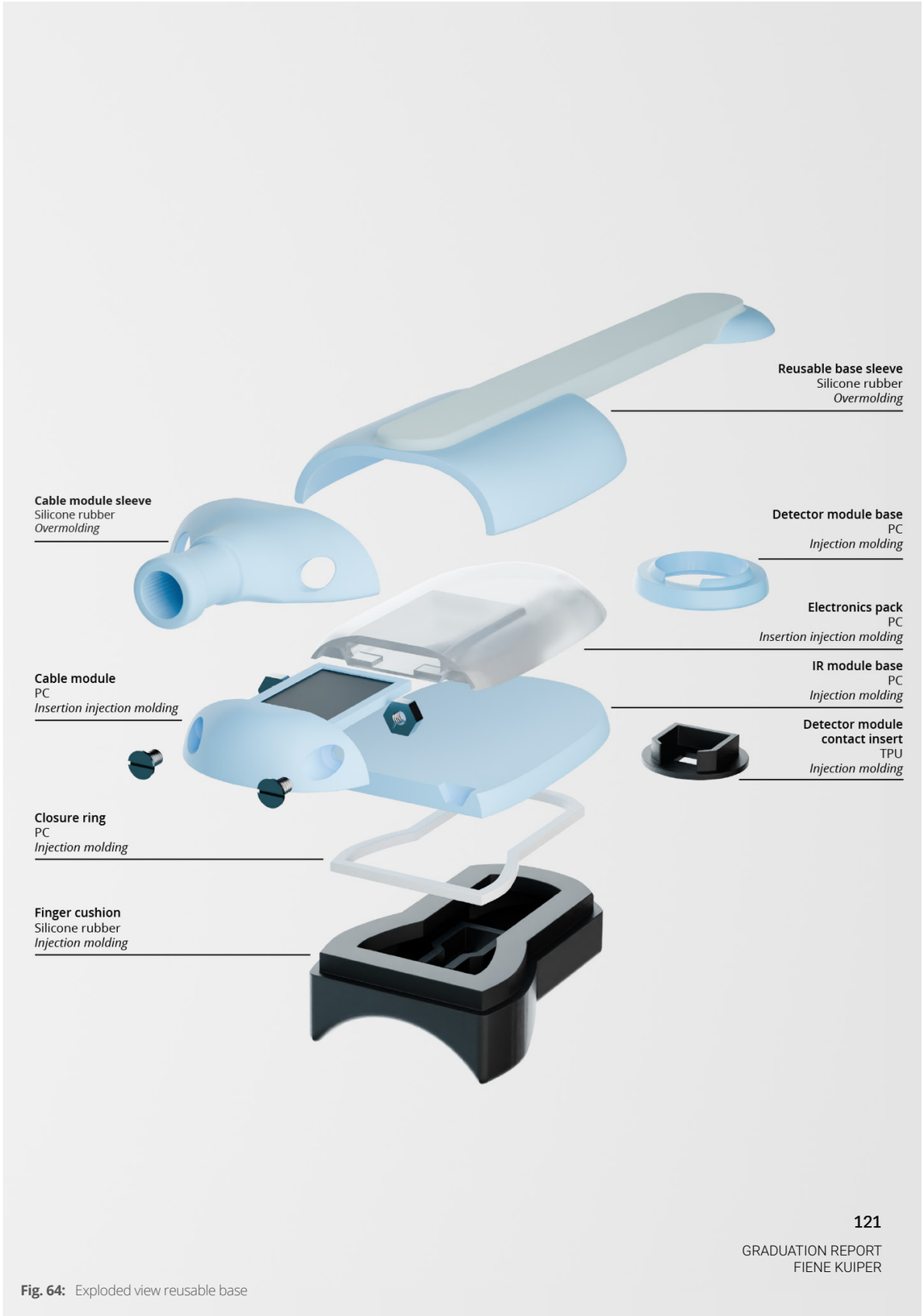


Fig. 64: Exploded view reusable base

9.3 / SINGLE-USE PATCH

Req ID	Category	Requirement
SP3.1	Price	The Single-use patch costs €0,10 or less to manufacturing
SP3.2	Usability	The adhesive peeling time should be limited to 2 seconds
SP3.3	Usability	Adhesive components should be designed to avoid sticking together during and after backing peeling
SP3.4	Usability	The sticker can be applied to the finger before adding on the reusabel component
SP3.5	Usability	The design of the patch informs proper aligment
SP3.6	Usability	The design of the patch shows what side is the top and which is the bottom
SP3.7	Technical functioning	No material may ubstruct the light path beside the finger
SP3.8	Manufacturing	Disposable element has to be producable in quantities of 1.800.000 yearly

Patch design

The design of the single-use patch is based on the current single-use pulse oximeter, ensuring a familiar application process for nurses while guiding proper alignment (Req. SP3.5). As with the current single-use design, a printed finger icon on the top of the patch clearly distinguishes the top from the bottom (Req. SP3.6). Additionally, perpendicular alignment stripes help ensure that the infrared (IR) lights and detector remain vertically aligned during application (Req. R2.7).

To facilitate the connection between the patch and the reusable base, snap-fit mechanisms have been incorporated into the patch design (explained in 8.2). To prevent any obstruction of the light path, certain areas of the sticker have been removed (Req. SP3.7). The overall shape of the patch has also been refined, featuring a slimmer middle section and an extended top half to prevent the wings from interfering with the snap fits.

For ease of use, a peel-up edge has been integrated into the design. This small, non-adhesive section allows users to easily lift the patch from its backing.

Finally, all design elements on the sticker are white, a color widely associated with single-use items in hospital settings, reinforcing its disposable nature.

TAKEAWAYS

- The single-use patch application is familiar, resulting in easy adoption.
- The top and bottom of the patch are easy to differentiate.

Production and assembly

The single-use patch is made from extruded low-density polyethylene (LDPE) and is securely attached to the high-density polyethylene (HDPE) injection-molded snap fits using either PE adhesive or overmolding techniques. The material compatibility between LDPE and HDPE ensures a strong bond while also allowing for potential future recycling opportunities.

The LDPE material of the patch is slightly elastic, ensuring a comfortable fit around the skin. Additionally, like 3M Transpore tape, the patch is porous, allowing proper skin ventilation (3MTM TransporeTM Surgical Tape, 1527, z.d.).

The patch backing is also made out of LDPE, but avoids the paper like look of the current single-use backing, to avoid incorrect waste separation.

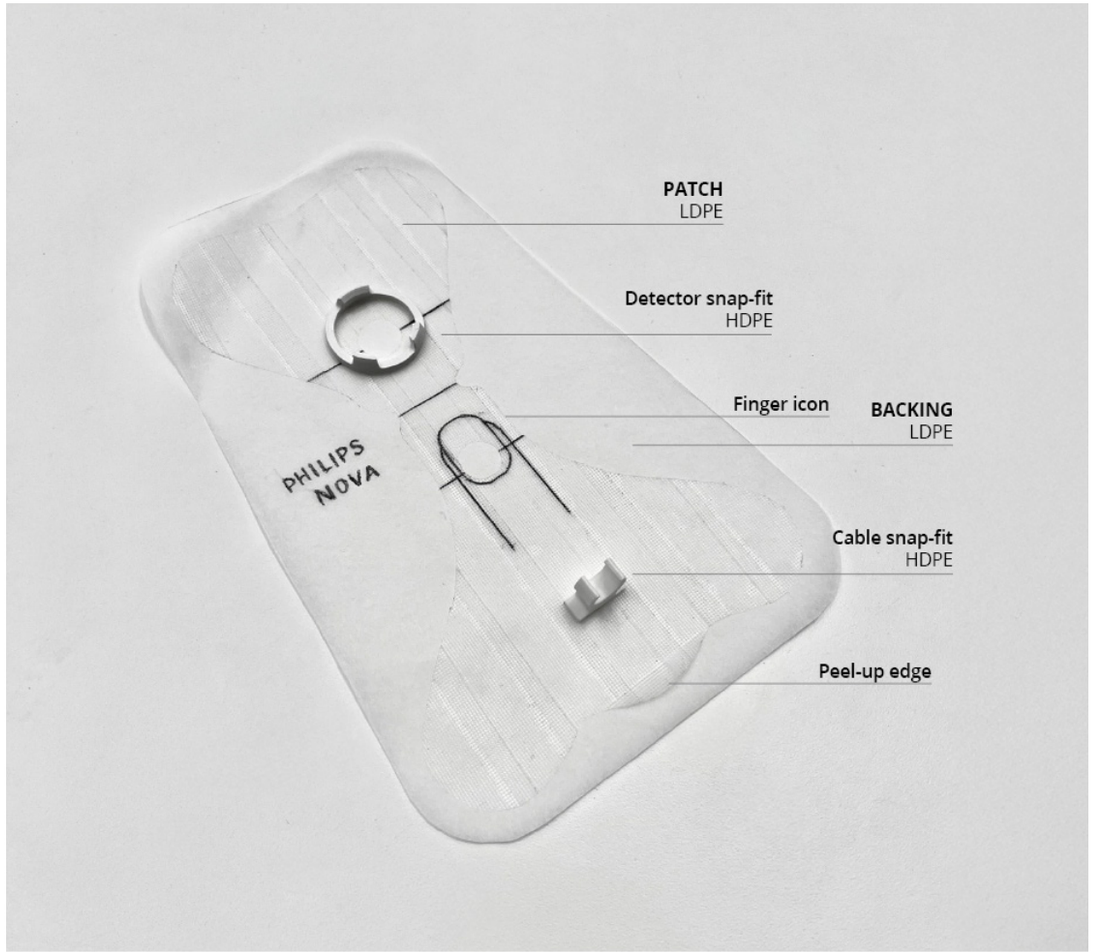


Fig. 65: Single-use patch design

9.4 / USABILITY STUDY

To compare the Philips Nova with existing pulse oximeters used at Erasmus MC, a usability evaluation was conducted (Appendix I). The evaluation focused on five key requirements: ease and speed of application, sensor stability, comfort and technical sophistication.

Testing took place in a simulated ICU environment using a training patient room, identical to real patient setups. Six ICU nurses were instructed to apply the Philips Nova, the single-use sensor, and the reusable sleeve sensor to a fellow student acting as a patient. Prior to application, they viewed an instructional video. Observations and survey-guided interviews formed the basis for this evaluation.

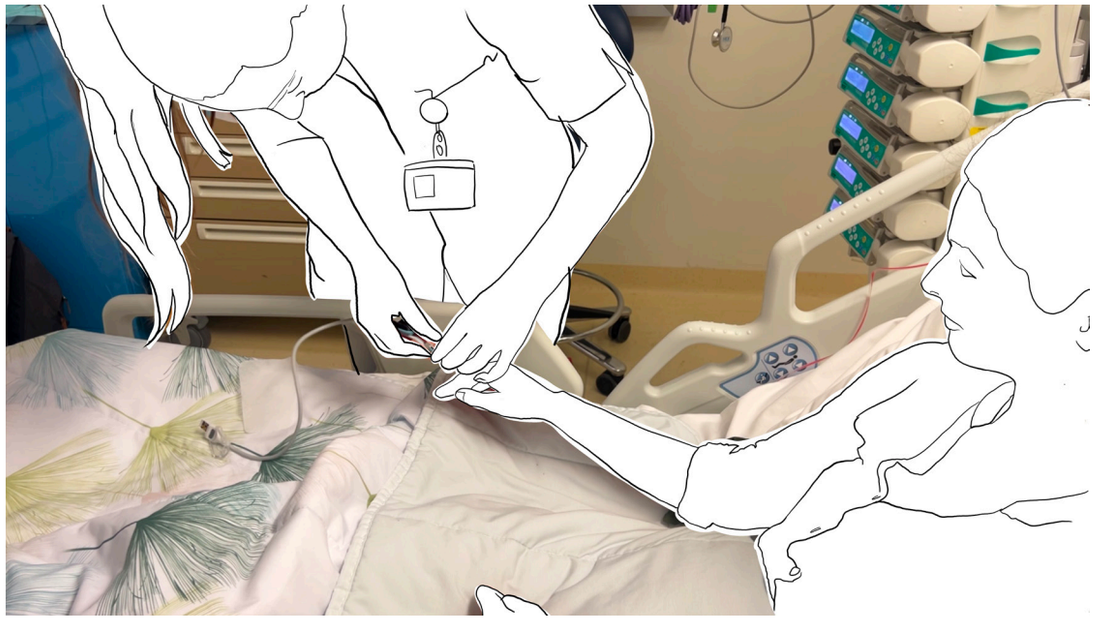


Fig. 66: Usability study context

Application time

As shown in Figure 67, the Philips Nova had a significantly longer application time (41 seconds) compared to the single-use (12s) and reusable (9s) sensors. A large portion of this time, around 37%, was spent on closing the bottom snap-fit, hindered by prototype limitations such as inconsistent tolerances and inflexible materials.

Aside from prototype flaws, the application also required more precision, particularly with the small snap-fits. This was evident in the nurses' posture, as they leaned in more closely when applying the Philips Nova. Redesigning the snap-fits with better tolerances, bevels, and more forgiving materials could help reduce application time and improve usability in urgent settings. (see Recommendations)

Speed of application was also evaluated through the interview, see figure 69. The nurses recognized that the Philips Nova took longer to apply than both the single-use and reusable sensor, however they still rated the speed of application high on the likert scale. They emphasized that the extra step would not form a barrier and could easily be integrated into their routine.

"Practice makes perfect."

"The extra step really isn't a problem! Really, it's not!"

The application time evaluation confirms that in very time-sensitive situations, like patient transfers to the ICU, the reusable sensor is most optimal. This sensor would therefore live alongside the Philips Nova (chapter 8.6).

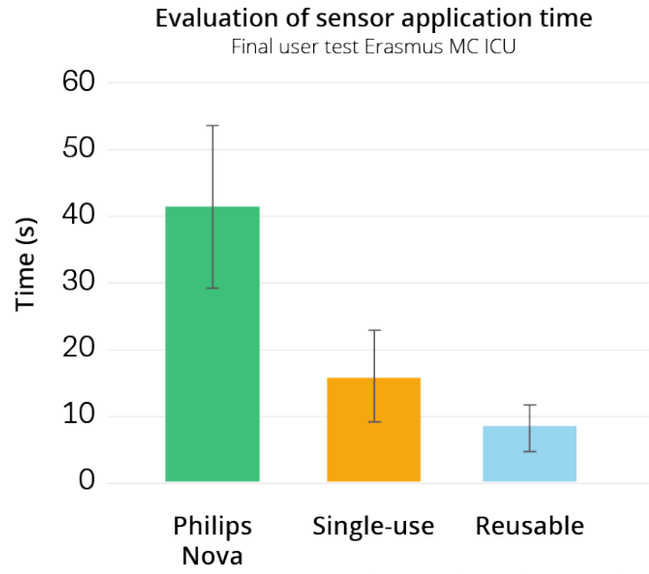


Fig. 67: Evaluation of sensor application time diagram

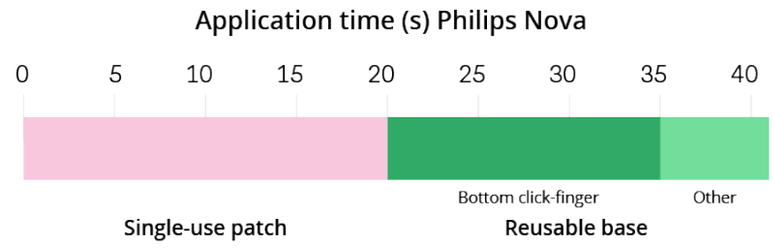


Fig. 68: Application time Philips Nova split per component

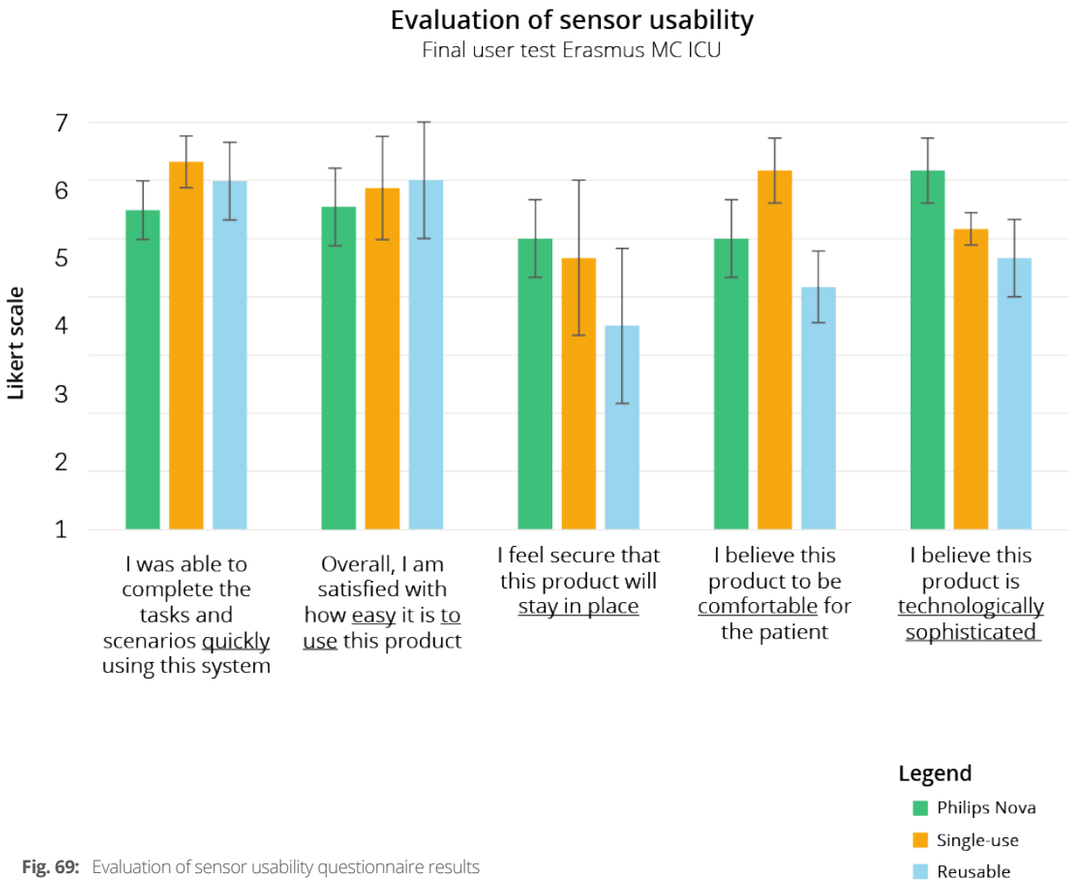


Fig. 69: Evaluation of sensor usability questionnaire results

Ease of use

The Philips Nova use was instructed through an instructional video at the start of the test. After watching this video most nurses applied the Philips Nova without hesitation. Initial uncertainty disappeared entirely by the second application.

"Well that should be easy"

"Once you've used it once, you know how it works."

Two notable deviations from the video were observed. First, nurses didn't rotate the hand to see the bottom snap, instead completing the step by feel. The audible click served as a reassuring cue. Second, many nurses applied the bottom snap sideways before rotating it into place, an unintended but intuitive use interaction enabled by the prototype's looser tolerances. Though not part of the original design, this motion was preferred. It may be worth exploring in future iterations, provided it doesn't introduce more movement artifacts (see Recommendations).

Overall, the application of the Philips Nova was perceived as straightforward and intuitive, with minimal hesitation from nurses despite minor prototype limitations. The instructional video proved effective in building confidence and understanding, making it a valuable tool for onboarding staff when the sensor is introduced to the department.

Security

Nurses rated the Philips Nova highest in terms of perceived security. Generally, nurses were not worried the base would come loose from the patch. The physical snap connection gave a strong sense of reliability, even higher than the single-use sensor in some cases.

For semi-conscious patients who pull at their sensors, nurses often apply sensors to the toe, which is an approved use site (RD SET® Series, 2020). This was tested with one nurse, who found the Nova's base slightly too short. A minor adjustment (Recommendations) could enable toe application and broaden the Nova's applicability.

Comfort

The Philips Nova was experienced as relatively comfortable, especially compared to the reusable. A big advantage compared to the reusable was the breathable material and flexibility for different finger sizes.

"The reusable one is really annoying, it's too loose on thin fingers and doesn't fit thick ones. It's never quite right."

However, nurses noted concerns about potential pressure ulcers if patients lay on the base for extended periods. This concern also applied to the reusable sensor and should be studied further (recommendations). The slightly reduced hand dexterity due to the rigid base was another drawback. Future iterations could explore smaller and softer detector module designs for improved ergonomics.

If, the risk of pressure ulcers would be ruled out, the single-use sensor and Philips Nova would be ranked similarly on level of comfort for the patient.

"You hardly notice either the Philips Nova or the single-use sensor."

Technical Sophistication

Of all requirements, the Philips Nova ranked the highest on the level of technical sophistication. People were intrigued by the look of the product, which excelled over the other sensors.

"I think it's a beautiful product"

"It looks professional."

In contrast, the reusable sensor was perceived as outdated.

"This is definitely a bit of an older device."

The perception of technological sophistication is hoped to decrease the likelihood of accidental disposal of the reusable base, and is likely to inspire user trust.

The single-use' disposable nature and unreliable measurements resulted in a lower perceived technological sophistication.

"The single-use is really sensitive to movement."

Cleaning

Although not a primary focus, cleanability came up repeatedly in interviews. The reusable sensor was criticized as being difficult to clean, particularly on the inside:

“They’re the most sustainable, but also the dirtiest”

The Philips Nova was seen as much easier to clean due to limited skin contact and accessible surfaces.

Overall, nurses responded positively to the Philips Nova. Despite a longer application time, they found it intuitive, secure, comfortable, and technologically advanced. Superior technological components in the reusable base, resulting in more stable measurements would outweigh many of the Nova’s downsides. With clear communication of the sustainable advantage and recommended design adjustments, the transition to this new hybrid sensor could be a welcome one:

“I look forward to seeing them on our ward!”

Further design recommendations are discussed in Chapter 10.2.

TAKEAWAYS

- Philips Nova took longer to apply due to its two-part setup, but nurses didn’t see this as a barrier
- Nurses quickly understood how to use the sensor, especially after one application and video instruction.
- The sensor is perceived as modern and professional, boosting trust and perceived value of the sensor.

9.5 / TRACEABILITY

Req ID	Category	Requirement
T4.1	Price	The increase in sensor price to accomodate traceability, should not lower purchase attractiveness
T4.2	Data	Centralized cleaning cycles should be able to be registered to the pulse oximeter
T4.3	Data	Last use location of the pulse oximeters within the hospital should be identifiable digitally by hospital personel
T4.4	Data	Product lifespan should be identifiable by the Medical Technology department to determine coverage by manufacturer warrenty
T4.5	Data	Lifespan of sensors at end-of-life should be known to Philips to identify product improvements
T4.6	Data	The sensor tracks utilization time and frequency
T4.7	Data	The sensor tracks maintenance records
T4.8	Data	The sensor tracks part cable repair
T4.9	Usability	The tracking of utilization time and frequency and last use location can not be obstructed by user error

Required data

To allow the possibility of implementing a product-as-a-service business model, and to facilitate product traceability through the hospital a list of minimal required data and nice-to-have's was set up, in collaboration with Philips, see figure 70. This list of data set barriers for exploring and filtering technical system components.

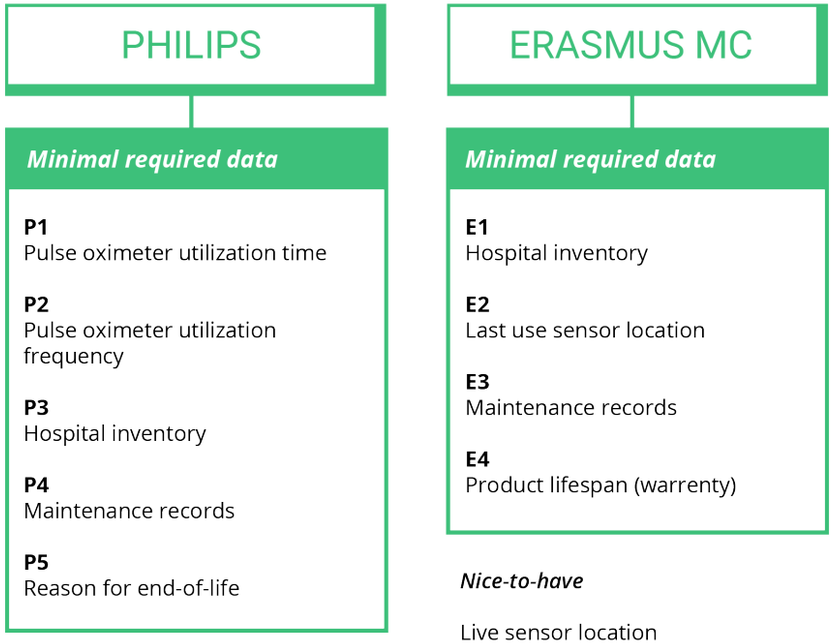


Fig. 70: Required data for traceability system

Implemented technologies

The traceability system is built around three core technologies, integrated into both the sensor and an additional adapter.

Sensor

1. ***Digital chip (EEPROM)***
   An Electrically Erasable Programmable Read-Only Memory (EEPROM) chip enables the storage of small amounts of data within the circuit board of the Philips Nova. Within the Philips Connect system, each sensor is assigned a unique sensor ID, which can be read by the adapter when plugged in. This ensures that all usage data is linked to the correct sensor (A Guide to EEPROM, z.d.).
   The EEPROM requires two additional contact points on the cable connection, one for data transfer and one for power. This increases the contact points on the cable end from 7, required for infrared lights and detector, to 9.

2. ***Unique Device Identifier (UDI)***
   A Unique Device Identifier (UDI) is a mandatory alphanumeric code assigned to all medical devices. It connects to the Global UDI Database, which stores essential manufacturing information such as serial numbers. Additionally, the UDI can be linked to an EMC or Philips-specific databases, allowing maintenance and cleaning teams to scan the code and register product updates, including cable replacements,

Fig. 71: EEPROM chip (Modify Stored Data with EEPROM, z.d.)

Fig. 72: UDI on pulse oximeter

testing frequency, and reasons for end-of-life (Unique Device Identifier, 2024).

EMC currently uses hospital-specific barcodes, which, when scanned, provide access to the Ultimo asset management system. The integration of UDI into this system prevents the need for an additional code.

Adapter
The adapter is plugged into the vital sign sensor ports of the 'broodje' (monitoring unit). It is powered directly by the 'broodje' and includes cloud connectivity and a Wi-Fi positioning system for location tracking.

An external adapter was chosen instead of embedding tracking features into individual sensors to enhance scalability across the entire monitoring system, including all vital sign sensors and the 'broodje' itself. By integrating high-cost components such as cloud connectivity and Wi-Fi positioning into the adapter rather than the sensors, hospitals can implement an efficient tracking system without significantly increasing sensor costs. Since a broodje costs approximately €10,000, preventing its loss with a relatively low-cost adapter provides a clear financial benefit and improves overall equipment tracking.

3. ***Wi-Fi positioning system (WPS)***
   A Wi-Fi-positioning system uses the existing Wi-Fi infrastructure in the hospital to determine the location of the adapter. It does this by identifying existing Wi-Fi signals in the range of the adapter, measuring the signal strength of the Wi-Fi access point and using their known locations to distill its own location. This positioning system is great for indoor localization, and has low investment costs due to the reliance on existing infrastructure.
   The accuracy of a WPS can vary from 5-20 meters, depending on the amount of Wi-Fi access points. This meets the requirement of determining product location on department level. (Zandbergen, 2009).

System in use steps

1. Connect the sensor to the 'broodje' through the adapter.
2. The adapter reads the unique sensor ID from the EEPROM
3. The adapter records the usage time of the sensor
4. The adapter stores the usage data in the Philips Connect cloud database together with the recorded sensor ID and adapter location
5. Philips and the EMC gain access to usage data of the sensors and 'broodje'
6. The EMC can look up the last use location of sensors and real-time location of 'broodjes' allowing redistribution over departments.

TAKEAWAYS

- The EEPROM chip allows the adapter to recognise every individual sensor's ID.
- The UDI can be connected to a EMC or Philips-specific database to store equipment usage and maintenance data.
- The adapter, as the most expensive component is attached to the most valuable monitoring component, the broodje.
- Wi-Fi positionin systems allow traceability on department level, using the existing hospital infrastructure.

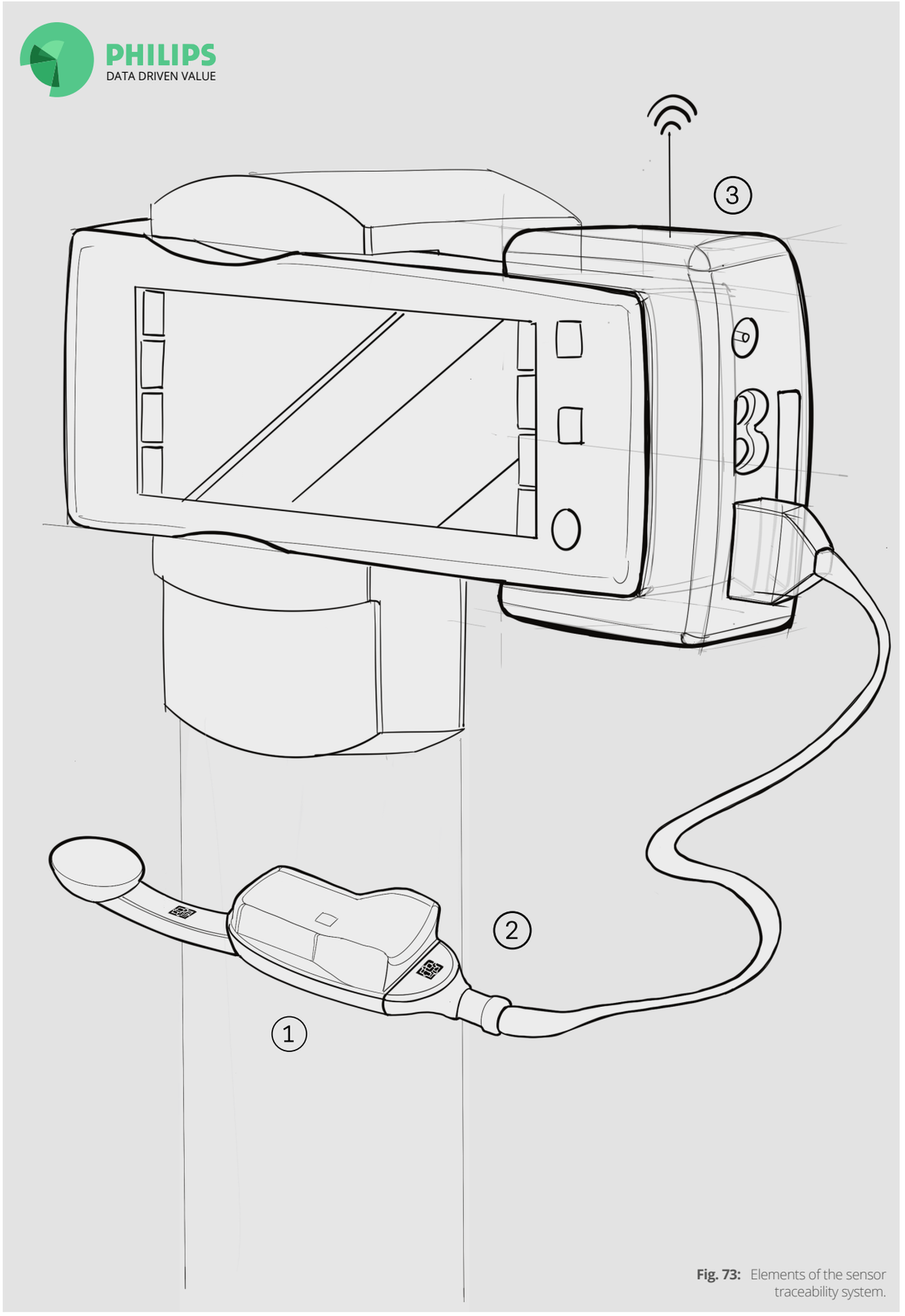


Fig. 73: Elements of the sensor traceability system.

10

CONCLUSION

This chapter concludes the thesis by outlining the implications of the research and design for Erasmus Medical Center, Philips, and the environment. It highlights areas where the research could be expanded or further detailed, including limitations and recommendations related to project scope, potential unintended consequences, sustainability considerations, technical development, and usability. The chapter comes full circle by providing a final answer to the main research questions and includes a reflection on my personal journey throughout the project.

10.1 / IMPLICATIONS

The research findings and product redesign aim to have implications for both collaborating parties, the EMC and Philips as well as for the environment.

Implications for the EMC

This project highlights the crucial role hospital systems play in enabling the adoption of sustainable medical devices. Within Erasmus MC, the research uncovered several key barriers for transitioning toward a reusable pulse oximeter system. Through collaborative solution brainstorming, the foundation for addressing these barriers has already been laid, but should be developed further.

Looking ahead, the Philips Nova concept, with its hybrid design and traceability features, offers a promising opportunity for hospitals to reduce waste and emissions while improving patient comfort and reducing the workload for nursing and medical technology staff. By replacing current single-use sensors with this redesigned model, hospitals can also lower costs by preventing unnecessary repeat purchases of reusable sensors due to loss. Furthermore, this shift enables the adoption of a circular procurement strategy, such as product-as-a-service.

Implications for Philips

For Philips, the Nova concept represents a next step toward sustainability-driven product innovation. By combining a reusable sensor base with a single-use patch, it supports existing business models through continuous revenue from patch repurchasing, providing a steady and predictable cash flow. At the same time, the design places reusability at the core, encouraging longer product lifespans through repairability and traceability. Nova also opens the door for new service-based models, such as product-as-a-service or centralized cleaning.

The project illustrates the importance of designing with system integration in mind, encouraging Philips to carefully map the current and future journeys of their products, to align with pressing user needs and easy system integration. Furthermore, the findings highlight a gap in reusable options for low-perfusion monitoring, offering a strategic opportunity for Philips to expand its product line in this area

Implications for the environment

This project highlights the importance of integrating both product and system redesign to accelerate sustainability transitions in healthcare. The fast-track Life Cycle Assessment confirms a significant environmental advantage of reusable sensors compared to single-use alternatives. This report provides practical guidance for enabling the transition toward reusable pulse oximeters, both in the short term through system-level interventions, and in the long term through product redesign. This results in immediate and lasting sustainable change.

The Philips Nova sensor showcases how multiple R-strategies can be applied across the product lifecycle to retain material and product value for as long as possible. Together, these strategies bring pulse oximetry closer to achieving circularity.

10.2 / LIMITATIONS AND RECOMMENDATIONS

Although this project aimed to take a holistic approach by addressing sustainable vital sign sensing at both the systemic and product levels, certain limitations remain. These reflect the complexity of implementing sustainability within the healthcare sector and point to areas for further exploration. The following sections present the most relevant limitations and recommendations, grouped into categories: study scope, potential adverse effects, sustainability, technical development, and usability.

Study scope

Limited context
This study focused solely on the adult departments of the EMC, limiting its generalizability across different hospital types and patient populations. Hospitals such as Reinier de Graaf have already transitioned to full reuse, suggesting that contextual factors can significantly influence adoption success. Understanding what enables reuse in those settings could offer valuable insights for broader implementation strategies.

Additionally, pediatric departments, where single-use sensor consumption is often even higher, were not included. These departments may present additional challenges, which require customized reusable solutions.

Finally, the research was conducted within the Dutch healthcare system, where cleaning responsibilities, liability frameworks, and procurement structures differ from those in other countries. In the United States for example, stricter cleaning protocols and legal liability concerns may present further barriers. To scale reusable innovations globally, Philips should explore how global differences shape the feasibility of reuse across different healthcare contexts.

Medical device regulations
This project did not include an in-depth investigation into the medical regulations applicable to pulse oximeters. While key requirements were validated through consultation with a Philips product lead, the Nova has not yet undergone full regulatory assessment. To ensure market viability, further research is needed to verify compliance with relevant medical device standards.

Additionally, safety, performance, and quality requirements must be addressed through extensive clinical testing.

Low perfusion patient group
A significant portion of ICU patients suffer from low peripheral perfusion, making standard finger-based pulse oximetry unreliable. In such cases, the Philips Nova offers limited added value, as it relies on the same measurement principles. Currently available reusable low-perfusion sensors present notable drawbacks, such as discomfort, instability, or limited availability.

Given the size and clinical relevance of this patient group, Philips is recommended to explore the development of a new reusable sensor specifically optimized for low-perfusion scenarios. This sensor could significantly reduce single-use sensor dependence in critical care environments.

Adverse effects

Transition from Reusable to Philips Nova
While the Philips Nova is intended to replace single-use sensors where full reuse is not feasible, there is a risk that departments may switch from existing reusable sensors to Nova, which could increase environmental impact (figure 74). The design aims to prevent this by aligning more closely with single-use sensor characteristics (like stability and long-term comfort), making it less appealing in contexts where reusable sensors are already functioning well (like time-sensitive scenarios). However, in some cases, improved comfort and fewer nuisance alarms may still prompt such a switch. A more detailed LCA using manufacturer data is recommended to assess this risk. Philips should also clearly communicate environmental trade-offs to hospitals to guide responsible purchasing decisions.

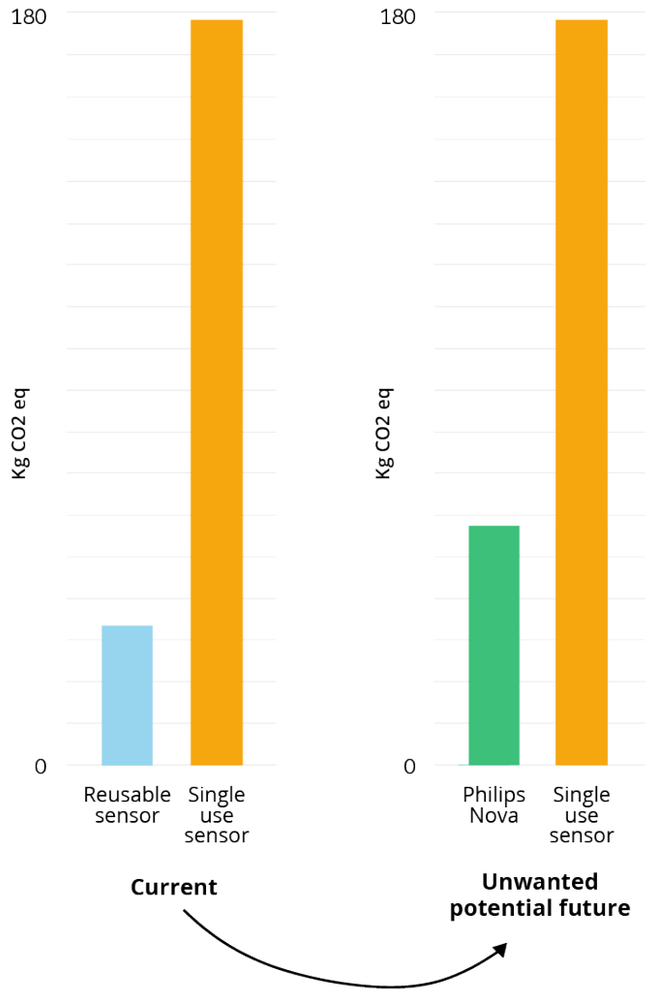


Fig. 74: Unwanted sustainability transition from reuse to Nova.

Risk of discarding the reusable base
The hybrid design of the Philips Nova introduces a risk that nurses may mistakenly discard the reusable base along with the single-use patch. While the product and system were designed to mitigate this, by separating the components and providing awareness materials during implementation, the risk remains. Premature disposal of the base could reduce or negate the product's sustainability benefits, making continued attention to this issue essential during rollout and training.

Sustainability

Recyclability of precious metals
While copper recovery from medical cables is well-supported by existing recycling technologies (Loibl & Tercero Espinoza, 2021), other aspects of the sensor's end-of-life treatment remain uncertain. Parts of the Philips Nova's electronics are encapsulated in molded plastic to enhance durability, but this can hinder the recyclability of valuable materials. It is currently unclear which metals are present and whether effective separation is still feasible once the components are cast.

Further research is needed to evaluate the exact material composition and to investigate advanced recycling and manufacturing technologies. For example, a new separation layer cast techniques could be explored to allow material recycling of two-part injection molded electronics (Brasse et al., 2024).

Philips is encouraged to assess the trade-off between product durability and recyclability early in future design iterations. Identifying design strategies that preserve robustness while enabling material recovery could further improve the sensor's sustainability at end-of-life.

Technical development

Electronic functioning
The electronics were largely left out of scope for this project, with the current components being maintained for size and basic functionality requirements. Aside from adding an EEPROM chip, the core electronic components have remained unchanged. However, it is recommended to optimize the design for electronic integration and further enhance pulse oximetry readings by reducing movement artifacts and improving measurement accuracy on darker skin tones (Al-Halawani et al., 2023). These improvements could significantly enhance the sensor's desirability and inclusivity.

Design for manufacturing
The Philips Nova is still in an early design phase and not yet ready for market introduction. Beyond the electronics, the individual components require optimization for efficient and scalable production, and further validation is needed to ensure that the proposed manufacturing methods are technically and economically feasible. Additionally, mechanical durability remains to be tested. Force simulations and physical strength tests, such as Finite Element Method (FEM) analysis, are necessary to confirm that the reusable base meets the required performance standards during clinical use. These steps are essential to ensure both manufacturability and long-term product reliability in demanding hospital environments.

Usability

Prototyping limitations
The user test revealed several prototyping limitations that impacted application time. One key issue was the 3D-printed snap fit tolerances, particularly in the bottom snap fit, which accounted for 37% of the Philips Nova's total application time. These tolerances should be optimized for injection molding to reduce application time and improve durability. Additionally, the width of the bottom snap fit must be tested on a diverse range of finger sizes to ensure comfort across varying hand dimensions.

The single-use patch should also be produced using the same material as the adhesive wings of the current single-use sensor. These are slightly stiffer than the prototype patches, enabling faster and more efficient application.

Fit on the Toe
To increase versatility and applicability across different patient scenarios, the Philips Nova should be optimized to ensure a secure and comfortable fit on the toe. This alternative placement is particularly useful when finger sites are unavailable or when patients have a tendency to pull sensors off their fingers. In addition to design optimization, clinical validation of toe placement is necessary to allow for on-label use and ensure measurement accuracy in this location.

Pressure Ulcer Risk
Preventing pressure ulcers caused by medical equipment is critical in hospital settings. Sensors that cause discomfort or require frequent repositioning not only risk patient harm but also increase workload for nurses. During user testing, concerns were raised about the snap fit and detector module of the Philips Nova, particularly regarding the potential for pressure points if patients rest their hand on the sensor for extended periods. Further research is needed to evaluate the risk of pressure ulcers associated with long-term use and to explore design modifications that minimize localized pressure.

Sideways snap application
Since nurses typically stand beside the patient, it is more intuitive to insert the detector module into the snap fit from the side. From there, it can be rotated and aligned correctly before snapping into its final position on top. This application interaction is currently not allowed by the design, this should be changed. Whether this sideways application compromises the stability of the connection, by introducing more movement freedom, should be further investigated. However, this approach aligns more naturally with the user's workflow (figure 75).

Testing module
Currently, the Fluke Pro Sim 8 is used to test the pulse oximeter sensor, utilizing its finger-shaped module where the sensor can be attached for testing. With the current Philips Nova design, however, the single-use sticker needs to be applied to the test module for proper functionality. It would be beneficial if an additional component were developed to allow testing of the reusable base without the sticker, perhaps by creating a mechanism to slide the base into the testing module directly. This would improve the testing process, making it more efficient and reducing reliance on the disposable sticker. modifications that minimize localized pressure.

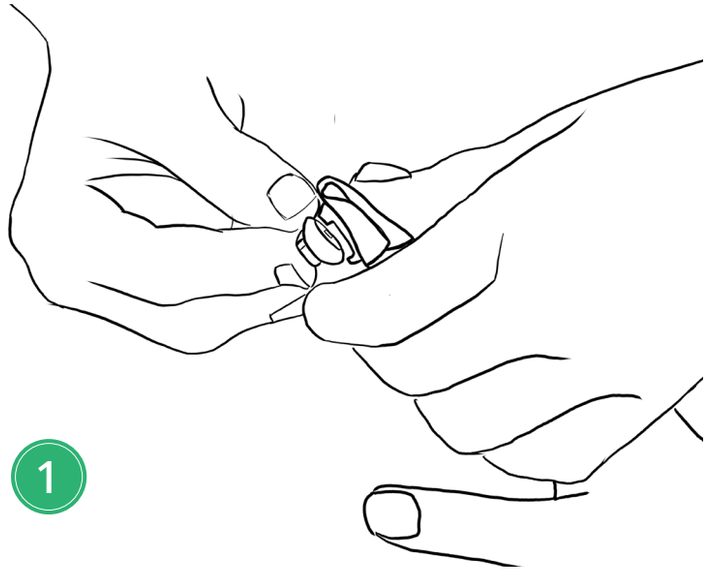


Fig. 75 Sideways snap application interaction sketch

10.3 / CONCLUSION

Research revealed that pulse oximetry in hospitals carries a significant environmental impact due to the high volume of single-use sensors (Noort et al., 2024). Although hospitals are actively aiming to transition to reusable alternatives, offering clear sustainability advantages, this shift is hindered by both systemic and product-level barriers (Duffy et al., 2023). This thesis identified and analyzed these barriers, and sought to address them through a combination of co-creation, product development, and system redesign. The goal was to reduce the environmental footprint of pulse oximetry within adult departments of Dutch hospitals by reducing the reliance on single-use sensors.

1. WHAT PRODUCT AND SYSTEM FEATURES FORM BARRIERS FOR REUSABLE PULSE OXIMETER USE?

Barriers to the adoption of reusable pulse oximeters were found at both the product and system levels. Systemic barriers include inconsistent cleaning responsibilities across departments, a lack of traceability and equipment exchange during patient transfers, unawareness of single-use consumption quantities, and the frequent off-label use of single-use sensors, especially in low-perfusion patients. At the product level, key issues are instability of the reusable sensor, alarm fatigue, discomfort during prolonged use, and a lack of options for patients with low peripheral perfusion. Together, these barriers cause nurses to gravitate toward single-use sensors, despite the availability of reusable alternatives. The current reusable sensors also present sustainability challenges due to limited durability, as their design allows for dirt buildup and frequent cable breakage, leading to early product failure without the possibility of repair.

2. HOW CAN THE CURRENT HOSPITAL SYSTEMS BE IMPROVED TO ELIMINATE BARRIERS FOR REUSABLE PULSE OXIMETER USE?

Through co-creation with hospital stakeholders, short-term intervention possibilities were identified to tailor the current hospital system towards reusable pulse oximetry: (1) improving the equipment exchange process through monthly redistribution of sensors, (2) aligning hygiene responsibilities and expectations across departments by assigning cleaning tasks to facility staff, and (3) conducting market research into safer low-perfusion sensors to reduce inaccurate off-label placements. These intervention possibilities should be further detailed and implemented to allow successful adoption of reusable sensors within the EMC.

3. HOW COULD A PRODUCT BE REDESIGNED TO OVERCOME THE BARRIERS FOR THE REUSABLE PULSE OXIMETER WITHIN THE HOSPITAL?

The Philips Nova was developed as a proof-of-concept hybrid sensor that addresses product-level barriers while incorporating circular strategies. It combines a reusable base with a single-use adhesive patch for patient comfort and stability. The design allows reuse through cleaning, repair by enabling cable replacement, critical material recovery through recycling and includes traceability through a Philips Connect adapter, EEPROM chip and QR-coded UDI. This enables lifecycle tracking and integration into circular business models. The Philips Nova minimizes disruption to hospital workflows by building on existing system opportunities, making it well-suited for integration into the EMC.

10.4 / PERSONAL REFLECTION

Over the past six months, I have had the opportunity to work on this thesis, marking the final chapter of my journey as a design student. This project has taught me a great deal, both personally and academically, and I would like to take a moment to reflect on that.

Balancing the system and the product

At the start of this project, I set a few personal ambitions. The first was to gain experience in systemic design. While my master's in Integrated Product Design has focused heavily on the product level, I wanted to broaden my perspective by exploring how design decisions affect the larger system and context in which a product operates. This thesis gave me exactly that opportunity. Investigating the complexities of the pulse oximetry system in the hospital allowed me to engage with a wide range of stakeholders and weigh their diverse needs. In this space, I discovered some of my strongest abilities.

Having such a broad focus did come with challenges, particularly with time management. Since the system analysis required significant attention, the product design phase had to move quickly. This was difficult for me, as I tend to be detail-oriented, but it taught me the value of fast idea validation through rapid prototyping and user testing. It was both an exciting and vulnerable process that helped me grow.

Stakeholder management

My second ambition was to strengthen my stakeholder management skills. This proved essential in a project involving such a diverse group of hospital and external stakeholders. I learned to dedicate real time to activities like scheduling meetings, reflecting on conversations, communicating findings, and aligning my own goals with those of Philips and Erasmus MC. I came to see that investing time in this process always paid off, and if anything, I could have done even more of it.

One of the most inspiring aspects of the project was organizing co-creation sessions. I enjoyed sharing my research and hearing personal stories from different stakeholders. It sparked my interest in working more with complex group dynamics, trying to align differing views and engaging non-designers in creative thinking. I would love to explore this further in my professional career.

Impact now!

One of the most meaningful lessons I learned is that the path to circularity is not only about the distant future. At the beginning of this project, I believed that my impact on sustainability would be long-term, contributing a concept that, after years of development and testing, might slightly reduce a hospital's footprint. While that is still true, I also discovered that simple, system-aware changes can already make a real difference. Once you truly understand the context around your product, small interventions can have immediate impact. The road to circularity is not just about advanced technologies or long-term innovation, but also about recognizing and acting on opportunities that exist today.

This project helped me reflect on my own professional direction. I learned that I am especially inspired by processes and systems design, perhaps even more than pure product design. It also confirmed that sustainability is a core driver for me in my work.

Thank you very much for reading my report. I hope it taught you something new, it certainly taught me a great deal.

If you have any questions or would like to discuss the project further, please don't hesitate to reach out.
I can always use another coffee ;)

10.5 / REFERENCES

Throughout the writing process, ChatGPT was used as a language support tool to improve the clarity and flow of the text. All content, analysis, and conclusions are my own.

3MTM TransporeTM Surgical Tape, 1527 (NL). (z.d.). Geraadpleegd 20 maart 2025, van https://www.3mnederland.nl/3M/nl_NL/p/d/b10105967/

About us. (z.d.). Philips. Geraadpleegd 22 februari 2025, van https://www.philips.com/a-w/about.html

Achterberg, E., Hinfelaar, J., & Bocken, N. (2016, september 22). Master Circular Business with the Value Hill—Insights—Circle Economy. https://www.circle-economy.com/resources/master-circular-business-with-the-value-hill

Al-Halawani, R., Charlton, P. H., Qassem, M., & Kyriacou, P. A. (2023). A review of the effect of skin pigmentation on pulse oximeter accuracy. Physiological Measurement, 44(5), 05TR01. https://doi.org/10.1088/1361-6579/acd51a

Arzoumanidis, I., D'Eusanio, M., Raggi, A., & Petti, L. (2019). Functional Unit Definition Criteria in Life Cycle Assessment and Social Life Cycle Assessment: A Discussion (pp. 1-10). https://doi.org/10.1007/978-3-030-01508-4_1

Bhutta, M. (2021). Our over-reliance on single-use equipment in the operating theatre is misguided, irrational and harming our planet. Annals of The Royal College of Surgeons of England, 103(10), 709-712. https://doi.org/10.1308/rcsann.2021.0297

Bocken, N. M. P., Mugge, R., Bom, C. A., & Lemstra, H.-J. (2018). Pay-per-use business models as a driver for sustainable consumption: Evidence from the case of HOMIE. Journal of Cleaner Production, 198, 498-510. https://doi.org/10.1016/j.jclepro.2018.07.043

Bordia, P., Hunt, E., Paulsen, N., Tourish, D., & Difonzo, N. (2004). Uncertainty during organizational change: Is it all about control? European Journal of Work & Organizational Psychology, 13. https://doi.org/10.1080/13594320444000128

Brasse, Y., Moreno, M. L., Blum, S., Horter, T., Janek, F., Gläser, K., Emmerechts, C., Clanet, J., Verhaert, M., Grymonprez, B., & Kraus, T. (2024). Recyclable In-Mold and Printed Electronics with Polymer Separation Layers. RSC Sustainability, 2(6), 1883–1894. https://doi.org/10.1039/d4su00092g

Bridges, J., De Jong, W., Hartemann, P., Stahl, D., & Thomsen, M. (2010). The Safety of Reprocessed Medical Devices Marketed for Single-Use. In European Commission. https://doi.org/10.2772/2166

Circular economy introduction. (z.d.). Geraadpleegd 19 december 2024, van https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Crede, S., Van der Merwe, G., Hutchinson, J., Woods, D., Karlen, W., & Lawn, J. (2013). Where do pulse oximeter probes break? Journal of clinical monitoring and computing, 28. https://doi.org/10.1007/s10877-013-9538-2

Critical raw materials: Will scarcity impede the energy transition. (z.d.). Tno. Geraadpleegd 30 januari 2025, van https://www.tno.nl/en/sustainable/circular-value-creation/critical-raw-materials-scarcity-impede/

Davies, J. F., McGain, F., Sloan, E., Francis, J., & Best, S. (2024). A qualitative exploration of barriers, enablers, and implementation strategies to replace disposable medical devices with reusable alternatives. The Lancet Planetary Health, 8(11), e937-e945. https://doi.org/10.1016/S2542-5196(24)00241-9

De Fazio, F., Bakker, C., Flipsen, B., & Balkenende, R. (2021). The Disassembly Map: A new method to enhance design for product repairability. Journal of Cleaner Production, 320, 128552. https://doi.org/10.1016/j.jclepro.2021.128552

Duffy, J., Slutzman, J. E., Thiel, C. L., & Landes, M. (2023). Sustainable Purchasing Practices: A Comparison of Single-use and Reusable Pulse Oximeters in the Emergency

Department. Western Journal of Emergency Medicine, 24(6), 1034. https://doi.org/10.5811/westjem.58258

Duncker, D., Svetlosak, M., & Guerra, F. (2020). Reprocessing of electrophysiology material in EHRA countries. https://academic.oup.com/europace/article/23/3/479/5934076

Environmental Impact of the Healthcare Sector. (2024, maart 6). Serres. https://www.serres.com/blog/environmental-impact-of-the-healthcare-sector-a-deep-dive/

Environmentally sustainable health systems: A strategic document. (z.d.). Geraadpleegd 30 december 2024, van https://www.who.int/publications/i/item/WHO-EURO-2017-2241-41996-57723

ESCH-R. (z.d.). ESCH-R Consortium. Geraadpleegd 22 februari 2025, van https://esch-r.org/

Essex, S., & Thording, L. (z.d.). Single-Use Device Reprocessing and the Circular Economy.

European Medicines Agency. (2024, augustus 28). Procurement. https://www.ema.europa.eu/en/about-us/procurement

Five reasons why healthcare providers are adopting as-a-service models in patient monitoring. (2023, 20 juni). Philips. https://www.philips.com/a-w/about/news/archive/features/2023/20230620-five-reasons-why-healthcare-providers-are-adopting-as-a-service-models-in-patient-monitoring.html

Fluke biomedical. (z.d.). ProSim 8 Vital Sign and ECG Patient Simulator. Geraadpleegd 21 januari 2025, van https://www.flukebiomedical.com/products/biomedical-test-equipment/patient-simulators/prosim-8-vital-signs-patient-simulator

Framework for Innovation. (z.d.). Design Council. Geraadpleegd 1 maart 2025, van https://www.designcouncil.org.uk/our-resources/framework-for-innovation/

Garcia-Gutierrez, P., Amadei, A. M., Klenert, D., Nessi, S., Tonini, D., Tosches, D., Ardente, F., & Saveyn, H. (2023). Environmental and economic assessment of plastic waste recycling. JRC Publications Repository. https://doi.org/10.2760/0472

Green Deal Duurzame Zorg 3.0. (z.d.). Green Deal duurzame zorg. Geraadpleegd 30 december 2024, van https://www.greendealduurzamezorg.nl/green-deal-duurzame-zorg/

Guzzo, D., Carvalho, M. M., Balkenende, R., & Mascarenhas, J. (2020). Circular business models in the medical device industry: Paths towards sustainable healthcare. Resources, Conservation and Recycling, 160, 104904. https://doi.org/10.1016/j.resconrec.2020.104904

Health, C. for D. and R. (2024, januari

8). Reprocessing Single-Use Medical Devices: Information for Health Care Facilities. FDA; FDA. https://www.fda.gov/medical-devices/products-and-medical-procedures/reprocessing-single-use-medical-devices-information-health-care-facilities

Hlavin, D., Bosma, G. N., Bolt, M. A., Sammel, M. D., Seyller, N., & Varty, M. (2024). Evaluating the Accuracy of Off-Label Placement of Pulse Oximetry Sensors in Comparison to On-Label Placement in the Adult Cardiac Intensive Care Unit Patient Population. Dimensions of Critical Care Nursing: DCCN, 43(4), 176-183. https://doi.org/10.1097/DCC.0000000000000647

Hoveling, T., Svindland Nijdam, A., Monincx, M., Faludi, J., & Bakker, C. (2024). Circular economy for medical devices: Barriers, opportunities and best practices from a design perspective. Resources, Conservation and Recycling, 208, 107719. https://doi.org/10.1016/j.resconrec.2024.107719

Huijben, J., Van Raaij, E., Wagelmans, A., Piscicelli, L., Shen, W., Van Vliet, B., Gommers, D., Tibboel, D., Bakker, E., Dekkers, F., Van Leeuwen, R., Diehl, J. C., & Hunfeld, N. (2025). Accelerating the transition from a linear to a circular healthcare sector: ESCH-R: study design and methodology. Frontiers in Public Health, 13. https://doi.org/10.3389/fpubh.2025.1542187

Jung, H., Kim, D., Lee, W., Seo, H., Seo, J., Choi, J., & Joo, E. Y. (2022). Performance evaluation of a wrist-worn reflectance pulse oximeter during sleep. Sleep Health, 8(5), 420-428. https://doi.org/10.1016/j.sleh.2022.04.003

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, 127, 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005

Lansdowne, K., Strauss, D. G., & Scully, C. G. (2016). Retrospective analysis of pulse oximeter alarm settings in an intensive care unit patient population. BMC Nursing, 15(1), 36. https://doi.org/10.1186/s12912-016-0149-3

Lee, H., Ko, H., & Lee, J. (2016). Reflectance pulse oximetry: Practical issues and limitations. ICT Express, 2(4), 195-198. https://doi.org/10.1016/j.icte.2016.10.004

Lewis, J. R. (1992). Psychometric Evaluation of the Post-Study System Usability Questionnaire: The PSSUQ. Proceedings Of The Human Factors Society Annual Meeting, 36(16), 1259–1260. https://doi.org/10.1177/154193129203601617

Lewandowska, K., Weisbrot, M., Cieloszyk, A., Mędrzycka-Dąbrowska, W., Krupa, S., & Ozga, D. (2020). Impact of Alarm Fatigue on the Work of Nurses in an Intensive Care Environment—A Systematic Review. International Journal of Environmental Research and Public Health, 17(22), 8409. https://doi.org/10.3390/ijerph17228409

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. Journal of Cleaner Production, 115, 36-51. https://doi.org/10.1016/j.jclepro.2015.12.042

Lockwood, C., Conroy-Hiller, T., & Page, T. (2004). Vital signs. JBI Evidence Synthesis, 2(6), 1. https://doi.org/10.11124/jbisrir-2004-371

Loibl, A., & Espinoza, L. A. T. (2021). Current challenges in copper recycling: aligning insights from material flow analysis with technological research developments and industry issues in Europe and North America. Resources Conservation And Recycling, 169, 105462. https://doi.org/10.1016/j.resconrec.2021.105462

Lucas, P., Wilting, H., & PBL Netherlands Environmental Assessment Agency. (2018). Using planetary boundaries to support national implementation of environment-related Sustainable Development Goals. In PBL. PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/sites/default/files/downloads/Using_planetary_boundaries_to_support_national_implementation_of_environmentrelated_Sustainable_Development_Goals_-_2748.pdf

Manufacturer and User Facility Device Experience (MAUDE) Database. (z.d.). Geraadpleegd 24 januari 2025, van https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfmaude/search.cfm

Masimo—RD SET Sensors. (z.d.). Geraadpleegd 10 maart 2025, van https://www.masimo.com/products/sensors/rd-set/

McAlister, S., Barratt, A. L., Bell, K. J., & McGain, F. (2020). The carbon footprint of pathology testing. The Medical Journal of Australia, 212(8), 377-382. https://doi.org/10.5694/mja2.50583

Miller, K. I., & Monge, P. R. (1986). Participation, Satisfaction, and Productivity: A Meta-Analytic Review. The Academy of Management Journal, 29(4), 727-753. https://doi.org/10.2307/255942

Miller, V., Johnson, J., & Grau, J. (1994). Antecedents to willingness to participate in a planned organizational change. Journal of Applied Communication Research, 22, 59-80. Journal of Applied Communication Research - J APPL COMMUN RES, 22, 59-80. https://doi.org/10.1080/00909889409365387

Ministerie van Volksgezondheid. (z.d.). Welke regels zijn er voor de herverwerking van medische hulpmiddelen? Ministerie van Algemene Zaken. Geraadpleegd 20 januari 2025, van https://www.rijksoverheid.nl/onderwerpen/medische-hulpmiddelen/vraag-en-antwoord/onderwerpen/medische-hulpmiddelen/vraag-en-antwoord/wat-zeggen-de-nieuwe-regels-over-medische-hulpmiddelen-over-herverwerking-en-hergebruik-van-hulpmiddelen

Modify Stored Data with EEPROM. (z.d.). Geraadpleegd 20 maart 2025, van https://www.futureelectronics.com/c/semiconductors/memory--RAM--eeprom

Nayak, A. (2022). CONCEPT OF CIRCULAR ECONOMY IN BUILDING CONSTRUCTION.

Nitzan, M., Romem, A., & Koppel, R. (2014). Pulse oximetry: Fundamentals and technology update. Medical Devices (Auckland, N.Z.), 7, 231-239. https://doi.org/10.2147/MDER.S47319

Nobre, G. C., & Tavares, E. (2021). The quest for a circular economy final definition: A scientific perspective. Journal of Cleaner Production, 314, 127973. https://doi.org/10.1016/j.jclepro.2021.127973

Noort, B., Gorter, S., De Vree, C., Smit, A., Vork, K., Visser, I., Cepella, G., À Nijeholt, J., Van der Pijl, M., & Breed, R. (2024). Landelijke Inventarisatie Medische Disposables UMC's. In Nederlandse Federatie van Universitair Medisch Centra. Green Deal Duurzame Zorg.

Ostapska, K., Rüther, P., Loli, A., & Gradeci, K. (2024). Design for Disassembly: A systematic scoping review and analysis of built structures Designed for Disassembly. Sustainable Production and Consumption, 48, 377-395. https://doi.org/10.1016/j.spc.2024.05.014

Pianegonda, L. (2022, november 20). Recycled Plastics and Medical Grade Plastics –

Can they go together? Gradical. https://gradical.ch/recycled-plastics-and-medical-grade-plastics-can-they-go-together/

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). Circular Economy: Measuring Innovation in the Product Chain (Nummer 2544). https://dspace.library.uu.nl/handle/1874/358310

Product Journey Mapping. (z.d.). Geraadpleegd 21 januari 2025, van https://www.circulardesignguide.com/post/product-lifecycle-mapping

RD SET® Series. (2020). techdocs.masimo. Geraadpleegd op 26 januari 2025, van https://techdocs.masimo.com/products/sensor/rd-set-adt/

RD SETTM DBI Reusable Soft Sensors. (2019). techdocs.masimo. Geraadpleegd op 26 januari 2025, van https://techdocs.masimo.com/products/sensor/rd-set-dbi-reusablesoft sensor/

Reprocessing overview Pulse oximeter. (z.d.). Stryker.

Sacher, F., Bacquelin, R., Bessiere, F., Ditac, G., Duchateau, J., Ait-Said, M., Boveda, S., Extramiana, F., Delsarte, L., Fauchier, L., Gandjbakhch, E., Garcia, R., Klug, D., Lellouche, N., Marijon, E., Martins, R., Maury, P., Mette, C., Piot, O., … Defaye, P. (2024). Position paper on sustainability in cardiac pacing and electrophysiology from the Working Group of Cardiac Pacing and Electrophysiology of the French Society of Cardiology. Archives of Cardiovascular Diseases, 117(3), 224-231. https://doi.org/10.1016/j.acvd.2023.11.016

Seeley, M.-C., PGrad, C., & McKenna. (2015, december). Graduate nurses' knowledge of the functions and limitations of pulse oximetry. https://oce.ovid.com/article/00019038-201512000-00022

Sensor Recycling Program. (z.d.). Geraadpleegd 8 maart 2025, van https://www.masimo.com/company/global-services/sensor-recycling-program/

Sinex, J. E. (1999). Pulse oximetry: Principles and limitations. The American Journal Of Emergency Medicine, 17(1), 59–66. https://doi.org/10.1016/s0735-6757(99)90019-0

Sleutelen op de werkplaats. (2022, 5 mei). Werken Bij EMC. https://www.werkenbijerasmusmc.nl/verhalen/medisch-technicus-romy

Soh, S. L., Ong, S. K., & Nee, A. Y. C. (2014). Design for Disassembly for Remanufacturing: Methodology and Technology. Procedia CIRP, 15, 407-412. https://doi.org/10.1016/j.procir.2014.06.053

Steenmeijer, M. A., Rodrigues, J. F. D., Zijp, M. C., & Loop, S. L. W. der. (2022). The environmental impact of the Dutch health-care sector beyond climate change: An input–output analysis. The Lancet Planetary Health, 6(12), e949-e957. https://doi.org/10.1016/S2542-5196(22)00244-3

Steenmeijer, M., Pieters, L., Warmenhoven, N., Huiberts, E., & Stoelinga, M. (2022). Het effect van de Nederlandse zorg op het milieu. Methode voor milieuvoetafdruk en voorbeelden voor een goede zorgomgeving. Rijksinstituut voor Volksgezondheid en Milieu RIVM. https://doi.org/10.21945/RIVM-2022-0127

Stretton, C., & Daphne, T. (2023, augustus 4). Unlock Product-as-a-Service (PaaS) business models with digital product passports. https://www.circularise.com/blogs/unlock-paas-models-with-dpps

Towards a circular economy. (z.d.).

Towards the circular economy Vol. 1: An economic and business rationale for an accelerated transition. (2013, januari 1). https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an

Unique Device Identifier. (2024, december 16). https://health.ec.europa.eu/medical-devices-topics-interest/unique-device-identifier-udi_en

Wiebe, L. I., & Machulla, H.-J. (1999). Hypoxia: An Introduction. In H.-J. Machulla (Red.), Imaging of Hypoxia: Tracer Developments (pp. 1-18). Springer Netherlands. https://doi.org/10.1007/978-94-017-1828-8_1

Zacharis, D. K., Zhao, D. Z., & Ganti, L. (z.d.). History and Social Implications of the Pulse Oximeter. Cureus, 16(8), e68250. https://doi.org/10.7759/cureus.68250

Zandbergen, P. A. (2009). Accuracy of iPhone Locations: A Comparison of Assisted GPS, WiFi and Cellular Positioning. Transactions in GIS, 13(s1), 5–25. https://doi.org/10.1111/j.1467-9671.2009.01152.x