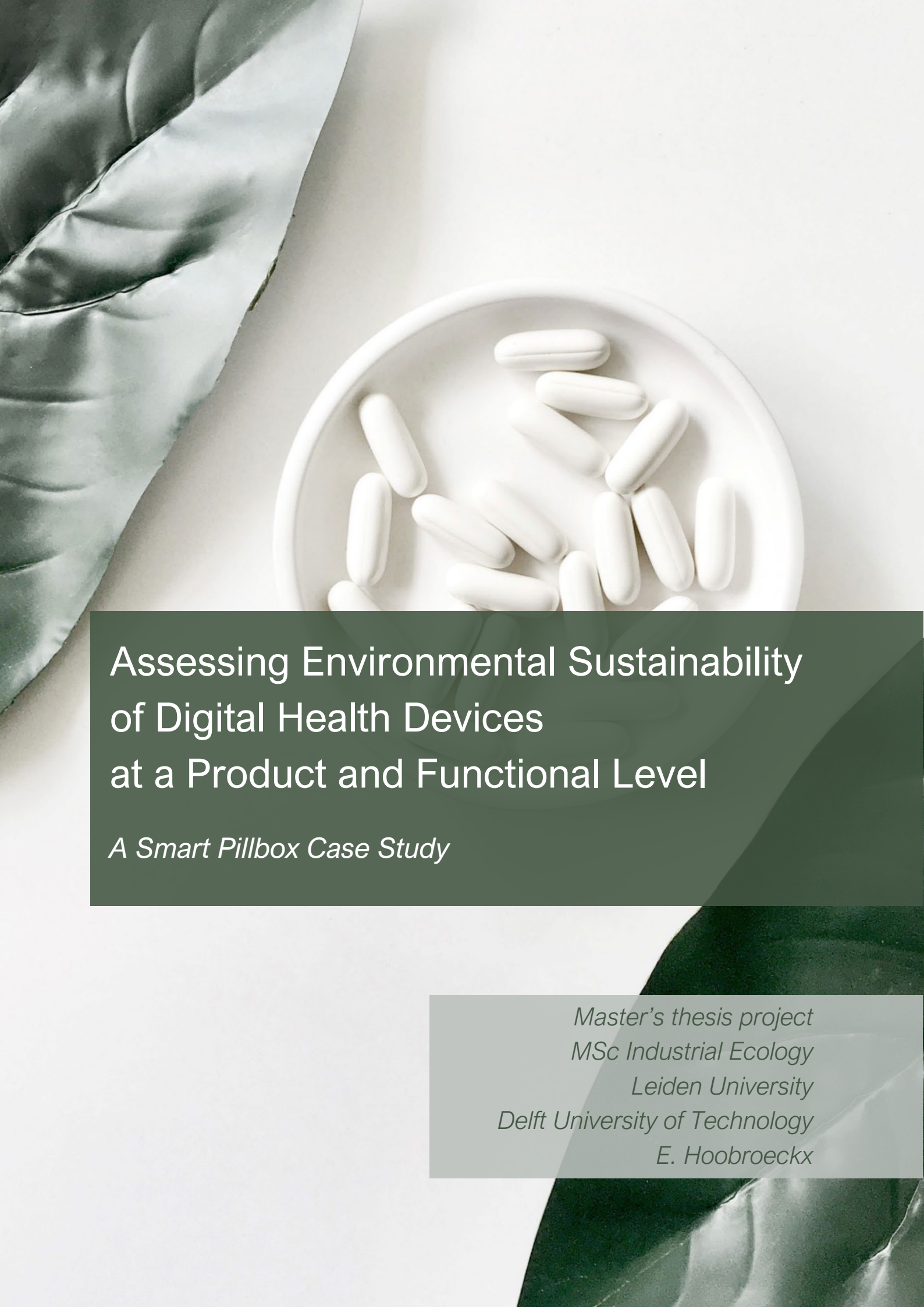

Assessing Environmental Sustainability of Digital Health Devices at a Product and Functional Level

A Smart Pillbox Case Study

Master's thesis project
MSc Industrial Ecology
Leiden University
Delft University of Technology
E. Hoobroeckx

Assessing Environmental Sustainability of Digital Health Devices at a Product and Functional Level

A Smart Pillbox Case Study

By

E. Hoobroeckx

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Graduation committee:

First supervisor:	Prof. dr. ir. C. A. Bakker	TU Delft, IDE
Second supervisor:	Dr. Ir. J. B. Guinée	Leiden University, CML

Universiteit Leiden

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Digital Health in the Circular Economy

Confidentiality statement *Data of a smart pillbox company used for the research is confidential, so the name of the company is not called in the report. The citation used in the report is:* (Anonymized smart pillbox company, 2022).

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This is my master's thesis, titled "Assessing Environmental Sustainability of Digital Health Devices at a Product and Functional Level: A Smart Pillbox Case Study". It was written as a requirement for the master's degree program in Industrial Ecology. Over the past six months, I have been researching the environmental sustainability of a smart pillbox on both the product and functional level. The DiCE project highlights the issues surrounding digital health devices and inspired the topic of my research. Through the DiCE project, I was introduced to the smart pillbox company that I focused on in my research.

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Evy Hoobroeckx

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Executive summary

The development of technology has brought many benefits to the healthcare industry, including the development of digital health devices such as smart pillboxes. These devices are designed to help patients to manage their medication, improve their health, and reduce the risks related with medication non-adherence. However, the extensive use of digital health devices has led to an increase in electronic and plastic waste, as well as a higher demand for critical raw materials. These materials are essential in the manufacture of digital health devices and are limited in availability. Additionally, while safety regulations are widely used for the medical industry, there are few environmental regulations controlling the development and disposal of digital health devices.

This raises questions about the potential environmental impacts of these devices and whether their health benefits outweigh their impact on the environment. The Digital Health in Circular Economy (DiCE) project aims to address these questions by examining the environmental sustainability of digital health devices, including smart pillboxes, and providing solutions to reduce their impact on the environment.

The aim of this research was to examine the environmental sustainability of a smart pillbox from both a product level and a functional level. The research addresses the knowledge gaps found in the literature by exploring the redesign recommendations for a smart pillbox based on circularity and sustainability assessments, and by comparing the (redesigned) smart pillbox to a conventional pillbox in terms of environmental burden and health benefits.

The research question for the product level (A) is: *What redesign recommendations can be provided to improve the environmental sustainability and the lifecycle of a smart pillbox based on circularity and sustainability assessments?*

The research question for the functional level (B) is: *How does the (redesigned) smart pillbox compare to a conventional pillbox considering the extra environmental burden (in DALY) and the benefits of healthier life years (QALY)?*

The methods used in the research to explore the environmental sustainability of the smart pillbox include Life Cycle Assessment (LCA), Disassembly Map, Recovery Assessment and Circular Product Readiness for product level sustainability. LCA was also used for functional level sustainability. On the product level, the disassembly assessments aimed to improve the product's lifetime, LCA focussed on hotspot analysis identified the key points in the lifecycle with the highest environmental impact, and the Circular Product Readiness method to recommend improvements on a systems level.

Life Cycle Assessment was applied to calculate the environmental impact in DALY and compare it to the benefits in QALY to answer research question B on a functional level.

Theoretically, the total improvement in an individual's quality of life (measured in QALY) resulting from using a pillbox is determined by subtracting the DALY impact of the pillbox from the benefits of medication adherence. To perform this calculation, an assumption is made that a user's adherence to their prescribed medication is 60% with a conventional pillbox and 80% with the smart pillbox.

For research question A, the repairability assessment of the smart pillbox showed that the priority parts of the product could be repaired by professionals, and consumers are not required to repair the product themselves, except when the battery detaches. The environmental hotspots identified were the charger, printed circuit board and other plastic parts. The Circular Product Readiness method identified points of improvement for the end-of-life stage of the product and not encouraging users to use their product sustainable.

Based on these results the following recommendations are proposed for the smart pillbox:

- Screws should be used instead of snap fits to attach the sub-assemblies.

- The battery should be fixated in a designated spot to prevent detaching.
- The silicone layer should be removed, or low impact material should be used for the polycarbonate of the top lid.
- A charger should not be included, or it should be an option for the consumer.
- An Eco-Steer design approach should be used to promote environmentally desirable habits, like providing guidance to the user to prolong battery life and guide end-of-life recovery of the product.
- More recycled materials should be used, and recycling solutions should be found by starting a conversation with the supplier and collaborating with a specialised electronic product recycling facility.

Research Question B revealed a small difference in the QALY improvement results between the smart pillbox and the conventional pillbox, with considerable uncertainty surrounding the assumption on health benefits and medication adherence rates at 80% and 60%. Due to the uncertainty, a break-even point analysis was carried out without considering these assumptions. The analysis indicates that a substantial improvement in QALY is required for the smart pillbox to balance out its environmental impact compared to the conventional alternatives. However, the redesigned smart pillbox alternatives show a smaller required QALY improvement to balance out its environmental impact compared to the conventional pillboxes.

The limitations of the study are acknowledged, and further research could be conducted to improve the accuracy and completeness of the results.

The data is mainly uncertain due to assumptions made about medication adherence and the difference in QALY improvement between the smart and conventional pillbox. These assumptions are sensitive and contribute to the data's overall uncertainty. To measure the relationship between impact and benefits, DALY and QALY were compared, which has not been done before. This method can allow for comparison of benefits and impacts, not only within the medical industry but across different sectors as well. By thoroughly assessing the benefits and impacts of products, companies can develop solutions that not only help individuals but also benefit the environment.

While the current findings do not lead to absolute conclusions, there is potential for further improvement to increase the product's environmental sustainability, which could potentially lead to an improved overall health.

This research creates a broader perspective on the overall impact of products and provides a basis for comparing the environmental impact and benefits. Instead of exclusively concentrating on the environmental impact of products this approach also considers their benefits.

Keywords: Digital health industry, Smart pillbox, Medication adherence, Environmental sustainability, Circular product design, Life Cycle Assessment

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List of abbreviations

AI	Artificial Intelligence
BOM	Bill of materials
DALY	Disability-adjusted Life Years
DiCE	Digital health in Circular Economy
eDIM	ease of Disassembly Metric
EU	European Union
IE	Industrial Ecology
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LYL	Life Years Lost
MOST	Maynard Operation Sequence Technique
PCB	Printed Circuit Board
QALY	Quality-adjusted Life Years
RIVM	Rijksinstituut voor Volksgezondheid en Milieu
VAS	Visual Analogue Scale

Glossary

Environmental hotspots	*Points of attention that contribute most to environmental burdens.*
Quality-adjusted Life Years	*Number of years of perfect health after treatment.*
Disability-adjusted Life Years	*Number of life years of full health lost.*
Life years lost	*Number of life years lost due to premature mortality.*
End-of-Life	*In context of products: the final stage of a product's existence.*
Medication adherence	*Taking 80% or more of medication as prescribed.*
Sankey diagram	*Specific type of flow diagram used for visualization of material, cost, or energy flows*.

Chapter 1. Introduction

The extensive use of fossil fuels is causing an increase in annual CO_2 emissions, leading to climate change. Rising temperatures related to these emissions cause potential problems like extreme weather events as floods and storms, sea-level rise and decrease of fresh water and crop growth. Therefore, the energy transition is needed to reduce the use of fossil fuels and stop climate change (Ritchie et al., 2020).

Critical raw materials play a crucial role in the energy transition as they are used in the manufacture of batteries for energy storage and solar cells for producing clean energy. These raw materials are called critical because they are economically important for European industry. Secondly, there is a supply risk because Europe consumes about a quarter of the world's raw materials and only 3% of the world's raw materials are mined in Europe (SGU, 2021). Additionally, most of these critical materials are limited in supply and are in high demand by multiple industries, making the future demand for them even higher. An example of a critical raw material is lithium which is used in batteries to store energy. However, lithium is also used in other products like mobile phones, laptops, and other digital devices with a battery (The Nature Conservancy, 2022).

One of the industries contributing to the use of critical raw materials is the medical industry. The medical industry is, like other industries, digitalizing rapidly. The industry strives to improve healthcare through digital products. Therefore, the demand of digital health devices are expected to increase yearly by almost 20% till 2027 (Mück et al., 2019). With that in mind, the amount of electronic and plastic waste will increase with an annual growth of roughly 4% (Statista, n.d.). The same materials are used in many electronic health devices and therefore contribute to the amount of waste that will be generated in the future. Currently, only a small portion of e-waste and plastics are properly recycled (UN Environment programme, 2022), and as a result, critical raw materials are not recovered from these products.

The health industry has many regulations related to the safety of patients, but environmental regulations are lacking. Because of these strict safety regulations, the healthcare industry is behind in implementing the circular economy in the development of digital health devices. In the design of medical products, financial considerations often take priority over the impact on society and the environment. To incorporate these aspects for digital health devices more research is needed. Digital health in Circular Economy (DiCE) is a project by the European Union (EU) to research this problem and create a more circular healthcare industry focused on these digital health devices. The DiCE project attempts to address the environmental sustainability concerns of the healthcare industry by conducting research on four different products in order to identify environmental problems and provide solutions (DiCE, 2022).

One of the four products that the DiCE project aims to examine is a smart pillbox.
A smart pillbox is designed to be used in combination with a mobile application that sends reminders to the user on when to take their medication. Each compartment contains one type of medication. The LED lights on top of the device tells the user which medication and the required quantity to take. As a result, the user no longer has to manually divide their medication into different compartments for different times, as traditional pillboxes require. One type of medication can just be placed in one compartment. Subsequently, the smart pillbox takes less time to use daily, and the app can track when you have taken your medication, so you know if you missed any. The smart pillbox is mostly used by people with heart disease to keep track of their medication (Anonymized smart pillbox company, 2022).

Like other digital health devices, a smart pillbox also strives to improve general health. Smart pillboxes are on the market to make medication adherence related to timing and dosing easier for patients. Medication non-adherence can decrease the effectiveness of a patient's treatment,

leading to health risks and sometimes even death (Crema et al., 2015). Medication non-adherence could also create high annual costs, by for example hospitalisation. The cost of medication non-adherence can go up to almost $20 000 in the case of patients with cardiovascular disease (Cutler et al., 2018). Though, as mentioned before, digital health devices create plastic and e-waste at end-of-life and they put extra pressure on the use of critical raw materials, including the smart pillbox.

This raises the questions: Do the health benefits of smart pillboxes outweigh their potential environmental impacts? And how can the environmental impacts be reduced?

Context: DiCE

This master thesis is in the context of the DiCE project, which aims to design and manufacture more circular digital health products. DiCE is funded by the EU and led by Janssen Pharmaceutica in collaboration with different stakeholders, the Delft University of Technology included. DiCE aims to reduce e-waste from the growing demand for digital health devices and acknowledges the growth in use of critical raw materials.

1.1 Literature and research questions

This research aims to understand the environmental sustainability of a smart pillbox[1] on a product level (=A) and on a functional level (=B). Section 1.1.1 describes the underlying concepts that are applied for the product level, specifically Circular Economy, Industrial Ecology and Circular product design. Section 1.1.2 elaborates on the positive effects of medical adherence and the negative effects of non-adherence. Additionally, the definitions of Quality-Adjusted Life Years (QALY) and Disability-adjusted Life Years (DALY) is explained.

A literature review was conducted for the product and functional level relevant to the smart pillbox. In the absence of literature specific to smart pillboxes, literature concerning the environmental sustainability of other products at both the product and functional levels was reviewed. This review resulted in the formulation of one research question for each of these levels, along with related sub-questions.

1.1.1 A: Product level environmental sustainability

Strategies drawn from the literature can be implemented to improve the environmentally sustainable design of products. Circular economy, Industrial Ecology, and Circular Product Design are all concepts that prioritize resource efficiency and waste reduction, which are important components of environmental sustainability.

These concepts can provide a scientific basis for analysing the environmental sustainability of products by prioritizing resource efficiency and waste reduction, which can lead to an improved environmental sustainability. Methods supporting these concepts can be used to evaluate the environmental sustainability of products. First, the concepts and their definitions are presented, followed by an exploration of literature relevant to each concept and this research, to finally form the first research question.

The concept of Circular Economy is popular nowadays and promoted by the EU (Korhonen et al., 2018). But there are many definitions out there. Geissdoerfer et al. (2017) did comprehensive research about the definition of Circular Economy and came to the following definition: *"Circular Economy is a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and*

[1] *Data of the smart pillbox company used for the research is confidential, therefore the name of the company is not called in the report.*

energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling". The definition states possible solutions to achieve the goal of minimizing waste and the use of materials, which could be applied in this research.

In order to explore potential solutions to sustainability challenges, it is first important to introduce the concept of Industrial Ecology (IE). IE is an emerging scientific discipline that adopts a systemic perspective to address sustainability issues. A multidisciplinary approach, which integrates perspectives from engineering, environmental science, and social science, is essential for achieving sustainable development. IE can be considered as a field that seeks to understand and improve the complex interactions between human society and the natural environment, with a particular focus on industrial systems and their impacts on the environment (ISIE, n.d.).

Because the product sustainability is analysed it is important to understand how these products can be designed. Circular product design can be a tool to lower the environmental impact and prioritise resource efficiency of products.
Circular Product Design *"Elevates design to a systems level (1), Strives to maintain product integrity (2), is about cycling at a different pace (3), explores new relationships and experiences with products (4) and is driven by different business models (5)"* (Bakker et al., 2014).

Circular Economy

Related to the Circular Economy concept a product should be easy to disassemble to *maintain, repair, and reuse* and extend the product's lifetime. When looking at the literature nothing was found about the repairability of smart pillboxes, but there are different studies about the reparability of household products, like vacuum cleaners (Bracquene et al., 2019; De Fazio et al., 2021). Similarities between a smart pillbox and a vacuum cleaner is that they are designed to improve practices. On a product construction level, they are both made up of multiple components, including electronic parts. Additionally, both devices require precise assembly to ensure that they function correctly.

De Fazio et al. (2021) used a method called the Disassembly map to analyse the repairability of the product.

Bracquene et al. (2019) mention that the focus of evaluating a product's repairability should be limited to priority parts. These are parts that have a higher failure rate than others and are more likely to need repairs.

Also evaluating product repairability should be tailored to a specific product (Bracquene et al., 2019). Doing this for the smart pillbox is therefore relevant as well. Specifically related to vacuum cleaners Bracquene et al. (2019) says that the use of snap fits increases in new products and that some parts are not easy to reach using regularly available tools. The smart pillbox could also have many connectors and parts which are hard to reach. Vacuum cleaners have a lifetime of around 9 years and 1 in 5 needed a repair in the first 6 years. To conclude, the smart pillbox might need repairs in the first years of its lifetime, so it is important to focus on the repairability of parts that need often repairs.

Industrial Ecology: *relation to Life Cycle Assessment*

Industrial Ecology (IE), as mentioned before, tries to understand, and improve the complex interactions between human society and the natural environment. A method which can analyse the interaction between a product and the environment is a Life Cycle Assessment (LCA) (Guinée et al., 2002). The relation between IE and LCA is that LCA can be used as a tool within IE to evaluate the environmental impacts of products. IE provides a framework for understanding the larger systems in which these products operate, while LCA provides a specific method for quantifying and evaluating the environmental impacts of individual products within that larger system.

A study by Jayanth (2019) tried to find the best design for a smart pillbox using LCA. The design choice between the two designs was made by comparing them on energy use, environmental impact in kg CO_2 and price. The impact of copper solenoids was included in the

LCA, but other electronic components were not. A large difference between the two designs was the use of 4 or 28 solenoids. The extra use of copper in the 28 solenoids design gave a higher energy use, more kg CO_2, and a higher price. Another LCA conducted in the medical industry to optimize material cycles is a study about two single-use medical staplers (Freund et al., 2022). There are no electronics used in the medical staplers, but an interesting aspect is that they expect that the higher mass in metals and plastics of one stapler resulted in a higher overall environmental impact.

Another comparable LCA study of disposable and reusable intubation scopes suggests that the electronic parts in the disposable product resulted in a high environmental impact. The electronic parts are a Printed Circuit Board (PCB) and copper wire. To better understand how electronics influence the environmental impact of a product an LCA of a Fairphone is also worth looking at (Güvendik, 2014). They suggest that the battery and PCB have a high share of the total environmental impact. As there were no studies found on the impact of a smart pillbox including electronic components, it is useful to research the environmental impact in this research. Looking at the studies discussed above the use of large amounts of metals and plastics, copper, a PCB, and a battery result in a higher environmental impact. It is expected that these materials are environmental hotspots.

Circular Product Design

Within this section, the final concept introduced is Circular Product Design. The concept's definition highlights that it improves design at a systemic level and uses different business models.

The Circulytics assessment of the Ellen MacArthur Foundation tries to look at companies on a system level to encourage them to be more circular on different levels in a company (Ellen Macarthur foundation, 2020). The results are mostly focused on money and not so much on a product level. Companies in the consumer products business score average on circularity (Ellen Macarthur foundation, 2021).

Another method, which is more focussed on product circularity is the 'Circular Product Readiness' from Boorsma et al. (2022). They looked at a washing machine company and a diesel injection system from Bosch.

They indicate that since each company is unique, comparing the results of similar companies as the smart pillbox company is not relevant.

Concluding from the literature and information above the first research question on a product level is formed. Based on the literature and information reviewed, the first research question regarding product level environmental sustainability has been established.

Main research question A:

What redesign recommendations can be provided to improve the environmental sustainability and the lifecycle of a smart pillbox based on circularity and sustainability assessments?

This question is answered using three sub-questions based on the different concepts, Circular economy, Industrial Ecology and Circular Product Design.

The first sub-question is related to the Circular Economy concept. In order to facilitate maintenance, repair, and reuse of a product, it is important that the product is designed for ease of disassembly, as a result extending its lifespan.

Sub-question 1. *How can the disassembly be improved to extend the lifetime and increase repairability of the smart pillbox?*

The second sub-question relates to the Industrial Ecology concept. Conducting an LCA may reveal the environmental hotspots of the smart pillbox and clarify how the product interacts with the natural environment. Based on these findings, redesign recommendations can be given. More about the LCA method is described in Chapter 2.2.

Sub-question 2. *What are the environmental hotspots of the current smart pillbox?*

To elevate the design to a system level as the definition of Circular Product Design states the product and its system can be evaluated on circularity to find points of improvement.

Sub-question 3. *How do the smart pillbox product and its system score on circularity?*

1.1.2 B: Functional level environmental sustainability

The function of the smart pillbox is to improve medication adherence related to timing and dosing (Crema et al., 2015). Medication adherence is, in most studies, defined as taking 80% or more of your medication as prescribed (Kleinsinger, 2018). Crema et al. (2015) and Abdul Minaam & Abd-ELfattah (2018) both designed smart pillboxes to help caregivers monitor treatment and prevent problems of medication non-adherence. The largest group of users of the smart pillbox are patients with heart disease (Anonymized smart pillbox company, 2022). Not taking their medication as prescribed can cause a heart attack, which could result in death. Medication non-adherence accounts for almost a third of all hospital admissions, of which heart failure is among the biggest group of people that are admitted (MacLaughlin et al., 2005). With that in mind only half of patients with heart failure are adherent to their medication (Choudhry et al., 2008), which could result in hospitalisation. A solution to this problem is using a smart pillbox. The pillbox company claims that 80% of people using their smart pillbox are more adherent than before. Finally, the financial burden of medication non-adherence of one patient with hearth (cardiovascular) disease can go up to around $20 000 and start at around $3000 (Cutler et al., 2018). From this research, using a smart pillbox could result in lower hospital admissions and lower costs.

Also, the positive impact of medication adherence on human health can be measured. A term used mostly in healthcare is Quality-adjusted Life Years (QALY), one QALY represents one year living in health gained after treatment. Other terms assessing the impact on human health are Life Years Lost (LYL), Years Lived with Disability (YLD) and Disability-Adjusted Life Years (DALY). LYL is the number of life years lost due to premature mortality. And DALY is the number of life years of full health lost (de Bruyn et al., 2017). Figure 1 shows a visual representation of DALY (Golsteijn, 2016).

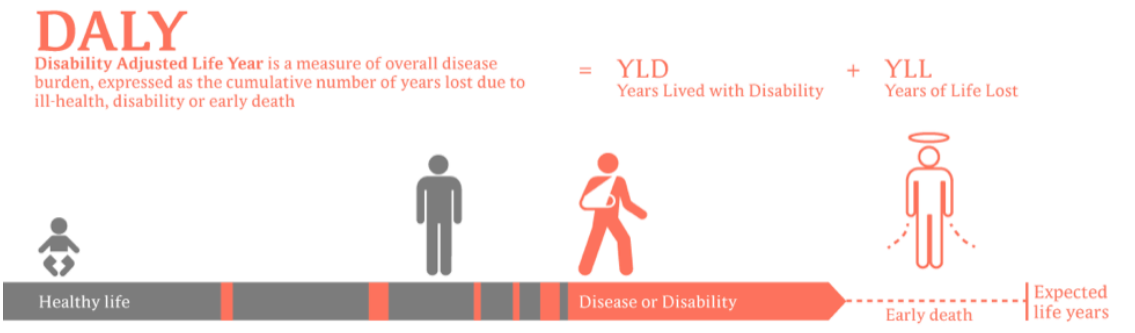

Figure 1. Visual representaiton of DALY (Golsteijn, 2016).

According to de Bruyn et al. (2017) QALY and DALY can be compared with one another with a 1.087 ratio. They also tried to give QALY an economic value, which they valued at around €70 000.

A study by Krack et al. (2018) tried to calculate the effects of medication adherence on human health. In order to do this, they calculated health-related quality of life (in QALY) as *visual analogue scale-adjusted life years* (VAS-AL) where QALY and VAS-AL have a linear correlation. VAS is a validated but subjective scale that measures pain. People are asked to grade their pain on a scale of 0 to 100, where 0 represents death and 100 perfect health. The reason they give for using VAS-AL was its ability to measure patient-reported health status, which is believed more suitable for describing subjective health than other techniques, and its implementation was based on a previous study.

While QALY is used mostly in healthcare, DALY is an indicator used to translate environmental impacts to human health impacts in some LCAs, e.g. based on the ReCiPe model of the RIVM (Huijbregts et al., 2016). More about this model is described in the methods Chapter 2.2.

The positive effect of taking medication on time is studied by Krack et al. (2018) who found that there was a significant increase of 0.34 VAS-AL (or QALY) with medication adherence (80% adherent) for patients that had a heart attack. But they found that forgetfulness was only 17% of reasons patients were not adherent to their medication.

The literature above implies that medication adherence leads to lower costs and higher QALY. There is no literature about how much smart pillboxes improve medication adherence, but studies suggest that some aspects improve adherence. Boeni et al. (2014) mention that drug reminder packaging improves adherence with patients having cardiovascular disease. Shah et al. (2015) say that video and telephone reminders increased adherence as well. Treskes et al. (2018) mention similar interventions that could help adherence. But they mention that educating patients about their treatment is important in combination with these interventions. For example interventions like phone calls, apps and the use of an electronic time cap reduced blood pressure of patients (McKenney et al., 1992; Treskes et al., 2018). Labovitz et al. (2017) studied the influence of medication adherence using a mobile app and Artificial Intelligence (AI). The app provided patients with reminders and dosing instructions and the AI captured if patients took their medication. They measured adherence by looking at a patient's plasma drug concentration. The intervention group was 100% adherent and the control group only 50%. And lastly, Naditz (2008) mentions that a conventional pillbox also improves medication adherence which resulted in 60% fewer hospital visits. But no evidence was found about how the benefits of a smart pillbox compare to a non-smart pillbox. Therefore, an assumption is made that suggests how adherent patients are when using a (smart) pillbox. The assumption is:

With the conventional pillbox a user is 60% adherent to their prescribed medication and with the smart pillbox 80%.

The assumption suggests that individuals using the smart pillbox are 80% adherent to their medication, but it does not indicate the amount to which medication adherence improves. This is a very rough estimation and is based on the literature that claims that reminders increase adherence (Boeni et al., 2014; MacLaughlin et al., 2005; Treskes et al., 2018). In the study by Labovitz et al. (2017), the control group showed 50% adherence to their medication, while the intervention group, which used a mobile app for reminders and instructions, achieved 100% adherence. Therefore, the assumption of 60% and 80% medication adherence was made. The assumption seems reasonable, because a conventional pillbox also reduces hospital visits as mentioned before (Naditz, 2008) and the smart pillbox does use a mobile app and gives reminders but does not completely reflect the research of Labovitz et al. (2017).

This difference in medication adherence can be compared to the difference in environmental impact on human health. As mentioned before, de Bruyn et al. (2017) mentioned that QALY and DALY can be compared to each other using a 1.087 ratio. Additionally, the study by Krack et al. (2018) which found that increasing medication adherence to 80% resulted in a 0.34 QALY improvement, which is equal to 0.37 DALY converted using the ratio mentioned by de Bruyn et al. (2017). Using this information, the overall quality of life improvement (in QALY) of an individual using a pillbox can be theoretically calculated by subtracting the DALY impact of the pillbox from the benefits of adherence. The amount of adherence can be linked to the amount of QALY improvement, which is assumed to have a lineal correlation between medication adherence and benefits.

The study by Duijndam (2022), which was mentioned before, concluded that the PCB resulted in a higher environmental impact. Expected is that the smart pillbox, due to the use of electronics and use of materials has a higher environmental impact. But how much higher this is of an (improved) smart pillbox compared to a conventional pillbox is not clear yet.

According to the literature described in this section, specific interventions can enhance medication adherence, resulting in better health outcomes. Comparably, a smart pillbox can also improve people's lives, but it is expected to have a more significant environmental impact. This raises the question of how the impact of a smart pillbox compares to its benefits related to human health, which leads to the second main research question.

Main research question B:

How does the (redesigned) smart pillbox compare to a conventional pillbox considering the extra environmental burden (in DALY) and the benefits of healthier life years (QALY)?

A final sub-question to answer main research question B is created to compare the smart pillbox to a conventional non-smart pillbox. Redesigned smart pillbox scenarios are included and are derived from research question A in this master's thesis. The (redesigned) smart pillbox scenario's will be analysed and compared to the conventional pillbox.

Sub-question 4. *What is the comparative analysis of the environmental impact of the current smart pillbox and redesigned smart pillbox scenarios, as obtained from research question A, with a* conventional *pillbox used in Europe in relation to their respective benefits to the quality of life of patients?*

Chapter 2. Research approach & Methods

In Chapter 1 two research questions, accompanied by four sub-questions are established. To address these questions, various methods drawn from the literature on Circular design and Industrial Ecology are used. The methods are described in detail, including their implementation within the context of this research.

The roadmap (Figure 2) visualises the approach of this research and shows which methods are applied to answer each of the sub questions. Section 2.1 describes the product disassembly, including the Disassembly Map method and the Recovery Assessment method. Section 2.2 describes the method, Life Cycle Assessment (LCA) and Section 2.3 Circular Product Readiness.

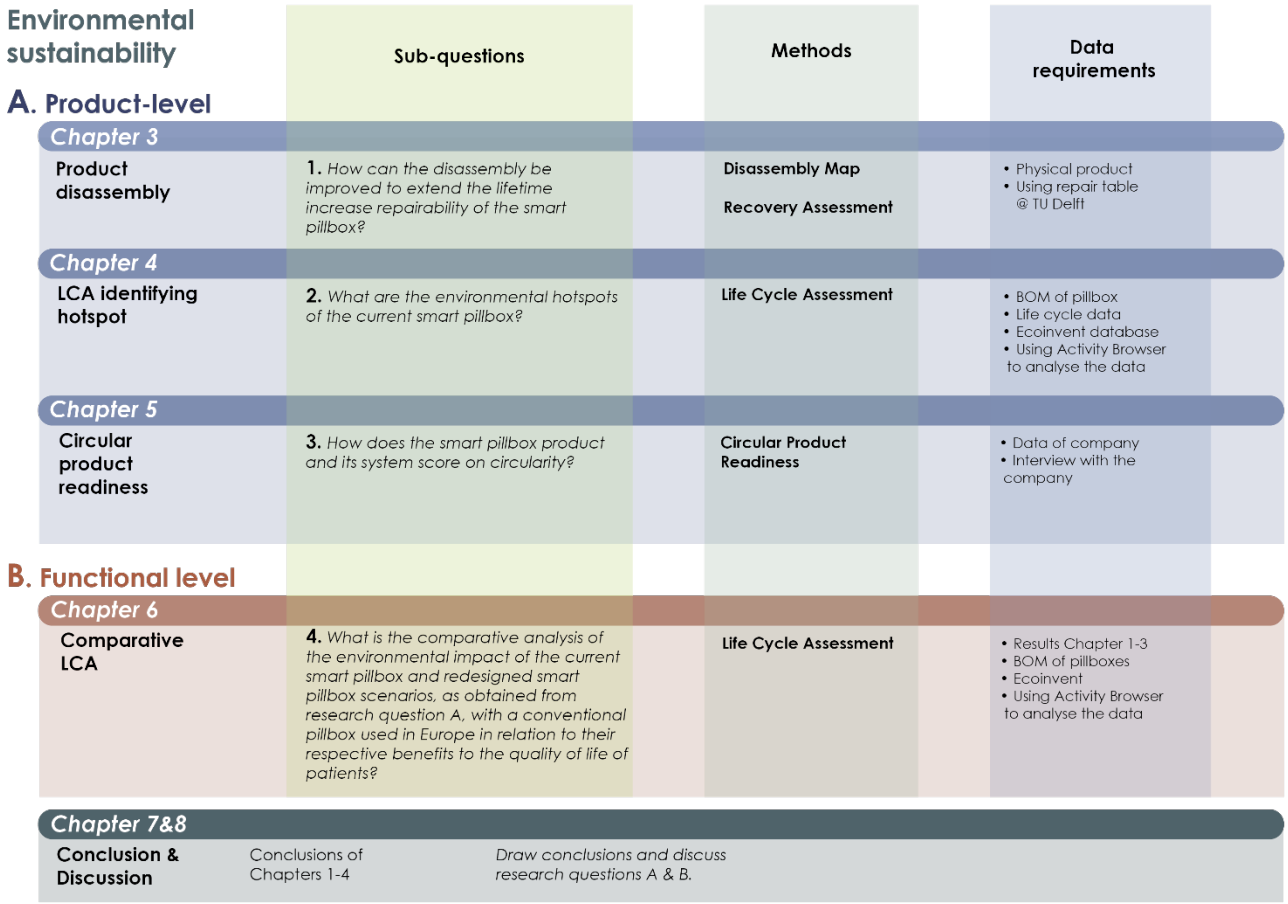

Figure 2. Roadmap research

Part A on product level sustainability is introduced after the explanation of the methods in this research and is summarized after Chapter 5. Part B on functional sustainability is introduced before Chapter 6.

2.1 Product disassembly

2.1.1 Disassembly Map

A method known as the Disassembly Map, developed by De Fazio et al., (2021), serves as a guide to enhance the repairability of products. The Disassembly Map method assesses the ease

of product disassembly based on four key design parameters: disassembly sequence, disassembly tools, connector reusability, and disassembly time. The method assists designers and engineers in evaluating each disassembly step to enhance product repairability. The map is created by disassembling a product and documenting all steps, then analysing the four design parameters. However, the developers caution that subjective interpretation of the rules may lead to varying results. The method is derived from the ease of Disassembly Metric (eDIM) (European Commission. Joint Research Centre., 2018) and the Maynard Operation Sequence Technique (MOST) (Zandin, 2002). MOST is a predetermined motion time system used to establish the standard time for a task by breaking it down into individual motion elements and assigning each element a time value. The eDIM method also tries to estimate the duration of disassembly tasks expressed in seconds.

The method developed by De Fazio et al., (2021) has a limitation of being tested on a single product group due to its recent development. However, De Fazio et al. (2020) improved the method by testing it on multiple products and making necessary modifications. The method's strength lies in its integration of all crucial design elements to evaluate product disassembly. The authors also note that the method is more visually and intuitively practical to use, but in order to use the method a physical product is necessary.

A Disassembly Map identifies seven different aspects, including the type of tool required for disassembly, if necessary, and the type of connector, e.g., snap-fit or friction fit. Target components and penalties are indicated with icons and what they represent is described in Table 1 and Table 2. In this research the environmental indicators are based on what was found in literature in Chapter 1.1.1 and confirmed by the LCA in Chapter 4. The Disassembly Map also highlights two other aspects: type of motion and intensity. The type of motion is classified as single or multiple actions, and motion intensity is indicated through colours based on the MOST index (Zandin, 2002). Finally, all components in the product are numbered and shown in a legend.

The further developed Disassembly Map by De Fazio et al. (2020) is used for this research in combination with the first version (De Fazio et al., 2021). In the further developed tool, the target components (Table 1) are not included anymore but are important for assessing the repairability of these components. Assessing the repairability of target/priority components is crucial, as they are the ones that require the most frequent access, as stated in the previous chapter (Bracquene et al., 2019). Therefore, they are re-added to the updated tool of De Fazio et al. (2020). For a more elaborate explanation of all the components we here refer to the publications of the Disassembly Map (De Fazio et al., 2020, 2021).

Table 1. Target indicators (De Fazio et al., 2021)

Target indicator	Indicator icon	Use description
Failure indicator		It indicates the components with the highest failure rate or functional importance
Environmental indicator		It indicates the most environmentally harmful components or those with the highest embedded environmental impact
Economic indicator		It indicates the components with the highest embedded economic value

Table 2. Penalties indicators (De Fazio et al., 2021)

Type of penalty	Penalty icon	MOST sequence	Use description
Product manipulation		A1B0G1+L3	Manipulation of moderate weight product or moving around it (max 2 steps)
Low visibility/ identifiability		T10	Hidden connector, difficult to reach with tool or to identify
Uncommon tool		–	Tool not included in the EN45554 common tool list
Non-reusable connector		–	Non-reusable connector after a first disassembly

Data needed for the analyses are collected by (dis)assembling the smart pillbox. The product is disassembled and assembled multiple times on a repair table using two cameras to capture the whole process. The process has been carried out by the researcher, who is not a professional disassembler. This can indicate how intuitively the disassembly process is for consumers. The process is executed a few times to get a better understanding of the actual (dis)assembly and is finally used as data for making the Disassembly Map.

As mentioned before a limitation of the method is that it can be interpreted differently and can therefore be subjective. To prevent subjectivity and enable the reader to make informed opinions, the findings are presented transparently and discussed thoroughly. The Disassembly Map is created using video footage of the latest disassembly, as the product structure is known after deconstructing it for several times. The quickest method of disassembling the product is determined by assembling and disassembling it several times.

2.1.2 Recovery Assessment

The Recovery Assessment method of de Jong (2022) adopted from de Aguiar et al. (2017). analyses the BOM (Bill of Materials) on disassembly indices, hygienic recovery indices and material recovery indices. There are four disassembly indices that help identify if a product can be disassembled and provide an indication if a part can be accessed for repair or recycling. Hygienic recovery indices indicate if a product can be cleaned, disinfected, and sterilised for reprocessing and recycling as some medical products come in contact with human skin. Material recovery indices are present to identify if a product can be recycled properly after end-of-life.

There are a total of 11 indices divided over these groups (Figure 3). Like the Disassembly Map, the product has to be disassembled to fill in the table. An empty version of the table is shown in Figure 3.

BOM data				Disassembly Indices					Hygienic recovery Indices			Material recovery Indices				Notes
BOM level	Item	Material	Weight (in g)	TFI	Reversibility	QFI	%FI	AI	TCI	ECI	SCI	MSI	MGI	MCI	MVI	
1																
2																
3																
4																
5																
6																
7																
8																
9																
10																
11																
12																
13																
14																
15																
16																
17																
...																
		Total	0		Total	0										

TFI	Type of fastener index
QFI	Quantity of fastener index
%FI	Perentage of fasteners index
AI	Accessibility index
TCI	Tissue contact index
ECI	Ease of cleaning index
SCI	Sterilization compatibility index
MSI	Material separation index
MGI	Material group index
MCI	Material coating index
MVI	Material value index

Figure 3. Recovery Assessment tool empty version.

The goal of this method is to analyse the different parts of a product to find parts that limit the recovery of materials or find parts that are suitable for end-of-life recovery. In that way, you can identify parts that might need to be redesigned to recover materials more sufficiently. While filling in the table different answers indicate different colours to visualize what parts need attention and which parts are already suitable for material recovery (Figure 4).

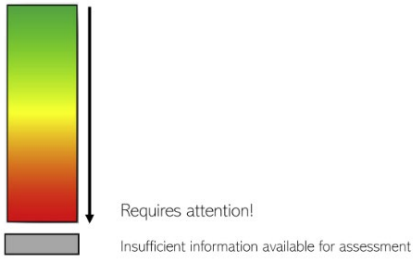

Figure 4. Colour scale of Recovery Assessment.

A limitation of the tool is that the tool's usability has never been validated. De Jong (2022) mentions that further research is needed for that. The components in the Bill of Materials (BOM) may be subject to varied grading by different individuals (de Jong, 2022), thereby emphasizing the importance of transparency.

The Disassembly Map is the base of the disassembly analysis, and the Recovery Assessment validates the Disassembly Map and possibly adds more insights. Due to this, the Recovery Assessment method is not utilized in its entirety, and modifications were made to facilitate a valid comparison with the Disassembly Map and to accurately address the sub-question (de Aguiar et al., 2017; de Jong, 2022).

See Figure 5 for the altered version of the tool and the alterations are further explained in this section. The material recovery indices are not included in the analyses because they don't express anything about the repairability/disassembly of the product. This does not indicate that they are not significant, but rather fall outside the scope of the sub-question being addressed. Secondly, the hygienic indices are also not included entirely, since the pillbox is not used in the same way as a catheter as in the research of de Jong (2022). The pillbox does not come in contact with human tissue and therefore does not need sterilisation. On the other hand, the pillbox should be cleaned properly to give it a second life, so only the ease of cleaning index is used in the analyses of the hygienic indices. This part is not covered by the Disassembly Map but is important to extend the lifetime of the pillbox. It is therefore of relevance to combine the two methods to answer the sub-question as completely as possible. Friction fits are not included in the disassembly indices, but they are in the Disassembly Map. Therefore, these are added to the fastener index in the Recovery Assessment. Friction fits have the same value as a snap-fit because they are both reversible. Aesthetic durability has been included as a separate category, with visual damage serving as indicator, due to the opinion on visual damage of the consumer (Zafarmand et al., 2003). And finally, the priority parts from the Disassembly Map are also included because it is important to see how these parts score in the Recovery Assessment.

BOM data			Disassembly indices					Hygienic recovery indices	Aesthetic durability
BOM level	Item	Weight (in g)	TFI	Reversibility	QFI	%FI	AI	ECI	VD
		0	Total		0				

TFI	Type of fastener index
QFI	Quantity of fastener index
%FI	Perentage of fasteners index
AI	Accessibility index
ECI	Ease of cleaning index
VD	Visual damage
Ⓟ	Priority part

Figure 5. Altered Recovery Assessment tool for this research

2.2 Life Cycle Assessment (LCA)

An LCA is a type of analysis that takes different environmental impacts into account over the lifecycle of a product. An LCA can be made in line with the framework of ISO14044 standards (Figure 6) (Finkbeiner et al., 2006). LCA is defined as a "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" by (Guinée et al., 2002). Main applications for an LCA are finding the main problems of a product, comparing different variations of a product, designing new products and compare for product selection. All these main applications are used in this research, except for the application of the design of a new product.

Figure 6. LCA framework (Finkbeiner et al., 2006)

The ISO framework (Figure 6) includes four phases, the goal and scope definition, the inventory analysis, impact assessment and interpretation. All phases are described in the text below and are based on information found in the handbook of LCA (Guinée et al., 2002) starting with the goal and scope definition.

The first phase of the LCA is the goal and scope definition, which is the base of the research. Initial choices are made to determine the plan of the LCA. The goal consists of the aim of the study, the target audience, and the application of the LCA. The scope covers the temporal, geographical and technology coverage and the level of analyses is described. This is followed by the definition of function, functional unit, alternative and reference flows. These are determined to understand what function the product alternatives fulfil and how much is considered in the analysis.

The Inventory analysis defines the product system(s), including the system boundaries, flow diagram(s) with unit processes, data collection of these processes and Life Cycle Inventory (LCI) analyses is conducted which includes the input and outputs to the environmental related to the functional unit mainly communicated via an inventory table.

The Life Cycle Impact Assessment (LCIA) is the next phase. In this phase the LCI results are converted to impact categories. Characterization families provide a method to translate the impact of the inventory table to certain impact categories, called classification. An example of an characterization family is ReCiPe, which has 18 impact categories that represent environmental issues (Huijbregts et al., 2017) (Figure 7). An example of an impact category is Climate Change expressed in kg CO_2-eq. These 18 impact categories are mid-point indicators (Figure 7) but can be calculated to end-point indicators as well. By using characterization factors, the LCI results are converted to these impact categories.

The Interpretation is the last phase of the LCA framework. The interpretation consists of an evaluation of the results in a consistency and completeness check, a contribution analyses and sensitivity analyses. The results of the analyses and certain choices that were made in the analyses are checked via the interpretation phase. This phase leads to conclusions and recommendations.

LCA data can be modelled in different software, like CMLCA (Heijungs, 2018) and Activity Browser (Steubing et al., 2020a). Because LCAs are quite complicated, databases can be used like ecoinvent (Wernet et al., 2016).

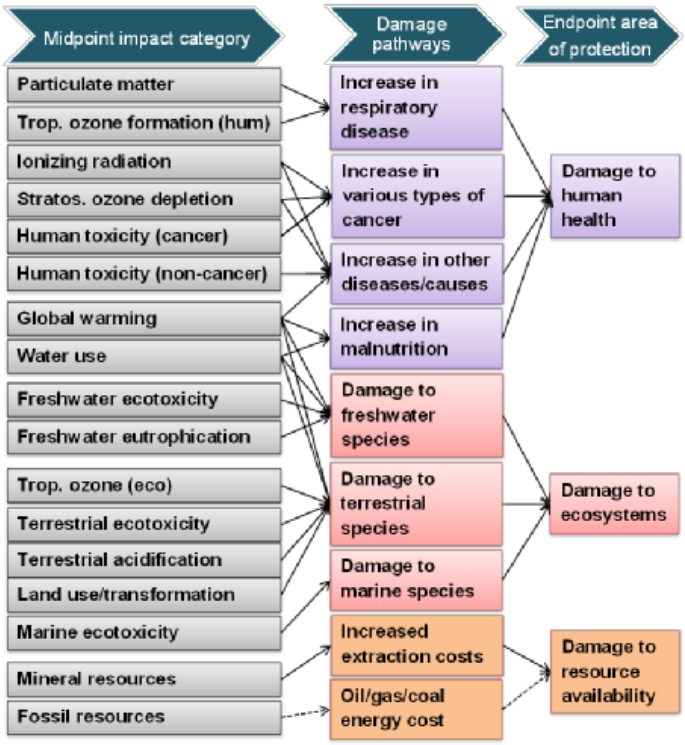

Figure 7. ReCiPe model (Huijbregts et al., 2017)

The strength of an LCA is that the holistic approach gives a very detailed analyses, and environmental problems can be defined over the complete lifecycle to understand the impact of certain products. This approach avoids problem shifting, where solving one problem can create another problem in the lifecycle. A limitation of this approach is that analysing such a broad scope also makes you simplify other aspects in order to analyse the data.

Another limitation of the method is that it is a complex methodology and there is a need for specialised modelling knowledge (Guinée et al., 2002). Therefore, it is also time-consuming, and a lot of data is needed to make an LCA. Also, local impacts in which emissions take place cannot be analysed by an LCA.

In this research LCA will be used to find the hotspots of the smart pillbox and compare different variations of the smart pillbox and conventional pillbox alternatives.

The hotspots of the smart pillbox are found using the contribution analysis in the interpretation part of the LCA based in the framework (Figure 7). This LCA is conducted in Chapter 4 to answer the second Sub-question. The contribution analyses will use the built in Sankey diagram tool in the Activity browser software to find the contributions of the parts of the smart pillbox. The Sankey diagrams are created by the tool using the impact assessment of the smart pillbox, in the impact assessment phase of the LCA framework. Based on these hotspots redesign recommendation will be given.

Different variations of the smart pillbox created from the redesign recommendations given in research question A are compared to a conventional pillbox in Chapter 6. The impact of the different alternatives is compared to each other. One end-point indicator from the ReCiPe impact family is 'damage to human health' expressed in DALY. The ReCiPe model is used as a baseline because it can calculate DALY, which is needed for research question B. The midpoint indicators are used for the 2nd sub-question and the end point indicators including 'damage to human health' in DALY is used for the 4th sub-question. How these midpoint and endpoint indicators are calculated are described in Chapter 4 & Chapter 6. The versions of the model used are ReCiPe Midpoint (H) v1.13 and ReCiPe Endpoint (H, A) (Huijbregts et al., 2017). In order to find the hotspots of the smart pillbox the mid-point indicators are used, while the endpoint indicators are used to compare the impact of the alternatives to the benefits.

More details about the LCA are described in Chapter 4 and Chapter 6, because it follows the structure according to ISO14044 standards (Figure 6).

2.3 Circular Product Readiness

The Circular Product Readiness method by Boorsma et al. (2022) is based on the Circulytics assessment by the Ellen Macarthur foundation (2020) to assess the products sustainability of companies and their products. By answering a list of questions, the circular product design is assessed on different levels to get an indication of a product-related company's sustainability. These different levels include company strengths, levels of readiness and creates opportunities for improvement. The method considers all lifecycle phases, evaluates product design aspects, and can be applied to a broad range of industries. The results of the method indicate levels of readiness of sustainability.

Sustainability on all 3 pillars (Elkington, 1999) is touched upon. People, planet, profit all come back in the method but there is less of a focus on the social aspect.

The topics of the questions are on the products durability, repair, remanufacturing, and recycling. Answers are graded from 0 to 100% which are translated to a scorecard with an overall score and a score on 6 themes (Figure 8). This score can be used to compare certain companies, but when not comparing companies, it can be used to find certain points in the lifecycle that can be improved.

A weakness is the translation of qualitative answers to semi-quantitative scores. The answers are sometimes only yes or no and therefore nuances are missing sometimes.

Another limitation is that everything is brought to an overall average. When one aspect is poor, and the others are exceptional this can give a distorted view of a company's performance. But when using the example of the visual tool in Figure 8, this can be partly prevented. But there are answers to questions that are not visually shown, so that is important to keep in mind.

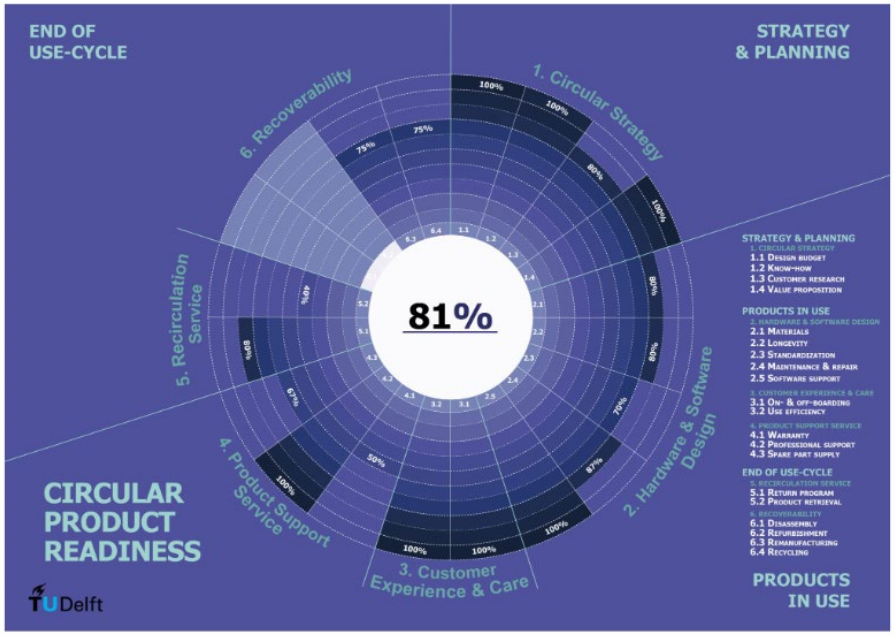

Figure 8. The Circular Product Readiness method visualized

In this research the Circular Product Readiness method is used as it was created by the developer (Boorsma et al., 2022). Data is gathered by letting the company fill in the questionnaire of the Circular Product Readiness method. A visual is created to see how the company scores on the different topics. Due to time constraints the answers are not validated via interview conversations with the company, as the method suggests. But the answers are critically analysed to understand if other answers were expected based on the conversations with the company in the past and the website of the company is also used.

A. Product level environmental sustainability

The research approach outlined in Chapter 2 provides the framework for this research. Part A focuses on answering the research question A regarding the product level environmental sustainability of the smart pillbox.

This section begins by evaluating product disassembly in Chapter 3 through the use of the Disassembly Map and Recovery Assessment Method, aimed to answer sub-question 1. Chapter 4 uses a Life Cycle Assessment to analyse the environmental impact of the smart pillbox and address sub-question 2. Sub-question 3 is answered in Chapter 5 using the Circular Product Readiness Method. Part A is summarized on page 52. The conclusion of Part A is presented in Chapter 8.1.

Chapter 3. Product disassembly

This chapter focusses on assessing product disassembly and answering the first sub-question: *How can the disassembly be improved to extend the lifetime and increase repairability of the smart pillbox?* The disassembly of the pillbox is analysed using 2 methods, described in Chapter 2.1. The results of the Disassembly Map and after the Recovery Assessment can be found in Sections 3.1.1 and 3.1.2. The results of both methods are combined (Section 3.1.3) and discussed (Chapter 3.2) to conclude the first sub-question (Chapter 3.3).

3.1 Results

3.1.1 Results Disassembly Map

The Disassembly Map is shown in Figure 9 and is based on the disassembly video. Further results are described below the picture. The legend clarifies all components in the map, but for further explanations we refer back to Chapter 2.1.1.

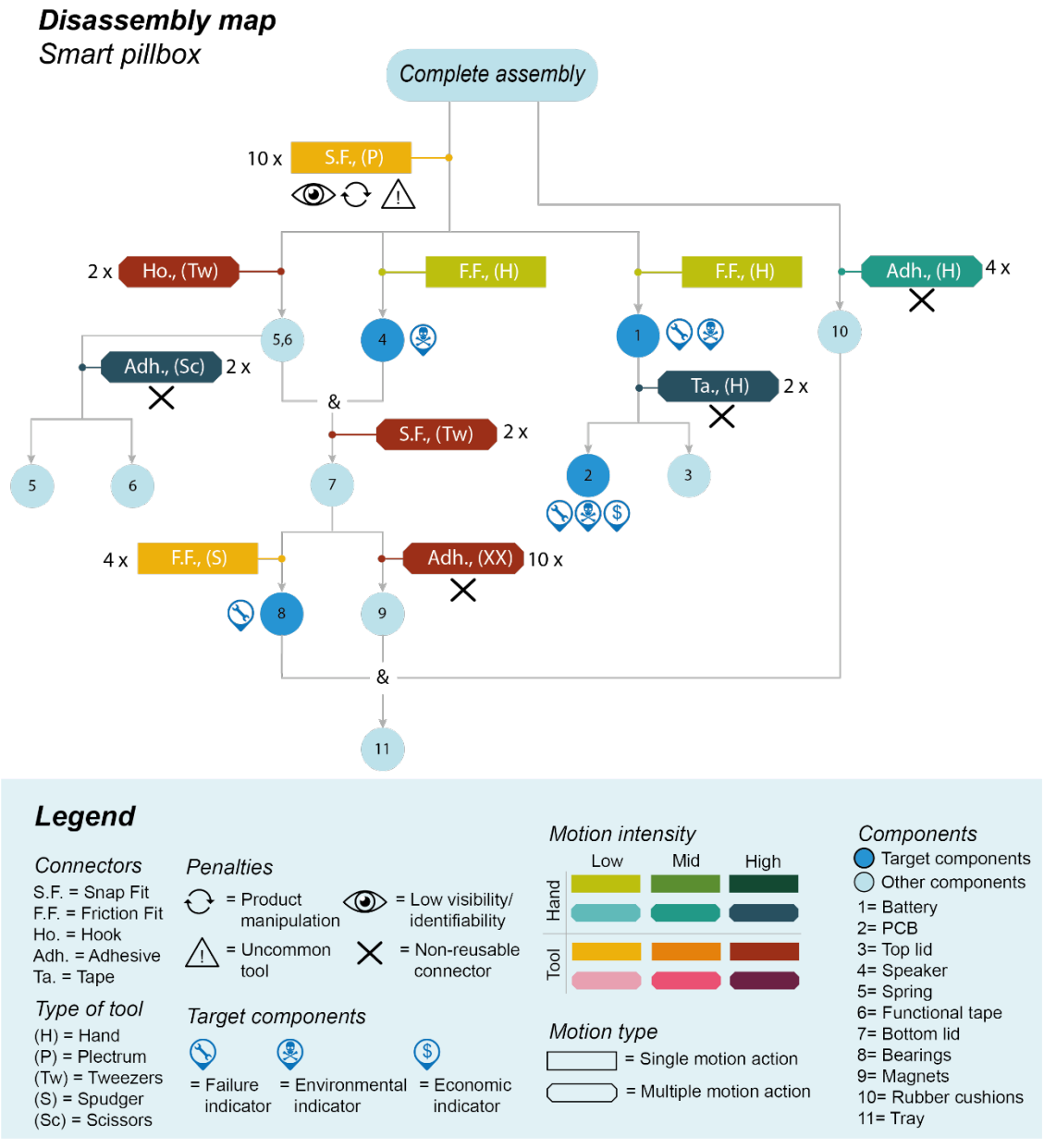

Figure 9. Disassembly map of the smart pillbox

The results are divided by consumer and professional repair because there is a difference between these types of repairs after disassembling the product e.g., tool availability and skillset difference. But first the priority parts are presented in Table 3 and including an explanation why they have certain indicators.

Table 3. Priority parts

Indicator/ Part	*Failure indicator*	*Environmental indicator*	*Economic indicator*
Battery	The battery detaches sometimes from the PCB; therefore, you have to re-attach the battery.	The materials in the battery are toxic and need special recycling.	-
Speaker	-	Contains Neodymium, which is a rare earth element.	-
PCB	-	The PCB contains rare earth metals.	It is the most expensive part of the product (Anonymized smart pillbox company, 2022).
Bearings	With longer/intense use the bearings wear out and need replacement.	-	-

Accessibility of the priority parts

The parts with an environmental indicator are the battery, speaker, and PCB. The first step of the disassembly process opens up the product and the battery and speaker can both be accessed immediately and are on the same level in the map in Figure 9. The PCB has an extra step in the disassembly process. It is attached to the top lid by tape which makes it harder to detach and the tape is not reusable after that.

For professionals the first step is fairly easy. When a repair manual is present, and the right tool is available the product can be repaired in a short amount of time. The pillbox company confirms this as well. Even though there are many snap fits, by using a plectrum the product could be opened-up within one minute.

The consumer on the other hand is not as skilled as a professional and it is not likely that they have a repair kit at home. They would not be able to open the product up to reach the priority parts.

For the repair of the product the first disassembly step is crucial to reach most of the priority parts. Because consumers are probably not able to open the product up, they are not able to repair anything. The battery detaches sometimes (Anonymized smart pillbox company, 2022), therefore the product has to be opened up when this happens. It would be preferable for the consumer to re-attach the battery themselves without having to send it to a repair facility. This problem could be resolved by redesigning the product, so consumers are able to repair certain parts, like the battery. The use of the snap fits now makes it harder to disassemble the product.

There are two parts with a failure indicator (Table 3). Because the battery detaches sometimes, this parts gets a failure indicator. Second, the bearings wear out after a longer or intense use. They are hard to reach but don't need repairs often. The Disassembly Map (Figure 9) indicates four actions needed before reaching the bearings, including 2 high motion intensity actions. The first is removing the bottom lid which is hard to disassemble. Disassembling the big snap fits is not complicated but it needs force, and the bottom lid might break when not done with care. This is the same as for consumers and professionals.

Second high motion part are the springs. The springs are there to keep the pillbox open or closed via tension. Therefore, the springs are not easy to remove. The removal takes round twice as much time than the disassembly of other parts.

Finally, a notable aspect about the product is the amount of non-reusable connecters.

To conclude the Disassembly Map, it can be presumed that the priority parts include the battery, speaker, PCB, and bearings, all of which can be effectively repaired by professionals. Especially, the first step of the disassembly process is a crucial step in reaching these priority parts. However, given the complicated nature of this first step, it is recommended to redesign this to enable consumers to repair the battery, particularly given the presence of a failure indicator.

3.1.2 Results Recovery Assessment

Secondly, the results of the Recovery Assessment (Figure 10) and explanations are shown in Table 4. The number the parts are given in the Disassembly map are kept the same for consistency. Some answers given in the Recovery Assessment need more explanation. The accessibility of parts is rated by disassembly steps derived from the disassembly video. For the ease of cleaning, 50% or more easy to clean means that the part can be cleaned but has properties that make proper cleaning harder. Further explanations about the answers are described in Table 4.

BOM data			Disassembly indices					Hygienic recovery indices	Aesthetic durability
BOM level	Item	Weight (in g)	TFI	Reversibility	QFI	%FI	AI	ECI	VWT
A	*Sub-assembly top*		Snap-fit	Yes	0	0%	Free access		
1	Battery Ⓟ	13.92	Friction-fit	Yes	1	4%	One disassembly step	Not needed to clean	Not visually affected by wear and tear
2	PCB Ⓟ	16.84	Adhesive or energy bonding	No	0	0%	At least two disassembly steps	Not needed to clean	Not visually affected by wear and tear
3	Top lid	68.3	Adhesive or energy bonding	No	2	7%	At least two disassembly steps	Smooth surface, easy to clean	Visually affected by wear and tear
B	*Sub-assembly bottom*		Snap-fit	Yes	10	36%	Free access		
4	Speaker Ⓟ	1.73	Friction-fit	Yes	1	4%	One disassembly step	Not needed to clean	Not visually affected by wear and tear
5	Spring	0.82	Friction-fit	Yes	2	7%	One disassembly step	Not needed to clean	Not visually affected by wear and tear
6	Functional tape	0.38	Adhesive or energy bonding	No	2	7%	One disassembly step	Not needed to clean	Not visually affected by wear and tear
7	Bottom lid	44.09	Snap-fit	Yes	2	7%	At least two disassembly steps	Smooth surface, easy to clean	Aesthetic durability
8	Bearings Ⓟ	0.76	Friction-fit	Yes	4	14%	At least two disassembly steps	Not needed to clean	Not visually affected by wear and tear
9	Magnets	0.96	Adhesive or energy bonding	No	0	0%	Cannot be detached	Not needed to clean	Not visually affected by wear and tear
10	Rubber cushions	0.32	Adhesive or energy bonding	No	4	14%	Free access	Smooth surface, easy to clean	Aesthetic durability
11	Tray	116.04	Adhesive or energy bonding	No	0	0%	Cannot be detached	50% or more of the component is easy to clean	Slightly visually affected over time
		264.16		Total	28				

Legend

TFI	Type of fastener index	*What connector in used to assemble the part?*
QFI	Quantity of fastener index	*How many fasteners are used for all parts?*
%FI	Perentage of fasteners index	*What percentage are these fasteners of the total amount?*
AI	Accessibility index	*How accessible is this part to disassemble?*
ECI	Ease of cleaning index	*How well can the part be cleaned or does it need cleaning at all?*
VWT	Visual wear and tear	*Is the part affected by visual wear and tear over time?*
Ⓟ	Priority part	

Figure 10. Recovery Assessment results

Table 4. Explanation of the results in the Recovery Assessment table. The information in the table is either from disassembling the product or information given by the pillbox company (Anonymized smart pillbox company, 2022). Ⓟ = Priority part

	Item	Notes
A	Sub-assembly top	The snap fits hold sub assembly A & B together, but the fastener index is not accounted for in this sub-assembly as (de Jong, 2022) mentions that the number of fasteners is connected to the part that is the most internal component.
1	Battery Ⓟ	The battery is connected via a wire in a connector in the PCB, so after taking out this part, it can be put back in the device. Almost free accessible but first have to remove sub-assembly.
2	PCB Ⓟ	The PCB is attached to the device via two big pieces of tape. The manufacturer of the product claims they can take the tape off easily without damaging the electronics.
3	Top lid	The top lid is attached to the snap-fits. They get detached in the first step of the disassembly, but the PCB is still taped to the top lid. Once the PCB is detached the top lid is free of the assembly. This means it is not so accessible mainly because of the taped PCB. The part can be cleaned properly. In terms of aesthetic durability, it gets damaged over time because of the nature of the material and will therefore be replaced once it is used.
B	Sub-assembly bottom	This sub-assembly holds parts 4-11 and the snap fits are designated to this part.
4	Speaker Ⓟ	The speaker is fitted in a designated spot on the bottom lid. It is easy to remove and place back in the same spot.
5	Spring	The springs can be reassembled, and freely accessible once the sub-assembly A is removed.
6	Black tape	The tape is attached to the springs and once it is taken off the springs it cannot be reused. A low score on most of the disassembly indices.
7	Bottom lid	The bottom lid is attached to the tray with big snap fits. The springs need to be detached before you can reach this part. Therefore, it is not as accessible as the springs. The bottom lid might get in contact with medication and therefore might need cleaning. The nature of the material makes it easy to clean.
8	Bearings Ⓟ	The bearings are underneath the bottom lid and are therefore even less accessible than other parts.
9	Magnets	The magnets are completely integrated into the tray. The magnets cannot be detached from it unless you damage the tray.
10	Rubber cushions	The rubber cushions are attached via a small adhesive sticker and can be detached but they need new stickers to re-attach. For this reason, this part gets a bad score.
11	Tray	The tray is easy to clean because of the nature of the material. There are cases where some medications will give discolouration on the tray, but it's not common, therefore it is 50% or easier to clean. For the same reason the visual damage grades lower as well.

3.1.3 Overall results

Both methods share similar results. First, most of the priority parts are fairly easy to reach as a professional. The bearings are on the other hand less reachable but do not need often repair and don't hold an environmental indicator either. Second, the first step in the Disassembly Map is the hardest of the complete disassembly. The reason for this is that 10 snap fits need to be found and disconnected. The Recovery Assessment confirms this because the snap fits are 50% of the total fasteners. The results indicate that this part of the disassembly is the hardest part. Lastly, there are many non-reversable connectors, which both methods show clearly.

3.2 Discussion: Product disassembly

By looking at the results of both methods there are some overlaps but also some differences. The most important differences are stated below.

- It is more visually clear what the effort for the disassembly is in the Disassembly Map, than the Recovery Assessment. The springs score well in the Recovery Assessment, but the Disassembly Map shows a need for high motion intensity. This means that the Recovery assessment cannot indicate how much effort goes into the disassembly of the springs and the Disassembly Map does.
- The disassembly depth in de Disassembly Map is not covered in the Recovery Assessment. Scoring the accessibility in the Recovery Assessment is quite subjective but by looking at the Disassembly Map, it is much more intuitive to understand how accessible certain parts are. Therefore, the Disassembly Map is more helpful method on this subject.
- The magnets are marked inaccessible in the Recovery Assessment because in reality these cannot be removed without demolishing the tray. The same counts for the tray. It cannot be separated from the magnets without demolishing it. This cannot be seen in the Disassembly Map. In this case, the Recovery Assessment is clearer than the Disassembly Map. The magnets could maybe still be reused when removed properly, but this will likely damage the tray. For recycling, this is not a problem, because when shredding the plastic tray, the magnets could be removed with a magnet.
- The type of tool is not shown in the Recovery Assessment. This cannot be assessed with the Recovery Assessment. And this aspect is relevant for the repairability for consumers and maybe sometimes even for professionals.
- In the Recovery Assessment you cannot see if two parts are connected after disconnecting a part of a sub-assembly. The Disassembly Map is in this part more visual. The parts in which you cannot recognise if they are still connected after a disassembly step are the PCB and top lid and second the springs and tape.

The cost of disassembling is not considered in the research but is still an important aspect of disassembling. The time of disassembling the product took a maximum of 2 minutes. When the product needs some repair, it will take around 5 minutes in total. There are not many man-hours needed so this seems viable. The pillbox company also does this in practice, which confirms that conclusion.

Possible solutions to identified repair or disassemble problems.

Target components with an environmental indicator (battery, PCB, and speaker) are accessible, but the first step of the disassembly could be made easier to understand. This depends on the target group that has to disassemble the product. If these are professionals, they might need simple instructions. This is a different story if consumers have to do it at home. The pillbox company offers free repairs so the first situation will be more likely. A good repair manual could be enough.

If it is desirable to make the repair or replacement of target components also feasible for consumers something has to be changed. The use of a screw or multiple screws instead of snap fits could be an option. Screws are a known connector and screwdrivers are a common tool for disassembly (De Fazio et al., 2020). People will find it more intuitive to open the product up because they see screws. This results in higher material use, which could result in a higher environmental burden. In consequence, this is a trade-off that needs to be kept in mind.

A target component with a failure indicator are the bearings. Because these parts are not likely to need repair in the first 3 years of the lifetime of the product repairability for professionals should be enough. They might need replacement if the smart pillbox is used for 7 years.

Replacing the bearings is possible looking at the results of the repairability assessments. It takes more time than the other priority parts but because they don't need regular repairs this is not worth changing. Another part with a failure indicator is the battery, which detaches sometimes (Anonymized smart pillbox company, 2022). The product has to be opened up when this happens, but this could be prevented by fixating the battery in the product, so it doesn't move that easily. In this way there is also less chance that the battery gets damaged. Making a designated spot in the bottom lid could be a simple design change but might result in a lower failure rate. A drawing demonstrating this design change is shown in Figure 11. One side doesn't have any extra support because this would conflict with the power inlet as seen in the figure.

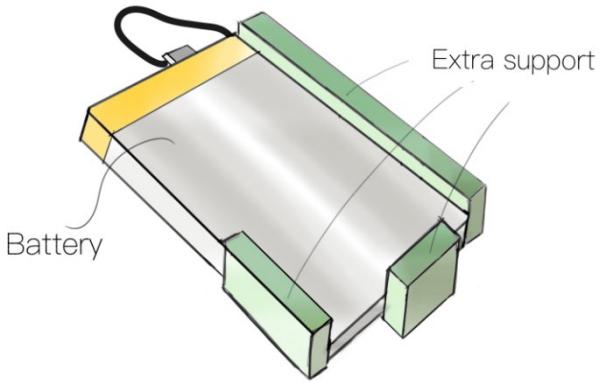

Figure 11. Design change for battery

The last repairability problem is the high amount of un-reusable connectors. The magnets have a low failure rate and don't need often repairs. A possible problem with the magnets could be that they fall off the product and need replacement. A magnet can be replaced in this case because it is already detached from the tray. The functional tape is replaceable but could be redesigned using durable materials that ensure the pills from getting in the top lid. Lastly, the un-reusable connectors, the rubber cushions, are replaceable using small new stickers to attach to the tray.

Finally, the top lid damages easily because of the silicone layer on top. It can be cleaned properly but needs replacement after longer use because it is not aesthetically durable due to visual damage. The material of the top lid silicone could be changed to make this part more aesthetically durable. The design could just leave out the layer of silicone. A consideration of this intervention is that the look and feel would change of the product and the pillbox company mentioned that this part is important in their design.

3.3 Conclusion and recommendations: Product disassembly

This section will answer the first sub-question: *How can the disassembly be improved to extend the lifetime and increase repairability of the smart pillbox?*

From the results and discussion, the following answer can be given to this sub question.
Professionals can repair all the priority parts using a manual. All priority parts can be repaired or replaced without needing new connectors except for the tape on the PCB.
If consumers should be able to repair the smart pillbox, screws could be used instead of snap fits to make it more intuitive, and they can use tools they have at home.

The overall lifetime of the product can be easily extended to approximately 7 years without improving the disassembly at all. All priority parts can be removed or replaced without throwing away valuable parts. Remaining parts are also repairable or replaceable except for the magnets.

Nevertheless, changing some parts of the product reduces waste and transport impacts. The battery could be better fixated to reduce failure and therefore less need for repair and the connected transport. Waste could be reduced by replacing the un-reusable to reusable connectors.

To conclude, the priority parts can be replaced or repaired to extend the lifetime of the smart pillbox to 7 years. The top lid needs replacement because it gets damaged during use, this can be changed by not adding the silicone layer on the top lid, but it does go into the aesthetic design choice of the pillbox company. The recommendation of changing the lid can be presented to the pillbox company but it is a trade-off they have to decide on. If the company desires to keep the silicone layer on the top lid a low impactful material could be used to lower the overall impact of potential replacing the top lid. Table 5 gives an overview of the recommendations based on the disassembly assessments.

Table 5. Redesign recommendations based on disassambly assessments.

Part	Recommendation	Reason
Sub-assemblies	Use screws instead of snap fits to attach the sub-assemblies	Allows consumers to easily open up the product to reattach the battery.
Battery	Fixate battery in a designated spot. (See Figure 11)	The battery detaches sometimes and needs to be reconnected. Fixating it prevents repair requests and extra transport to a repair facility.
Top lid	Remove silicone layer or use low impact material for the main material.	The top lid needs replacement because visual wear and tear impact the aesthetic durability.

Chapter 4. Life Cycle Assessment identifying hotspots

This chapter presents an analysis of the environmental hotspots of the current smart pillbox using an LCA based approach. The analysis is carried out to answer sub-question 2: "*What are the environmental hotspots of the current smart pillbox*?"

The chapter begins by outlining the goal and scope definition in Chapter 4.1. It then goes on to describe the inventory analysis, including modelling choices, a flowchart, and data collection, which are presented in Chapter 4.2. The impact assessment is then described in Chapter 4.3, followed by the interpretation focussed on a hotspot analysis in Chapter 4.4.1, and a sensitivity analyses and completeness check for interpretation, in Section 4.4. The chapter concludes with a discussion and conclusion in Chapter 4.5 and 4.6, offering an answer to sub-question 2.

4.1 Goal and scope definition

4.1.1 Goal definition

The main goal of this LCA is to find the environmental hotspots of the smart pillbox. The LCA will be over the whole lifecycle (cradle to grave) of the product using the BOM of the pillbox company. This LCA can improve the smart pillbox's environmental performance by changing materials and/or the lifecycle. The target audience is the pillbox company, the DiCE project and the (digital) health industry. The study is conducted by Evy Hoobroeckx, a master's graduate student of Industrial Ecology regarding a master thesis project for the DiCE project. The research aims to improve the environmental sustainability of digital health devices.

4.1.2 Scope definition

The LCA is conducted according to ISO14044 standards (Finkbeiner et al., 2006) using the handbook of LCA (Guinée et al., 2002). The research is based on an existing pillbox that is currently on the market. An attributional LCA (ALCA) is appropriate because it analyses the data of the current state. The detail of the ALCA is limited because of data gaps and time constrains. The Activity Browser software (Steubing et al., 2020a) is used to calculate the impacts of the pillbox scenarios. The bill of materials (BOM) (Appendix A1) for the pillbox was used, however, the environmental impacts associated with the production of parts and assembly are not considered in the Life Cycle Assessment (LCA), due to the absence of data. Figure 12 is a representation of the modelled data described in the previous sentence.

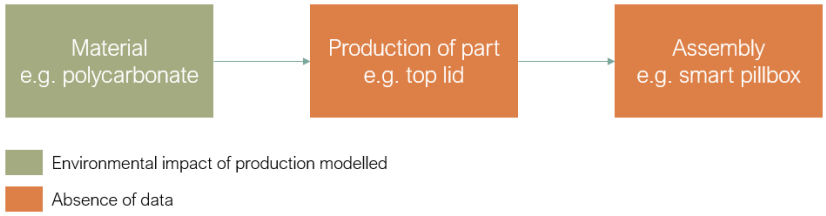

Figure 12. Representation of modelled data

Temporal coverage: The data available for the foreground processes comes from the smart pillbox company, which was collected in 2022. Background processes are based on historical data and are collected from the ecoinvent 3.8 (cut-off) database (Wernet et al., 2016).

Geographical coverage: As the DiCE project is EU based the geographical coverage of the pillbox is in the EU as well.

Technological coverage: Data about practises is not available for the company. Therefore, process data from the ecoinvent 3.8 database is used.

Environmental impact: The environmental impacts are based on the ReCiPe Midpoint (H) v1.13 family. The environmental impacts are calculated to 18 mid-point indicators (Huijbregts et al., 2017).

Use scenario of current smart pillbox

What does the situation 'as is' look like? The use scenario is based on data given by the pillbox company (Anonymized smart pillbox company, 2022). The product is used…

- … in the EU
- … by a person between 50-75 years old.
- … by someone taking 5 pills, 2/3 times a day.
- … for 3 years.
- … without notifications to a caregiver.
- … without needing any repairs.
- … at home.
- … for a week without needing a battery recharge.

To get a better understanding of the use of the product a persona is created. This persona is based on the average user for the pillbox company. Her name is Becky.

> *Becky has had a heart attack 1 year ago when she just turned 60 years old. She has to take medication around 2 times a day to prevent another heart attack. She is still capable of taking her medication without help from a caregiver, but she needs the smart pillbox to remind her to take her medication. She has different pills from which some she has to take only in the morning and others in the evening. The smart pillbox helps her to take the right ones at the right time without having to take time and plan out her entire week of pills herself.*

This section is based on the scenario and persona.
The function, functional unit, and reference flow are:

Function:	Taking medication on time
Functional unit:	Taking medication at prescribed specific times
Alternative:	Smart pillbox
Reference flow:	Taking medication on time for 3 years, with a smart pillbox at prescribed specific times

4.2 Inventory analysis

4.2.1 System boundary

Cut-offs

Some cut-offs are made in the life cycle of the analysis. In the use phase, the impact of the medication is not included because this is not in the scope of the research. But it is important to notice that the medications of a person using a smart pillbox does have an environmental footprint (Rosi-Marshall & Royer, 2012). The focus of this research is finding the impact of the smart pillbox, not the impact of the medication. Additionally, the medication is different per users as well. The impact of the use of the app is also not included. The phone is, in the scope of this research, only needed when the medication is programmed for the use of the smart pillbox and when there is a notification. The total energy use of a phone is 7.01 kWh per year (Proske et al., 2020), which is only a very small amount per day considering that the energy used for the app is even smaller. Therefore, the energy use of the phone is not included. The impact of the cable tie is also cut-off because the weight of the part is insignificant in the total impact of the product, and it's does not give a function to the smart pillbox.

4.2.2 Flow chart

The flowchart (Figure 13) is based on the information gathered during interview with the smart pillbox company. The colours group certain parts on region and type of part to make the flowchart more readable. The same counts for the transport which is indicated in the flows per group.

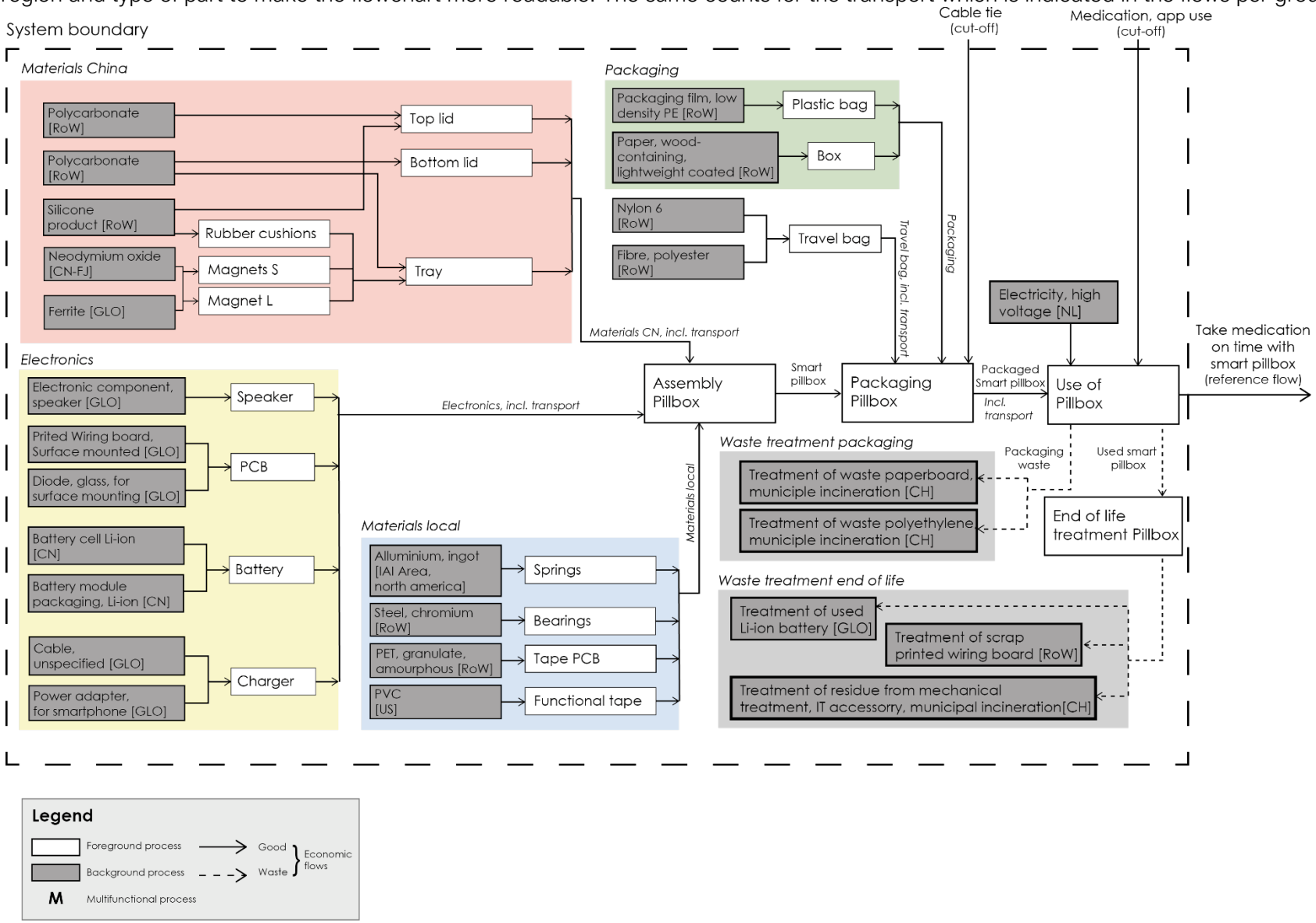

Figure 13. Flowchart of the baseline scenario

4.2.3 Data collection

Data from the anonymized pillbox company and ecoinvent 3.8 (cut-off) is used to model the smart pillbox in Activity Browser (Steubing et al., 2020b, 2017/2023). Not all materials are in the database, so proxies are used instead. Calculations and other assumptions are made, which are explained in this chapter. Other data used is located in Appendix A, which is confidential.

Proxies

Proxies used in this research are based on literature. Delrin is the first material used for two plastic parts, which is a thermoplastic named polyoxymethylene (POM).
There is no process available in the ecoinvent database for this material. The polycarbonate process is used as a proxy, because it has similar properties and CO_2 emissions as POM (Tinz et al., 2022).

The material composition of the speaker is not known. The ecoinvent process '*mobile phone, earpiece and speaker'* is used as a proxy for the speaker in the smart pillbox. An LCA study of a Fairphone analysed the material composition of the product's earpiece and speaker (Güvendik, 2014), the ecoinvent process is based on this research.

Additionally, the material composition of the magnets in the smart pillbox are not known. Therefore, data from literature is used to model this. According to Tripathy et al. (2021) the ratio of Neodymium and Ferrite is 26.7% and 72.3%, which is used to model the magnets.

For the charging cable a proxy is used because there is no specific charging cable available in the ecoinvent database. The process chosen is '*market for cable, unspecified'*.

There is no exact data available for the battery, therefore an ecoinvent process is used for this. The process '*market for Li-ion battery, rechargeable, Prismatic'* is used as a proxy.

Calculations

A calculation for the total energy use of the smart pillbox is made. According to the company the product needs a charge every week with the use scenario described in the scope. The battery states that it needs 2.405 Wh for a full charge.

Calculation: *2,405 Wh x 52 weeks = 125,06 Wh = 0.125 kWh per year = 0.375 kWh for 3 years.*

To calculate the material composition of the top lid, the total weight of the lid, which is 68.3 grams (g), is considered. The lid is composed of two layers of equal length and width: a 0.5 mm layer of silicone and a 2 mm layer of polycarbonate (PC). The density of silicone is 2.4 g/cm3, and PC has a density of 1.2 g/cm3.

The volume of silicone compared to PC is 0.5 mm : 2 mm. The densities of the two materials are 2.4 g/cm3 :1.2 g/cm3. This means that the weight ratios of silicone and PC in the lid are:

Calculation: 0.5 x 2.4e-3 : 2 x 1.2e-3 = 1.2 : 2.4 (= 0.33 : 0.67).
So, 0.33 of 68.3 grams is 22.8 grams of silicone, and 0.67 of 68.3 grams is 45.5 grams of PC.

The process used to model the power adapter is a power adapter for mobile phones in ecoinvent which weighs 0.0597 kg and the weight of the power adapter for the smart pillbox is 0.0269 kg. This results in 0.4508 unit needed for the smart pillbox adapter.

Other assumptions

Other assumptions are made for the calculation of the hotspots. When the location of a material is not in the database a market is used. The processes used mostly are based on a geographical data from RoW (Rest of the Word).

All numbers are rounded to 4 digits in the database, but results are communicated scientifically. And the waste treatment data that is used is from Switzerland as this is the closest

to waste treatment in Europe. The USB and micro-USB from the charging cable are not modelled, as there is no data available on these parts.

The processes in the ecoinvent database for PCB's use the unit m2. Because the relevant electronics of the PCB is only situated in one part of the PCB only this part is considered in the LCA. The rest of the PCB holds small LEDs in a larger plastic part, which is also not accounted for.

For the waste treatment process a proxy is used. The ecoinvent process '*treatment of residue from mechanical treatment, IT accessory, municipal waste incineration'* considers different materials that are usually found in IT accessory and is adopted a proxy process. The material composition used in the process is mainly plastics from electronic consumer and industrial goods and smaller parts of rubber, iron scrap, aluminium, and wiring copper.

Transport

Assumptions are made about the transport of parts as there is few data available and the use scenario is different from the situation as is. The product is so far only sold in the United States currently while the DiCE project aims to model a use scenario in the EU for research purposes.

- The product arrives in the Rotterdam port for use in the EU.
- The transport of the electronics is not included from supplier to distributor, because this data is not available. Including the battery because this is the only part of the electronics where the place of production is known.
- Transport is only added to the complete tray, including magnets and cushions, because the tray is already assembled before transport.
- Super small distance, under 30 km, is not included.

All unit process data is communicated in Appendix A2.1.

4.3 Impact assessment

All data is now gathered to calculate the impact of the smart pillbox. Life cycle inventory (LCI) results is the inventory table which includes the calculated inputs and outputs to the environment linked with the functional unit, for example kilograms of carbon dioxide. The LCI results are converted to characterization results. Impact categories are used to express environmental issues. There are models that can translate the impact of the inventory table to certain impact categories. This is called classification and models that do this are characterization families (Guinée et al., 2002).

The ReCiPe family is a characterization family and uses 18 impact categories which represent environmental issues to which LCI results are assigned. The LCI results are converted into characterization results, using characterisation factors for the different impact categories in the ReCiPe family (Figure 7). For the sensitivity analyses the PEF family is used to check the results of the first family (European Union, 2021), as the selection of a characterization family does influence the results. See Appendix C1 for the results, as the impact assessment is not the focus of this chapter. On the other hand, the hotspots of the smart pillbox are the focus of this chapter and are presented in section 4.4.1. The hotspots are calculated using the Activity Browser software (Steubing et al., 2020b). The hotspots are calculated and communicated via the Sankey diagram tool implemented in the Activity Browser software, using the characterization results of the smart pillbox.

4.4 Interpretation

4.4.1 Hotspots of smart pillbox

An environmental hotspot analysis is conducted which results in percentages of certain parts of the total impact in a specific impact category. Table 6 translates the data in the Sankey diagrams. The impact categories displayed in Table 6, but the elaborate hotspot analysis can be found in Appendix C2. The Sankey diagrams of all impact categories can be found in Appendix C3. The colours indicate the hotspots per impact category.

Table 6. Hotspots of the smart pillbox based on the ReCiPe impact categories

Impact category / part	Power adapter	PCB	Tray	Cable	Top lid	EoL	Battery	Bottom lid	Box	Speaker	Electricity	Other	Total
Particulate matter formation	31%	18%	12%	12%	6%	1%	5%	4%	4%	2%	1%	4%	100%
Photochemical oxidant formation	34%	14%	14%	7%	7%	1%	3%	5%	3%	3%	2%	7%	100%
Ionising radiation	48%	26%	4%	3%	2%	0%	3%	0%	4%	3%	5%	2%	100%
Ozone depletion	10%	4%	33%	0%	20%	0%	1%	13%	1%	1%	1%	16%	100%
Human toxicity	22%	15%	2%	30%	1%	16%	8%	0%	1%	3%	2%	0%	100%
Climate change	26%	14%	16%	2%	8%	15%	2%	6%	3%	2%	4%	2%	100%
Water depletion	27%	18%	15%	5%	12%	1%	3%	3%	8%	2%	2%	4%	100%
Metal depletion	55%	11%	2%	18%	0%	0%	11%	0%	0%	0%	0%	3%	100%
Agricultural land occupation	16%	12%	1%	4%	2%	0%	2%	0%	58%	2%	2%	1%	100%
Fossil depletion	29%	15%	20%	2%	9%	0%	2%	8%	4%	0%	4%	7%	100%
Freshwater ecotoxicity	11%	8%	0%	17%	0%	56%	4%	0%	0%	2%	1%	1%	100%
Freshwater eutrophication	34%	23%	1%	20%	1%	0%	6%	0%	3%	4%	4%	4%	100%
Marine ecotoxicity	11%	8%	0%	18%	0%	54%	5%	0%	0%	2%	1%	1%	100%
Marine eutrophication	20%	13%	40%	4%	3%	3%	3%	2%	3%	4%	2%	3%	100%
Terrestrial acidification	26%	16%	11%	19%	6%	1%	6%	4%	3%	2%	1%	5%	100%
Terrestrial ecotoxicity	9%	20%	2%	8%	1%	37%	3%	0%	20%	0%	0%	0%	100%
Urban land occupation	22%	19%	9%	23%	2%	1%	8%	0%	6%	4%	2%	4%	100%

4.4.2 Completeness check

Expectations based on literature was that large amounts of metals and plastics, copper, PCB and a battery would result in high contributions to the environmental impact (Freund et al., 2022; Duijndam, 2022; Güvendik, 2014). Looking at the results in Table 6 these expectations almost match the outcome from the environmental hotspot analysis. The charger contains high amounts of metals and plastics, including copper and a small PCB. The top/bottom lid and tray have a high mass of plastic and the PCB are also hotspots of the smart pillbox. Despite initial expectations, the battery did not turn out to be a hotspot of the product. In the next section (4.4.3), a sensitivity analysis is performed to determine whether alternative data would affect the findings.

4.4.3 Sensitivity analyses

Due to certain assumptions and unexpected outcomes in this research, specific areas undergo sensitivity analyses to ensure the validity of the findings. The first sensitivity analysis is on the power adapter, followed by the charging cable, battery, transport and ending with the characterization family.

Power adapter

The power adapter is the largest contributor in most of the impact categories. As mentioned in Chapter 4.2.3, the process used in the LCA is from the ecoinvent process '*power adapter for mobile phones'*. A calculation was made to match the weight from the used data to the adapter from the smart pillbox. Because it's not specifically found in the literature that a power adapter has the largest impact of an electronic product the adapter data is better looked at. The adapter is deconstructed to see if the same materials are present as in the ecoinvent process. The specific weights are not measured but when looking at all the components the smart pillbox power adapter matches the data used in ecoinvent. After deconstructing the adapter and finding a PCB and other metals it seems like the impact calculations corresponds with what is found in the literature.

Figure 14 shows the deconstructed adapter, with on the left the casing, the bottom of the PCB and some wiring. On the right the top of the PCB and mounted components are shown.

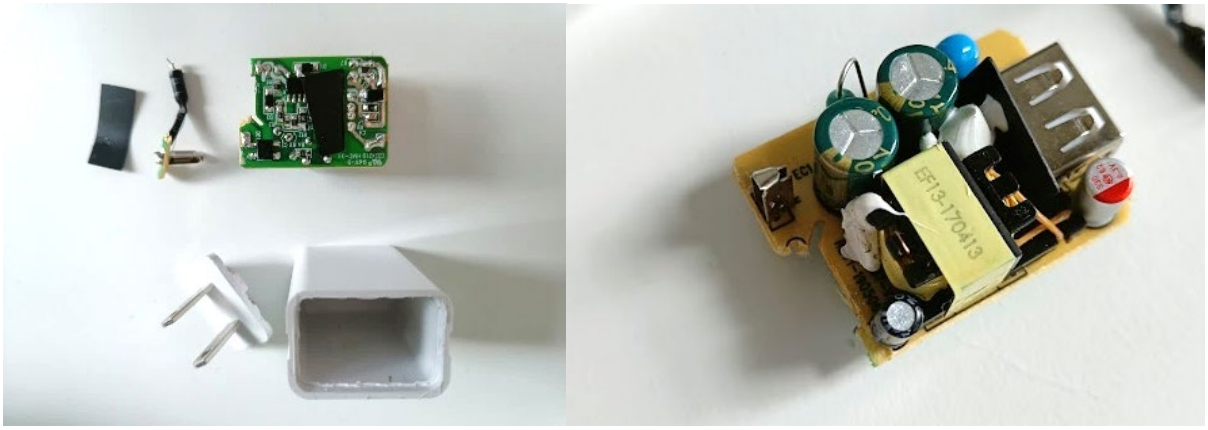

Figure 14. Deconstructed power adapter from smart pillbox

Charging cable

The assumption for the charging cable process is tested via a sensitivity analysis to understand if there is a difference in environmental hotspots using another process from ecoinvent. The process used for this is *Market for cable, connector for computer, without plugs*, which is quite similar to a charging cable. The ecoinvent process provides a cable that is 1 meter long and weighs 0.065 kg. The smart pillbox cable is 0.95 meters long and weighs 0.018 kg. Based on these numbers, the weight of the ecoinvent cable per meter is 0.065 kg, while the weight of the smart pillbox cable per meter is 0.0189 kg/meter (calculated as 0.018 kg divided by 0.95 meters). It can be concluded that the ecoinvent cable is 0.34 times heavier per meter than the smart pillbox cable (calculated as 0.065 kg divided by 0.0189 meters). To compensate for this difference, the length of the pillbox cable is modelled as a shorter cable by dividing 0.95 m by 0.344, which equals 0.277 m.

Most percentages of impact remained the same, but some changed for the cable. The impact categories with a change >1% are shown in Table 7. The difference between the alternatives in the category human toxicity results in the difference of contribution of copper processes.

Table 7. Changes in percentage with other cable process.

Changes in %	Cable unspecified	Cable, computer	Difference
Particulate matter formation (PMFP)	12%	8%	-4%
Photochemical oxidant formation (POFP)	7%	5%	-2%
Human toxicity (HTPinf)	30%	19%	-12%
Metal depletion (MDP)	18%	10%	-8%

Several percentages varied when using an alternative cable process, although the most significant difference was seen in the human toxicity category. Especially, the upstream process of copper did change when using different cable processes, which is an essential factor to interpretate the outcomes of the human toxicity category. However, relating to the hotspots analyses of other categories, the implementation of different cable processes is negligible.

Battery

The battery was expected to be one of the main hotspots of the smart pillbox. The results indicate that this is not the case. The ecoinvent process used as a proxy is changed to another type of battery to see if it gives different results. The process '*market for battery, Li-ion, NCA, rechargeable, prismatic'* is used for the sensitivity analyses. Most of the process contributions remained the same except for the impact categories presented in Table 8. The largest difference is in the category water depletion due to an upstream process for electricity for the cobalt industry.

Table 8. Changes in percentage using other battery process

Changes in %	Battery	Battery, sensitivity	Difference
Ionising radiation (IRP_HE)	0%	10%	10%
Marine eutrophication	0%	6%	6%
Metal depletion (MDP)	11%	15%	4%
Urban land occupation	8%	13%	5%
Water depletion (WDP)	0%	25%	25%
Particulate matter formation (PMFP)	0%	7%	7%

Proxy for POM

As mentioned before the material POM was not found in the ecoinvent process. The ecoinvent process used as a proxy is changed to another type of plastic to see if it gives different results. The process '*market for nylon 6'* is used for the sensitivity analyses. Most of the process contributions remained the same except for the impact categories presented in Table 9. The largest difference is in the category ozone depletion due to an upstream process of the polycarbonate production contribution more to ozone depletion than nylon.

Table 9. Changes in percentages using another proxy for POM

	Tray			Bottom lid		
Changes in %	PC	Nylon	Difference	PC	Nylon	Difference
Marine eutrophication	40%	46%	6%	2%	6%	4%
Photochemical oxidant formation	14%	18%	4%	5%	7%	2%
Ozone depletion	33%	2%	-31%	13%	0%	-13%

Transport

Many assumptions were made related to the transport of the smart pillbox. The assumption is that the product is used in the Netherlands and that there is no extra transport in Europe. A sensitivity analyses is done to see if extra transport changes a lot in the hotspots if the product is sent to the other side of Europe by lorry from the port of Rotterdam. Extra transport to Spain is taken as an example. Appendix C shows the result of the analysis, which conclude that there is no change in the hotspots when the product is transported to Spain instead of staying in The Netherlands.

Characterization family

Secondly, the results of the hotspot analyses using the ReCiPe family are compared to the results of another impact family. The PEF family is used for this because the impact categories of both families are quite similar and the PEF family is recommended by the European union (European Union, 2021). The results are in Appendix B and no huge differences were found.

4.5 Discussion: LCA hotspots identification

From the results in this chapter the charger has the highest impact, including other electronic parts and plastic components like the tray and top lid.

Nevertheless, these findings are based on assumptions due to the limited availability of data. The assumptions made regarding transportation, proxies, and other factors were explored in the sensitivity analyses in Section 4.4 and would not result in significant differences, except for the use of different proxies for the cable, battery, and POM. Using other process gave a slight difference in results. Further research could find more accurate data on these parts to understand if this gives a difference in result.

It should be emphasized that the functional unit of the smart pillbox was set to 3 years and that further analysis of longer usage scenarios will be conducted in Chapter 6 to better understand the impact of this.

The impact of the smart pillbox on the environment can be reduced by not including a complete charger (cable and/or adapter) or allowing consumers to choose when they purchase the product. This is a simple intervention that does not require any changes to the product design. To ensure that consumers have a charger at home, the smart pillbox can be equipped with a USB-C port, which is in line with the new EU regulation that requires all mobile devices to have a USB-C charging port by the end of 2024 (European Parliament, 2022). Additionally, when changing the port, testing the charging capabilities of the smart pillbox with chargers that use this port might be necessary.

Optimizing the materials used in the smart pillbox, such as changing the PCB including LEDs, is a more complex task. The material used for the top lid can be changed to a less impactful material, but this may impact the durability of the lid. Nevertheless, Chapter 3.1.2 concluded that the top lid needs to be replaced due to aesthetic durability. Therefore, the company could consider using a less impactful plastic material that is less durable, when they wish to preserve the appearance of the top lid.

The lithium-ion batteries used in the smart pillbox are already considered the most promising type of batteries for the future. Ongoing research is aimed at making these batteries more environmentally sustainable, but more time is needed before these technologies are ready for implementation (Yaghoobnejad Asl & Manthiram, 2021). Finally, the tray can be replaced by another plastic, but this change may not be necessary given that the tray does not need to be replaced during the longer lifetime of the product.

4.6 Conclusion and recommendation: LCA hotspots identification

This chapter aimed to answer the second sub-question using an environmental hotspot analysis. *What are the environmental hotspots of the current smart pillbox and how could they be lowered or removed?*

To conclude, the environmental hotspots of the current smart pillbox were identified as followed. Where the largest hotspot, 1, is expected to have the highest impact.

1. Power adapter
2. PCB including LEDs
3. Tray
4. Cable
5. Top lid
6. Battery
7. Bottom lid

To reduce or remove these hotspots, the following measures can be taken: (1) not including a charger or giving it as an option, while changing the charging port to the EU standardized USB-C port (2) changing the Polycarbonate of the top lid to a less impactful material. These changes are aimed at reducing the environmental footprint of the smart pillbox and ensuring its sustainability. Further research is needed to understand what material is less impactful compared to Polycarbonate. Table 10 shows an overview of these recommendations.

Table 10. Redesign recommendations based on LCA hotspot identification

Part	Recommendation	Reason
Power adapter	Do not include a charger or give it as an option to the consumer. Replace the existing charging port with a USB-C port that corresponds to EU standards and ensure the smart pillbox functions with chargers that use this port.	The power adapter contributes most to a larger amount of impact categories. The USB-C charger is in line with new EU regulations; therefore, the USB-C charging port is recommended.
Top lid	Changing the Polycarbonate to a less impactful material. Further research is needed to understand what material functions as a better alternative.	The lid is in the top 5 of parts that contribute most to the overall impact of the smart pillbox.

Chapter 5. Circular Product Readiness

This chapter focusses on the Circular Product Readiness method and in doing so tries to answer sub question 3: *How does the smart pillbox product and its system score on circularity?*
The chapter starts with data collection from the pillbox company via a questionnaire in Chapter 5.1, followed by the visualised results in Chapter 5.2. The results are discussed (Chapter 5.3) and verified by the information given in interviews. Finally, the third sub-question is answered at the end of this chapter.

5.1 Data collection

The data is collected by letting the company fill in the questionnaire; see Appendix D1 for the questionnaire. Someone within the company with knowledge about the company structure was asked to fill in the answers. It is possible for all responses to receive equal credit in a point system where the total value is 1. An example of a question including a score is shown in Figure 15. The pink numbers represent the scores an answer receives. In the example question an answer can also be N/A, which represents that the question is out of scope, shown in Figure 16 and Figure 17 as a X.

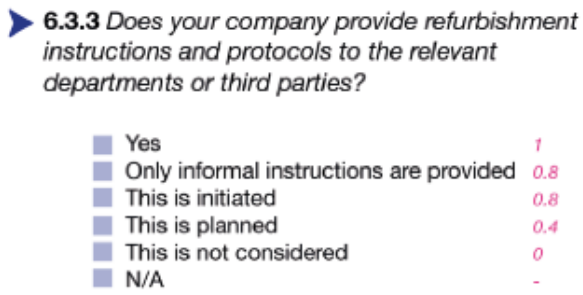

Figure 15. Example question of the Circular product Readiness method.

Figure 16 and Figure 17 presents the results of the questionnaire through visualization. The purple dots represent the scores received for each answer, with a value of 0.2 points per dot. The pink bars represent the average score, which is further calculated to the overall score, illustrated by the pink circles.

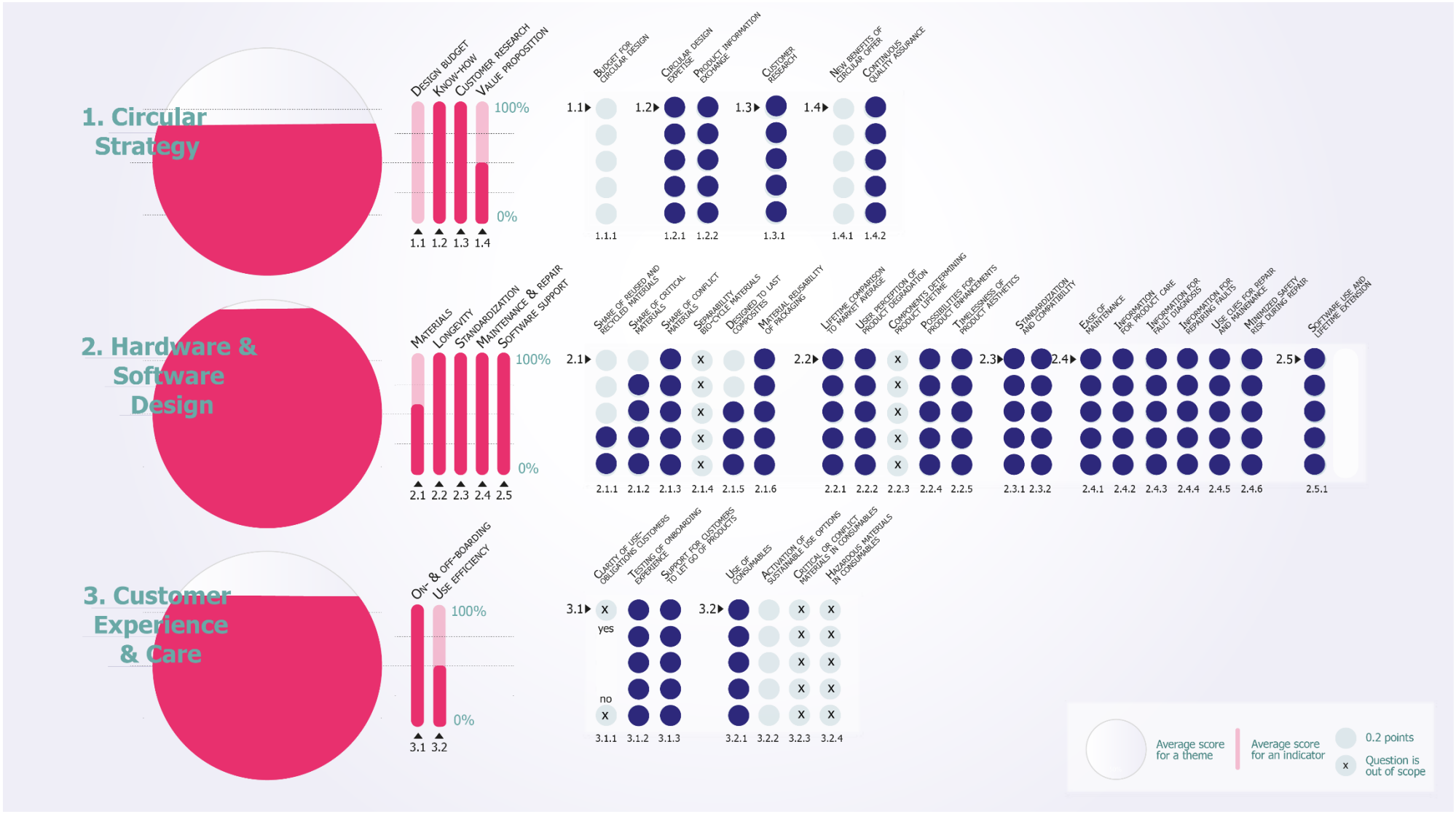

Figure 16. Visualisation of answers of the questionnaire (1-3)

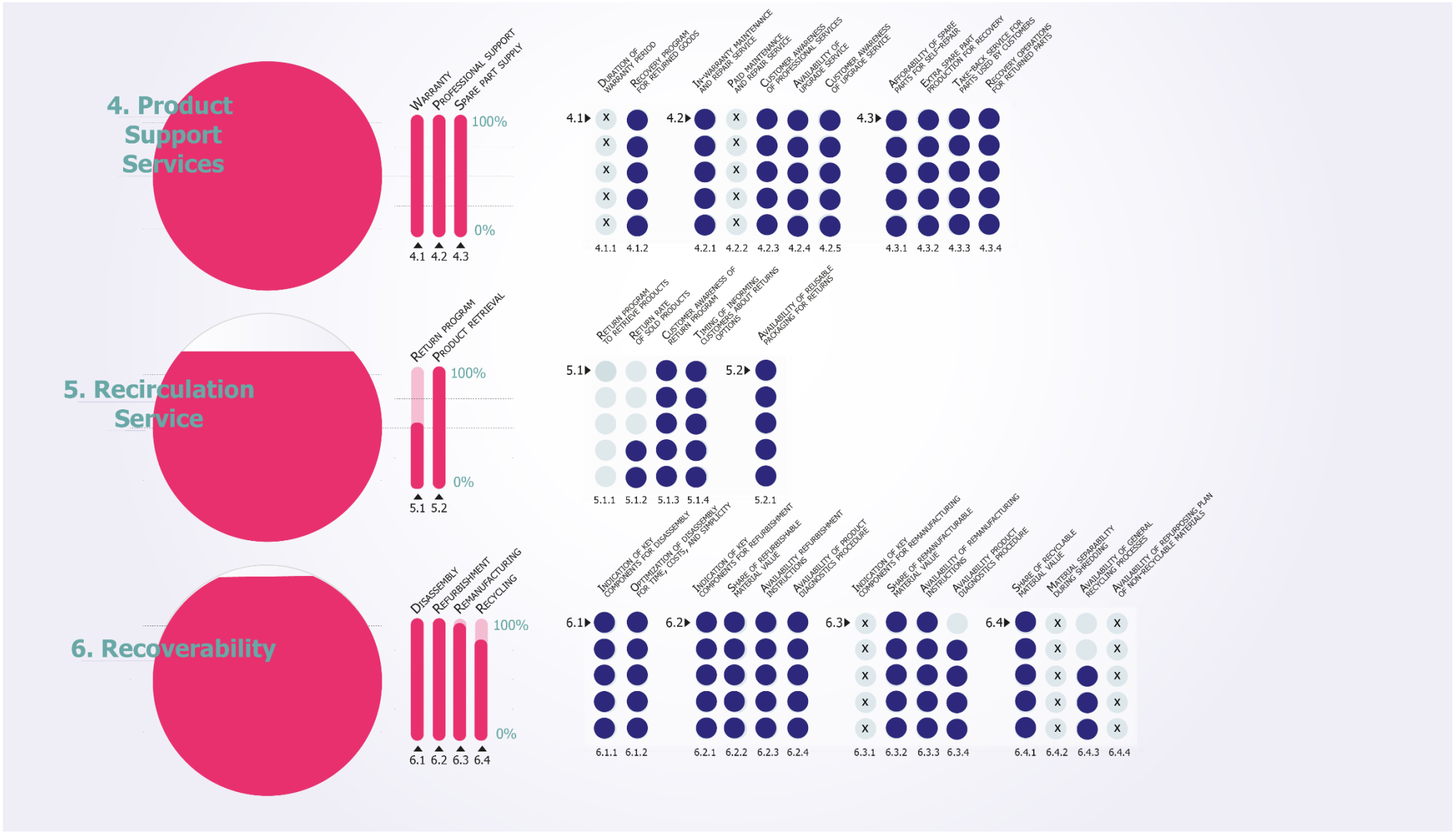

Figure 17. Visualisation of answers of the questionnaire (4-6)

5.2 Results

The results shown in Figure 16 and Figure 17 are translated to a visual and is shown in Figure 18.

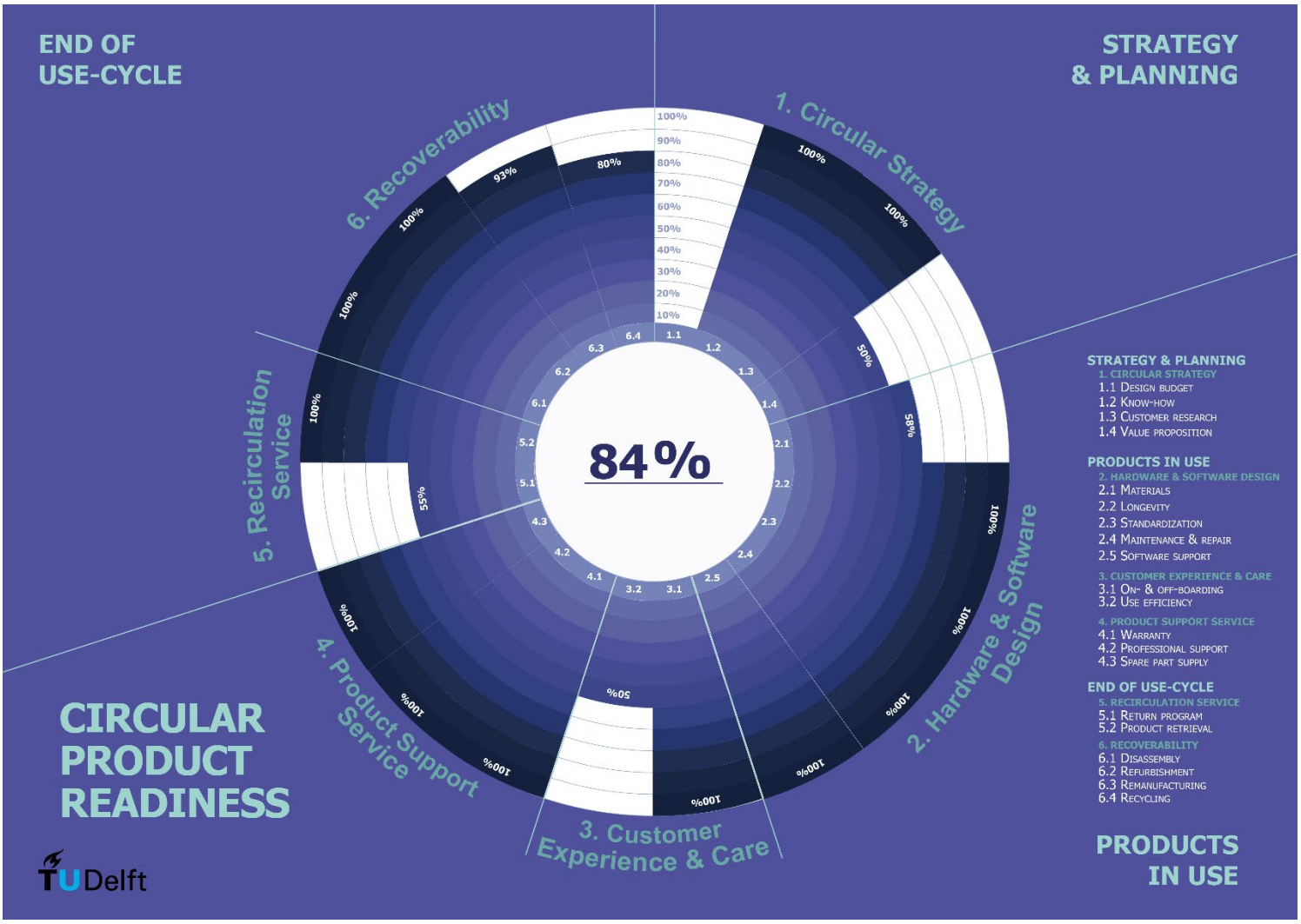

Figure 18. Visual of the results of the Circular Product Readiness method

The design indicators show that the pillbox company achieved an overall score of 84%, but without a comparison to another company, it is difficult to interpret the score's significance. However, examining the scores closely can help identify potential areas for improvement within the company. Some categories score lower than the others, therefore they are analysed more closely. The design budget category scores 0% (1.1), under the Circular Strategy indicator. In the same indicator the value proposition answers score 50% (1.4).

Materials choices (2.1), product use efficiency (3.2) and recirculation service (5.1) also score around 50%. The rest of the design indicators scored 80% to 100%. The answers to why certain parts score lower is shown in Table 11. The pink numbers behind the answer indicate the number of points.

Table 11. Lower results in assessment

Nr.	Score topic	Topic	Answers to individual questions, which lower the overall score for the specific topic.
1.1	0%	Design budget	**1.1.1** *Has your company made a budget available for circular design?* Yes 1 This is initiated 0.8 This is planned 0.4 ✓ This is not considered 0
1.4	50%	Value proposition	**1.4.1** *Does the circular value proposition and its related service and product offer new benefits to customers?* Yes, there are new benefits to this circular value proposition 1 We are in the process of adding new benefits 0.4 ✓ No, there are no new benefits to this circular value proposition 0 N/A -
2.1	58%	Materials	No use of recycled (2.2.1), or biodegradable components (2.1.4). The use of critical materials is also lowering the score (2.1.2).
3.2	50%	Use efficiency	**3.2.2** *Does the product activate end-users to opt for sustainable use options?* For example by a button for energy or water saving modes. Yes 1 This is initiated 0.8 This is planned 0.4 ✓ This is not considered 0 N/A -
5.1	50%	Return program	**5.1.1** *Does your company have a program to actively retrieve products from the market?* Yes 1 ✓ No 0 N/A - **5.1.2** *What percentage of the sold products are returned to the company or to partnered companies?* This includes returned part from buy-back schemes and pay-per service models. 0% 0 ✓ 1-9% 0.4 10-19% 0.6 20-49% 0.8 50-100% 1

As mentioned before in Chapter 2.3, due to time constraints the answers are not validated via interview conversations with the company, as the method suggests. But the answers are critically analysed to understand if other answers were expected based on the conversations with the company in the past and the website of the company is also used.

Question 2.4.5 (Figure 19) is highlighted because the answer does not match the results of the Disassembly Map. However, from the results of the Disassembly Map in Chapter 3 there are no design cues that support maintenance or repair of the product.

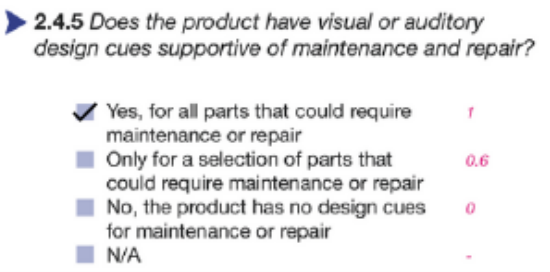

Figure 19. Question 2.4.5 and answer

The answer to 3.1.1 is 'N/A' and is about the communication of return to customers. But the company does sell to consumers as well as B2B. The end-of-life is not communicated to customers at this moment. Therefore, the correct answer would be 'No'.

The answers around the recycling topic are not cohesive. Question 6.4.4 answers N/A while question 6.4.3 related to the same topic is just answered, which makes the answers in the recycling topics not cohesive.

To conclude, some questions were not answered cohesively or correctly. The reason for this could be because of the interpretation or unclarity of the questions. The company was very willing to answer all questions correctly and are eager to become more circular.

5.3 Discussion: Circular Product Readiness

The results in this chapter indicate that the company scores well on multiple design indicators, except on the design budget because there is no budget available for their circular strategy.

An interesting aspect of this method is that despite the absence of a design budget, other components of the "Circular Strategy" receive a full score of 100%. This relates to the company's access to circular design expertise. An expectation would be that expertise requires a design budget; however, the approach assumes that if the question concerning the budget for circular product design is not considered, the remaining questions can still be answered. The responses of the other questions suggest the availability of design expertise, and it is therefore logical to conclude that the company is investing in circular design. For this reason, this shows as a limitation of the approach. As the other answers suggest that there is a circular design budget, further research could analyse if this is the case.

Expected was that every company scores different so a hypothesis could not be formed. The questions were answered by the company and might have been interpreted differently than was intended. There is a possibility that the company scored lower or higher in some areas. But most answers were checked critically to understand if other answers were expected based on the conversations with the company in the past and the website of the company.

According to the Circular Product Readiness method some areas of improvement for the company structure are activate the user to use their product in a sustainable way and try to actively retrieve their product when people don't use it anymore.

A solution to activate the user for sustainable use is Eco-Steer. This design approach uses constraints implemented within product design to promote the acceptance of environmentally and socially desirable use habits by users. This guides users towards sustainable actions and behaviours, ultimately leading to more eco-friendly and socially responsible product use (Bhamra et al., 2011). An example for the smart pillbox is that it could provide guidance to the user on how to prolong battery life, such as specifying the optimal duration and timing for charging.

Furthermore, the app could ask users to assess whether the product is still fulfilling their needs if it has remained unused for an extended period. If the user determines that it no longer serves a purpose, the app could instruct the user to return the product to the company, thereby enabling end-of-life retrieval and reducing waste.

These are quite small interventions to create a more circular company structure. Besides that, topics related to the product itself can be improved around the use of recycled materials and the recycling of the product needs more attention when the product or parts are not reusable anymore.

As a design recommendation, suggested is to explore the use of recycled materials, specifically in plastic components. To facilitate this, we suggest starting a conversation with the supplier of the plastic components in China to determine the feasibility of incorporating more recycled materials instead of the raw materials that are currently used in the manufacturing process.

As a design recommendation for recycling solutions, recommended is to connect with a specialized recycling facility that deals with electronic devices. Through this collaboration, we suggest identifying potential pain points in the recycling process specific to the smart pillbox and use design to address these issues, optimizing the product's recyclability. By actively seeking out and addressing such issues, the smart pillbox can be effectively recycled.

This approach has the potential to enhance the circularity of the product's lifecycle and promoting more sustainable practices.

5.4 Conclusion and recommendations: Circular Product Readiness

How does the smart pillbox product and its system score on circularity? In terms of circularity, the smart pillbox product and its system scored 84% based on the Circular Product Readiness method, but without a comparison to another company, it is difficult to interpret the score's meaning. To determine this score, a questionnaire was used along with information obtained from a previous interview and online sources to verify if the expected answers were provided.

However, there are several opportunities for improvement at both the company and product level. The company can encourage users to use the product sustainably, and actively recover end-of-life products. The product itself can be improved by using recycled materials and exploring potential recycling processes for its components. Table 12 presents the Circular Product Readiness method's recommendations and the reasons behind them.

Table 12. Redesign recommendations based on Circular Product Readiness

Part	Recommendation	Reason(s)
All	Use Eco-Steer design approach by promoting environmentally desirable habits. For the smart pillbox, provide guidance to the user on how to prolong battery life and ask users to assess whether the product is still fulfilling their needs if it has remained unused for an extended period. If not, request the user to send the product back to the company.	- Users are not encouraged to use the product sustainably. - Active end-of-life retreatment is not considered.

Plastic components	Explore the use of recycled materials in plastic components by starting a conversation with the supplier to determine the possibilities.	Recycled materials are not used.
All	Collaborating with a specialized electronic recycling facility to identify and address recycling pain points specific to the smart pillbox, thereby optimizing its recyclability.	Recycling processes are not explored.

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Summary of part A: Product level environmental sustainability

All components of answering research question A are now discussed. A small summary of the recommendations is presented in Table 13. Possible overlaps are presented and finally part A will be ended. This summary table is also presented in the conclusion in Chapter 8.1. The plastic material used for various parts, particularly the top lid, is a common element across different methods, resulting in a slight overlap in the findings.

Table 13. Redesign recommendation based on product level environmental sustainability assessments

Part	Recommendation	Reason	Chapter
Sub-question 1: *How can the disassembly be improved to extend the lifetime and increase repairability of the smart pillbox?*			Chapter 3
Sub-assemblies	Use screws instead of snap fits to attach the sub-assemblies	Allows consumers to easily open up the product to reattach the battery.	Chapter 3
Battery	Fixate battery in a designated spot. (See Figure 11)	The battery detaches sometimes and needs to be reconnected. Fixating it prevents repair requests and extra transport to a repair facility.	Chapter 3
Top lid	Remove silicone layer or use low impact material for the main material.	The top lid needs replacement because visual wear and tear impact the aesthetic durability.	Chapter 3
Sub-question 2: *What are the environmental hotspots of the current smart pillbox?*			Chapter 4
Power adapter	Do not include a charger or give it as an option to the consumer. Replace the existing charging port with a USB-C port that corresponds to EU standards and ensure the smart pillbox functions with chargers that use this port.	The power adapter contributes most to a larger amount of impact categories. The USB-C charger is in line with new EU regulations; therefore, the USB-C charging port is recommended.	Chapter 4
Top lid	Changing the Polycarbonate to a less impactful material. Further research is needed to understand what material functions as a better alternative.	The lid is in the top 5 of parts that contribute most to the overall impact of the smart pillbox.	Chapter 4
Sub-question 3: *How do the smart pillbox product and its system score on circularity?*			Chapter 5
All	Use Eco-Steer design approach by promoting environmentally desirable habits. For the smart pillbox, provide guidance to the user on how to prolong battery life and ask users to assess whether the product is still fulfilling their needs if it has remained unused for an extended period. If not, request the user to send the product back to the company.	- Users are not encouraged to use the product sustainably. - Active end-of-life retreatment is not considered.	Chapter 5
Plastic components	Explore the use of recycled materials in plastic components by starting a conversation with the supplier to determine the possibilities.	Recycled materials are not used.	Chapter 5
All	Collaborating with a specialized electronic product recycling facility to identify and address recycling pain points specific to the smart pillbox, thereby optimizing its recyclability.	Recycling processes are not explored.	Chapter 5
Overlap all sub-questions			
Plastic components	Change to lower impact/recyclable materials.	Top lid needs replacement, contributes to the overall impact of the smart pillbox. And recycled materials are not used.	-

B. Functional level environmental sustainability

The research approach outlined in Chapter 2 provides the framework for this research. Part A focussed on the product level environmental sustainability using four methods. Part B focuses on answering the research question B regarding the functional level of the smart pillbox and the environmental sustainability.

This part only contains Chapter 6 which aims to answer Sub-question 4 using the Life Cycle Assessment (LCA) method. The discussion and conclusion are presented in Chapter 7 and Chapter 8.2.

Chapter 6. Life Cycle Assessment comparing conventional and smart pillboxes

The aim of this chapter is to compare different smart and non-smart pillbox scenarios in an LCA on environmental impact, followed by a discussion on the difference in DALY and QALY. This analysis is carried out to answer the fourth sub-question, which is: "*What is the comparative analysis of the environmental impact of the current smart pillbox and redesigned smart pillbox scenarios, as obtained from research question A, with a conventional pillbox used in Europe in relation to their respective benefits to the quality of life of patients?* "

This chapter starts by introducing the conventional pillbox scenario, followed by the goals and scope definition in Chapter 6.1. The inventory analyses (6.2) includes the flowchart of the conventional pillbox in section 6.2.2 and data collection and modelling choices in section 6.2.3. This information is used to conduct the impact assessment in Chapter 6.3, including characterization results in DALY. These results are discussed in Chapter 6.4 for interpretation. The chapter concludes with a discussion on the results in DALY and the benefits in QALY in Chapters 6.5 and 6.6, presenting the answer to sub-question 4.

In this chapter a conventional pillbox is compared to the smart pillbox. Figure 20 shows the conventional pillbox. In Section 4.1.2, the user scenario involving a medication schedule of twice daily dosing can be associated with the conventional pillbox, which features two compartments per day. The assumed expected lifespan of this pillbox is consistent with that of the smart pillbox, estimated to be 3 years.

Figure 20. Conventional pillbox

6.1 Goal and scope definition

6.1.1 Goal definition

The main goal of the LCA is to find the environmental impacts of different pillbox scenarios and their impact on human health (DALY). The LCA will be over the whole lifecycle (cradle to grave) of the products using the BOM of the smart pillbox company and a physical conventional pillbox. This LCA can be used to understand the difference in environmental impact of pillboxes and the effect of redesigning a smart pillbox. The target audience and intended application is the same as in the goal definition of the LCA in Chapter 4.1.1.

6.1.2 Scope definition

The scope of this LCA is described in Chapter 4.1.2 Parts that are different from that scope are described in this section.

The temporal, geographical and technological coverage are all the same as in the LCA in Chapter 4.1.2.

Environmental impact: The environmental impacts are based on the ReCiPe Endpoint (H, A) family. The environmental impacts are calculated to 3 end-point indicators, damage to human health (DALY), ecosystem quality and resource availability (Huijbregts et al., 2017).

The use scenario of the smart pillbox is also outlined in Section 4.1.2. In order to make a meaningful comparison between different scenarios, it is necessary to ensure that the functions of the pillboxes are comparable. The lifespan of the pillboxes has a significant impact on their annual environmental impact. The key difference between the smart and conventional pillboxes is the reminder function provided by the smart pillbox. For this reason, it was considered to include the reminder function in the reference flow designated as 'on-time.' This does not imply that users of conventional pillboxes always forget to take their medication, but rather that the reminder feature of the smart pillbox serves as an incentive to take medication at the prescribed time.

Based on the results of the smart pillbox disassembly, alternatives *b* and *c* were developed. Alternative *d* was derived from the results presented in Chapter 4. A combination of these two alternatives resulted in alternative *e*. Additionally, the wear and tear on the smart pillbox was found to result in the replacement of its top lid. Alternative *f* was created to investigate the impact of this, while taking alternative *e* as a baseline but with no need for top lid replacement. Table 15 provides a more detailed explanation of the data used to create these alternatives."

The different steps of the function, functional unit, alternatives, and reference flows are shown in Table 14.

Table 14. function, functional unit, alternatives, and reference flows

Step		
1	*Function*	Take medication
2	*Functional unit*	Take medication 2 times a day
3	*Alternatives*	*a. On-time for 3 years, with a smart pillbox* *b. On-time for 5 years, with smart pillbox* *c. On-time for 7 years, with smart pillbox* *d. On-time for 3 years, without a charger* *e. On-time for 7 years, without a charger* *f. On-time for 7 years, without a charger and not replacing the top lid.* *g. For 3 years, with conventional pillbox* *h. For 7 years, with conventional pillbox*
4	*Reference flows*	*a.* Take medication 2 times a day *on-time for 3 years, with a smart pillbox.* *b.* Take medication 2 times a day o*n-time for 5 years, with smart pillbox.* c. Take medication 2 times a day o*n-time for 7 years, with smart pillbox.* *d.* Take medication 2 times a day o*n-time for 3 years, without a charger.* *e.* Take medication 2 times a day o*n-time for 7 years, without a charger.* *f.* Take medication 2 times a day o*n-time for 7 years, without a charger and not replacing the top lid.* *g.* Take medication 2 times a day *for 3 years, with conventional pillbox.* *h.* Take medication 2 times a day *for 7 years, with conventional pillbox.*

6.2 Inventory analysis

6.2.1 System boundaries

Cut-offs

Some processes are not included in the analysis and are therefore cut-off. The same cut-offs are considerate in this LCA as the LCA of the smart pillbox in Chapter 4.2.1. This includes the impact of medication, the app use, and the cable tie. The conventional pillbox shares a similar boundary to make an equal comparison to the smart pillbox. The impact of the medication taken with the conventional pillbox is not included either in the LCA. There is no app needed for a non-smart pillbox and there are no small packaging parts that come with the pillbox.

Economy-environment system boundary

The LCA is based on analysing economic processes that relate to the pillboxes. Economic processes are processes that create value and are done by humans. The processes either produce a good or a waste as you could see in the flowchart in Figure 13. In LCA every economic in and output is followed until they are translated into environmental interventions. Environmental interventions are flows entering or leaving a product system without human transformation, which means that they cross the boundary between the economy and the environment (Guinée et al., 2002).

An example of a process that interacts with the economy and environment is the use of oil to create the plastic for the pillboxes. The extraction process brings the oil, which is an environmental flow, to the economy system. And finally, with the recycling of that plastic the emissions are flows going from the economy to the environmental system. Of course, there are many more processes like this, but this is just an example of this exchange between the economy and the environment.

6.2.2 *Flowchart*

Flowchart of the conventional pillbox alternative *g* and *h* is shown in Figure 21. Figure 13 in Chapter 4.2.2 shows the flowchart of the smart pillbox alternative *a*.

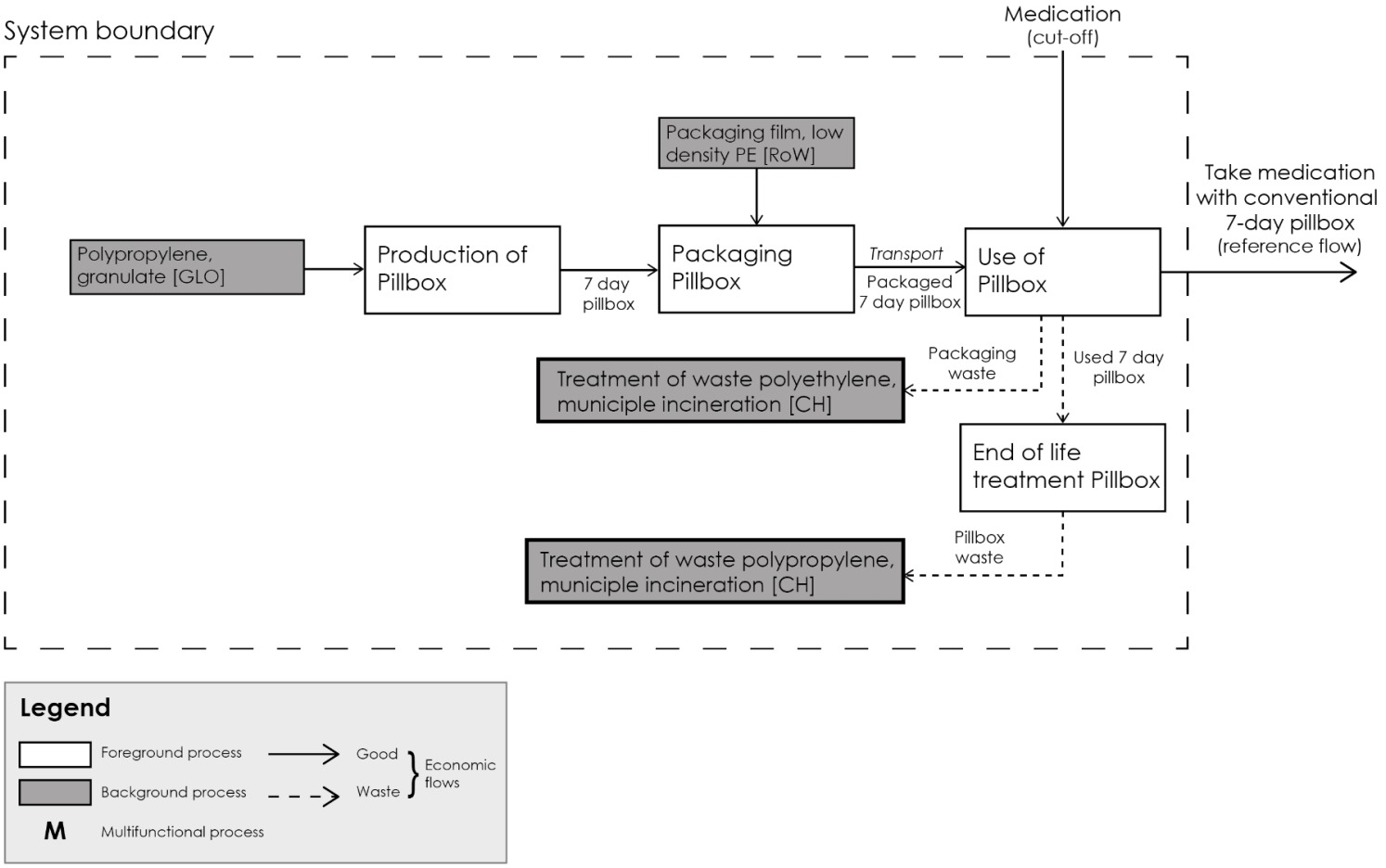

Figure 21. Flowchart conventional pillbox

6.2.3 Data collection and modelling choices

The same data from the LCA focussed on hotspots (Chapter 4) including the flowchart (Figure 13) is used in this LCA. Detailed data collection information can be found in Chapter 4.2.3 for alternative *a*. Alteration made to alternative *a* used for the other alternatives is shown in Table 15. The changes that are made to the alternatives is based on the results of Chapter 3 and Chapter 4. Alternative *g* is the conventional pillbox and alternative *h* is a version of alternative *g*.

Most manufacturers expect that a battery lasts 5 years (Lerma, 2019). Therefore, the battery is only replaced in alternative *c* and not in alternative *b.*

The assumption is that the non-smart pillbox lasts 3 years before needing replacement. Therefore, alternative *h* requires $2\frac{1}{3}$ conventional pillboxes. The power adapter is one of the environmental hotspots (Chapter 4), thus alternatives *d, e* and *f* are created without charger (power adapter + charging cable).

Table 15. Alternatives and altered data from alternative a and g

	Pillbox	*Alternatives*	*Years*	*Replacement/remove parts*	*Based on results of chapter*
a	Smart	Baseline user scenario	3	-	-
b	Smart	Longer use phase: 5 years	5	*Replace*: Top lid, Tape PCB, bearings, box *Add:* extra waste, transport	*1*
c	Smart	Longer use phase: 7 years	7	*Replace*: Top lid 2x, Tape PCB 2x, Bearings 2x, box 2x, battery *Add:* extra waste, transport	*1*
d	Smart	Not giving a charger	3	*Remove*: Charger (cable and adapter)	*2*
e	Smart	Longer use phase: 7 years & Not giving charger	7	*Replace*: Top lid 2x, Tape PCB 2x, Bearings 2x, box 2x, battery *Remove*: Charger (cable and adapter) Add: extra waste, transport	*1 & 2*
f	Smart	Longer use phase: 7 years, Not giving a charger & Not replacing the Top lid	7	*Replace*: Tape PCB 2x, Bearings 2x, box 2x, battery *Remove*: Charger (cable and adapter) Add: extra waste, transport	*1 & 2*
g	Conventional	See flowchart Chapter 6.2.2.	3	-	-
h	Conventional	3 years lifetime per pillbox, so replaced 1.33 times	7	*Replace*: conventional pillbox + transport 2.33 x *Add:* waste x 2.33	-

Transport & repair

For the alternatives, with a longer lifetime (b, c, e, f), repair is most likely needed, or parts have to be replaced. In Chapter 3 the conclusion was that the repair and maintenance was more suitable for professionals. Therefore, some assumptions related to this topic had to be made. Assumed is that the product is repaired in a European repair centre of the smart pillbox. The bearings, tape and box would be sourced locally as these parts are not specifically parts that are used only for the smart pillbox. The only part that needs transport is the top lid as it is made specifically for the smart pillbox and its production is in China. There is no transport data available for the battery as mentioned in Chapter 4.2.3, so this is again not accounted for. For the conventional pillbox (h) the transport is multiplied by 3 to cover the transport for 3 individual pillboxes.

Waste

The extra waste created related to packaging and the extra tape is included in the LCA for the smart pillbox alternatives. Only the extra waste of the top lid is not included as there is no waste process available for polycarbonate or silicone. As mentioned in Chapter 4.2.3 the process now used is '*treatment of residue from mechanical treatment, IT accessory, municipal waste incineration'* which includes all the parts of the pillbox, except the battery and PCB. This makes it complicated to add only the extra waste of the top lid.

Unit process data of alternatives *a* and *g* can be found in Appendix A2. Adopted transport processes of the other alternatives can be found in Appendix A3. Table 15 displays the further adoption of these unit processes, which consist of multiple parts that contain equal data of the unit processes of alternative *a* and *g*.

6.2.4 Inventory table

The inventory table is created using the Activity browser software (Appendix B).

6.3 Impact assessment

All data is now gathered to calculate the impact of the alternatives. See Chapter 4.3 for an explanation on how the impact assessment is conducted. See Appendix E1 for the impact assessment on mid-point indicators, as this is not the focus of this chapter.

In Chapter 4 of the other LCA, mid-point indicators were used to identify the hotspots of the smart pillbox. However, in this chapter, end-point indicators are used to determine the trade-off between the environmental impact and benefits of various pillbox alternatives. The remainder of the chapter explains how end-point indicators are used and what these indicators represent.

6.3.1 Characterization results

The endpoint indicators reflect areas of protection closely, which are Human health, Natural environment, and Resource scarcity (Table 16). Certain mid-point indicators get assigned to an end-point indicator (Figure 7). The end-point indicators are 'damage to ecosystem quality', 'damage to human health' and 'damage to resource availability'. See Table 16 for an overview of the end-point indicators. Human health represented in DALYs are a person's healthy years lost due to disease or an accident. Ecosystem quality is defined as the loss of local species combined with time. And last the resource scarcity means the extra cost in dollar needed for the extraction of resources in the future.

Table 16. Explanation of the endpoints of ReCiPe (Huijbregts et al., 2017)

Area of protection	Endpoint	Name	Unit
Human health	Damage to human health	Disability adjusted loss of life years (DALY)	year
Natural environment	Damage to ecosystem quality	Time-integrated species loss	Species x yr
Resource scarcity	Damage to resource availability	Surplus cost	Dollar

The results in Figure 22 show that the smart pillbox in alternative *a* has the largest impact in all indicators. A shared second place are alternatives *c* and *f*. Followed by the rest of the smart pillbox alternatives (e, g, h) and ending with the two conventional pillbox alternatives with the lowest impact. The difference between the smart pillbox alternatives is relatively big compared to the conventional pillboxes.

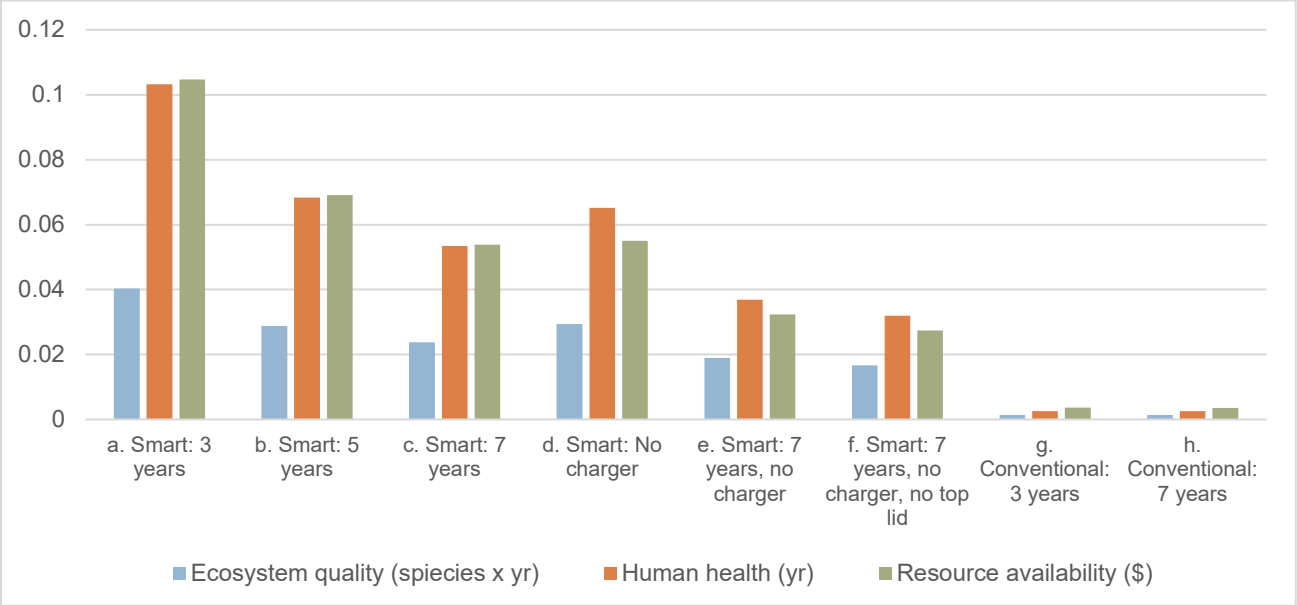

Figure 22. Characterization results (endpoint level)

6.3.2 Results in DALY

To evaluate the trade-off between the benefits of pillboxes and their potential environmental impact, it is necessary to examine their effects on human health. While other indicators such as ecosystem quality and resource availability are also important, they are currently set aside in order to focus on the trade-off evaluation. For the purpose of comparing the benefits and impact of the smart pillbox, the focus is now on DALY. This is because the smart pillbox has the potential to improve and maybe even extend people's lives, which can be expressed in terms of DALY and QALY.

Figure 23 shows only the result of the ReCiPe endpoint characterization for human health impact expressed in DALY. The smart pillbox creates a DALY of more than 0.1. And the conventional pillbox less than 0,005 DALY.

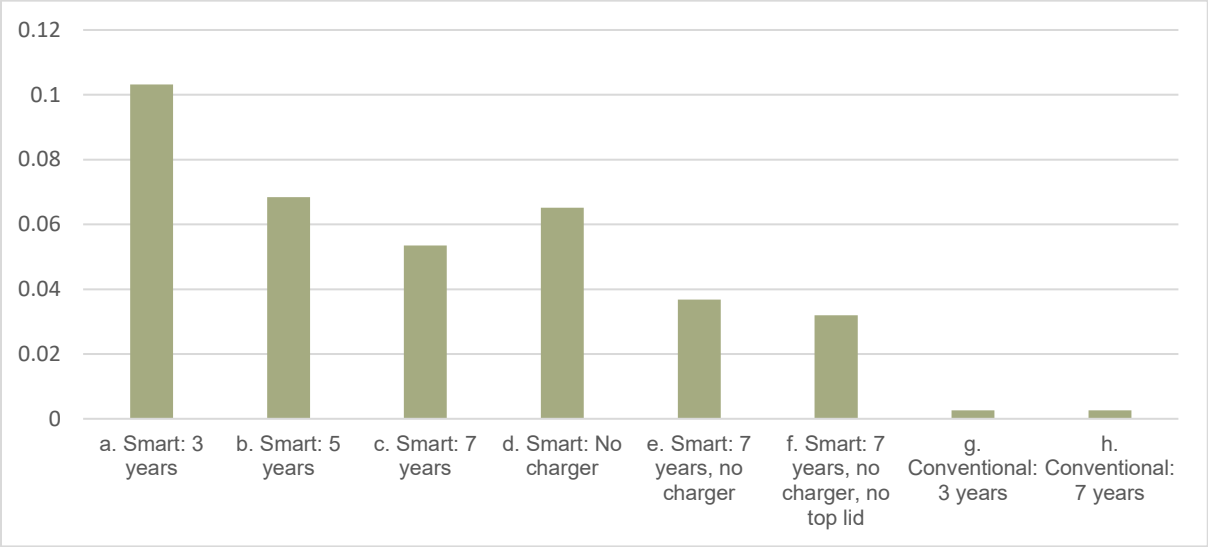

Figure 23. Damage to human health: Disability-adjusted life years (DALY)

The numbers in DALY are quite small and its visually hard to see what the exact numbers are. Therefore, Table 17 shows these numbers in the second column and represent negative impacts in DALY. An explanation of the other details is described in the next part of this section.

Table 17. DALY in numbers per alternative

Alternatives	DALY (Damage to human health)	Benefits (DALY) based on (Krack et al., 2018)	Benefits - impact = (DALY)	Overall benefit (QALY)
a. Smart: 3 years	0.103	0.37	0.267	0.245
b. Smart: 5 years	0.068	0.37	0.302	0.277
c. Smart: 7 years	0.053	0.37	0.317	0.291
d. Smart: No charger	0.065	0.37	0.305	0.280
e. Smart: 7 years, no charger	0.037	0.37	0.333	0.306
f. Smart: 7 years, no charger, no top lid	0.032	0.37	0.338	0.311
g. Conventional: 3 years	0.003	0.30	0.293	0.270
h. Conventional: 7 years	0.003	0.30	0.293	0.270

As previously stated, QALY can be converted to DALY using a ratio of 1.087 (de Bruyn et al., 2017). The 0.34 QALY improvement in medication adherence, as reported by Krack et al. (2018), when adherence is increased to 80%, corresponds to 0.37 DALY. By subtracting the DALY impact of the pillboxes from the benefits of adherence, one can theoretically calculate the overall quality of life improvement of an individual using a pillbox. At the beginning of the research, two assumptions were made regarding medication adherence and the use of pillboxes. It was assumed that the conventional pillbox had 60% adherence, while the smart pillbox created 80% adherence. A linear correlation was established between adherence and benefits, meaning that QALY improvement is 20% lower when using a conventional pillbox. The results of these calculations are presented in Table 17. These assumptions will be further examined in the sensitivity analyses in section 6.4.4.

Table 17 presents the results, which indicate a QALY improvement of 0.245 for alternative *a* and 0.270 for the conventional pillbox, assuming that the smart pillbox leads to improved medication intake and related benefits. The results can be translated to approximately 3 months QALY for the smart pillbox and 3 months and a week for the conventional pillbox. Given the uncertainty, this is an insignificant difference between the alternatives. However, the improved version of the smart pillbox does have a small impact on overall benefits. This suggests that enhancing the environmental sustainability of the product can make a difference in the overall benefits for patients.

6.4 Interpretation

6.4.1 Consistency check

A check of consistency of the alternatives (Table 14) in this research is shown in Table 18. Only the use of proxies is in the smart pillbox alternative larger than in the conventional pillbox alternative as there are more complicated parts and materials. Further and more detailed research is needed to change that inconsistency. A more detailed LCA has to be created to bridge that gap between those alternatives.

Table 18. Consistency check

Check	**a. Smart pillbox**		**Alternatives smart pillbox (b, c, d, e, f)**		**g. Conventional pillbox**		**h. Alternative conventional**		**Compare Alternatives**	**Action**
Data Source	Supplier, Secondary	✓	Supplier, Secondary & Primary	✓	Supplier, Secondary	✓	Supplier, Secondary & Primary	✓	Inconsistent	No action, alternatives based on data
Missing Data Source	Primary	✓	Data Smart pillbox	✓	Primary	✓	Data conventional pillbox	✓	Consistent	-
Data Accuracy *Transport*	Good	✓	Extra parts	×	Medium	✓	Medium	✓	Inconsistent	Sensitivity analysis
Data Accuracy *Proxies*	Multiple proxies	×	Multiple proxies	×	Good	✓	Good	✓	Inconsistent	Further research
Data Age	½ year	✓	½ year	✓	½ year	✓	½ year	✓	Consistent	-
Technology Coverage	State-of-the-art	✓	State-of-the-art	✓	State-of-the-art	✓	State-of-the-art	✓	Consistent	-
Time Related Coverage	Recent	✓	Recent	✓	Recent	✓	Recent	✓	Consistent	-
Geographical Coverage	NL	✓	NL	✓	NL	✓	NL	✓	Consistent	-

6.4.2 Completeness check

The completeness check examines if all information and data is complete to interpret the results.

Expert judgement
The results of the LCA were checked by the pillbox company and discussed. The assumption about medication adherence was further discussed and will be questioned in the sensitivity analyses (Chapter 6.4.4) to understand the influence of this assumption on the results.

Comparison with other studies
The study by (Duijndam, 2022) which was mentioned before concluded that the PCB resulted in a higher environmental impact. Expected was that the smart pillbox, due to the use of electronics and use of larger number of materials has a higher environmental impact. This corresponds with the results in this research.

Difference between alternatives
As was mentioned in the consistency check most data is comparable to each other. The data of the smart pillbox related to proxies the largest difference between the alternatives.

6.4.3 Hotspot analysis

The contributions of different flows to the environmental impact of the alternatives are reviewed in the Activity Browser model (Appendix B). This section presents the most significant results of the analysis. The effect of excluding certain components, such as the charger, on these contributions is of particular interest.

The aim of this hotspot analysis is not to examine the impacts related to human health. Instead, the focus is on comparing the hotspot results of alternative a (discussed in Chapter 4.4.1) to the newly developed alternatives of the smart pillbox in this chapter. The aim is to determine whether these changes have made a difference to the hotspots on mid-point indicators as done in precious LCA chapter (Chapter 4).

The exclusion of the charger results in the largest contribution in almost every impact category to the PCB. Exceptions to this include Ozone depletion, where the top lid, tray, and travel bag are the largest contributors, and Metal depletion, where the battery and PCB are the largest contributors.

The process contributions do not vary significantly when the product is used for 5 or 7 years, as compared to the 3-year scenario (see Chapter 4.4.1 for the results of the 3-year scenario). Some differences in process contributions are observed due to the modelled new parts. The following observations can be found in Appendix E2:

- In the 5- and 7-year scenarios, the Box process has a higher contribution to Photochemical oxidant formation, Climate change, Particulate matter formation, and Water depletion.
- Electricity has a larger contribution to Ionizing radiation and Climate change. The contribution of electricity has a linear relationship with the number of years of product use.

In the scenario where both the charger is removed and the product is used for 7 years, the results are a combination of the above observations.

6.4.4 *Sensitivity analyses*

To understand what some choices and assumptions have on the results some sensitivity analyses are conducted. This section explains the sensitivity analyses about the characterization family and replacement of parts. Followed by different sensitivity analyses on the assumption of medication adherence and improvement of QALY of the smart and conventional pillbox scenarios.

Characterization family
The first analysis is using another characterization family to validate the midpoint results of ReCiPe, using the PEF family. The order in which the alternatives have the highest impact to the lowest is the same as with the ReCiPe family. There is no significant difference between the two families.

Sensitivity: replacement of parts
The replacement of some parts is not included in the LCA, but there might be a situation where the smart pillbox is in perfect condition in the use of 7 years. This situation is analysed in this sensitivity analyses. For this reason, instead of replacing the top lid, bearings, box, battery and PCB tape, nothing is replaced. The alternative that is used to compare the result to is the smart pillbox that is used for 7 years. The results in Figure 24 show that there is a difference in impact when there are no parts replaced. The extra parts have an impact on the human health category.

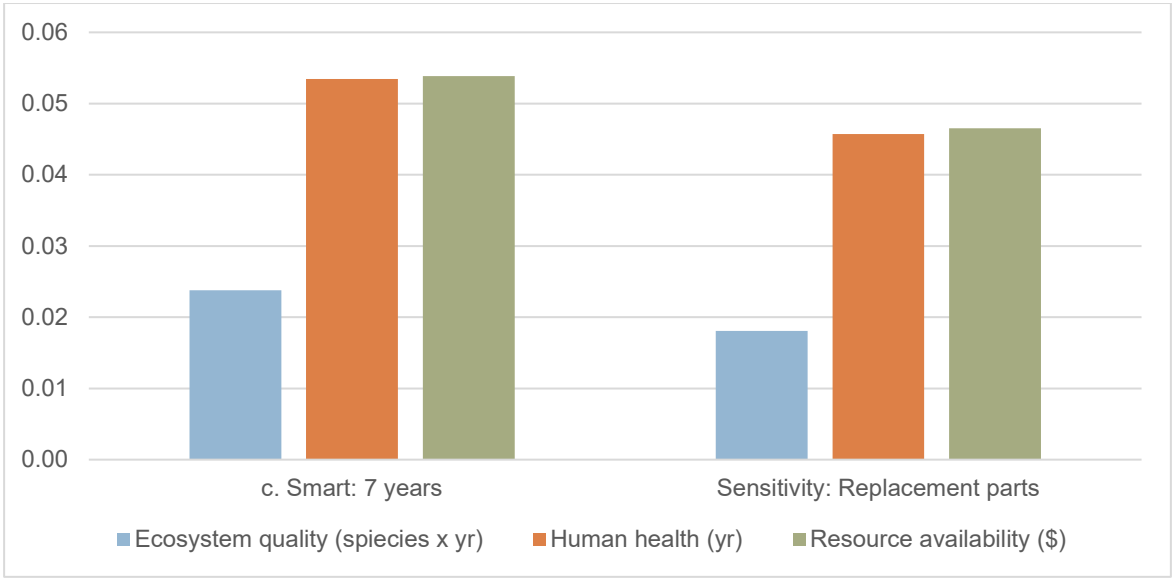

Figure 24. Sensitivity analysis: parts replacements

Assumption adherence
In the beginning of the research an assumption was made about the medication adherence of the smart and conventional pillbox alternatives, which influenced the results in Chapter 6.3.2 related to the results in QALY. The assumption was: *With the conventional pillbox a user is 60% adherent to their prescribed medication and with the smart pillbox 80%.*
Calculations about this assumption can be found in Appendix E3.3.

Sensitivity: QALY difference
A sensitivity analyses related to this topic is done to understand the effect of this assumptions. It is now assumed that the QALY improvement is the same with both alternatives. Therefore, the conventional and smart pillbox alternatives have a benefit of 0.34 QALY.

Table 19. Sensitivity assumption adherence

Alternatives	DALY (Damage to human health)	Benefits (DALY) *based on* (Krack et al., 2018) *	Benefits - impact = (DALY)	Overall benefit (QALY)
a. Smart: 3 years	0.103	0.37	0.267	0.245
b. Smart: 5 years	0.068	0.37	0.302	0.277
c. Smart: 7 years	0.053	0.37	0.317	0.291
d. Smart: No charger	0.065	0.37	0.305	0.280
e. Smart: 7 years, no charger	0.037	0.37	0.333	0.306
f. Smart: 7 years, no charger, no top lid	0.032	0.37	0.338	0.311
g. Conventional: 3 years	0.003	0.37	0.367	0.338
h. Conventional: 7 years	0.003	0.37	0.367	0.338

* QALY can be converted to DALY using a ratio of 1,087 (de Bruyn et al., 2017).

The impact of the smart pillbox (a) now results in a lower benefit than the conventional pillbox (g) (Table 19). The assumption about the benefits of each pillbox related to medication adherence does influence the results. In this case alternative *f* comes closest to the conventional pillbox alternative *h*.

Sensitivity: Assumption QALY improvement
As mentioned, in the beginning of this research forgetfulness was only 17% of the reasons why people where not adherent with their medication (Krack et al., 2018). The purpose of the smart pillbox is to ensure that medication is not forgotten. In this sensitivity analyses it is assumed that the benefits are only 17% of that 0.34 QALY. And again, assumed is that the conventional pillbox creates less benefits, in relation also less QALY improvement (second row in Table 20).

Table 20. Sensitivity QALY improvement

Alternatives	DALY (Damage to human health)	Benefits (DALY) *based on* (Krack et al., 2018) *	Benefits - impact = (DALY)	Overall benefit (QALY)
a. Smart: 3 years	0.103	0.06	-0.040	-0.037
b. Smart: 5 years	0.068	0.06	-0.005	-0.005
c. Smart: 7 years	0.053	0.06	0.009	0.009
d. Smart: No charger	0.065	0.06	-0.002	-0.002
e. Smart: 7 years, no charger	0.037	0.06	0.026	0.024
f. Smart: 7 years, no charger, no top lid	0.032	0.06	0.031	0.028
g. Conventional: 3 years	0.003	0.05	0.048	0.044
h. Conventional: 7 years	0.003	0.05	0.048	0.044

* QALY can be converted to DALY using a ratio of 1,087 (de Bruyn et al., 2017).

Table 20 shows a negative effect on human health for the smart pillbox alternatives. The improved alternatives of the smart pillboxes (c, e, f) do give positive effects in this scenario.

Sensitivity: Break-even point

To assess the performance of the smart pillbox, a break-even point analysis is conducted. This analysis consists of two calculations. First, the calculation of the QALY benefit required to offset the DALY impact of the alternatives. Second, the calculation of the difference in QALY improvement necessary for the smart pillbox to compete with the conventional pillbox.

The first column is the required benefits needed in QALY to compensate the environmental impact in DALY. This is calculated by using the conversion rate between DALY and QALY of 1.087 by de Bruyn et al. (2017). Calculation for the Required QALY = QALY-DALY = 0

Example Alternative a: 0.103 DALY / 1.087 = 0.095 QALY

The second column shows the difference between the smart pillbox alternatives and the conventional pillbox.

Calculation break-even with conventional = Adherence Smart pillbox / Conventional pillbox = x

Example Alternative a: 0.095 / 0.002 = 40

The adherence needs to be 40 times higher for alternative *a* in order to compete with the conventional pillbox (g). Additionally, the improved smart pillbox (f) only needs to improve QALY 12 times more than the alternative conventional pillbox (h).

Table 21. Break-even sensitivity

Alternatives	Required QALY (QALY-DALY = 0)	Break even with conventional: Adherence * x = conventional pillbox
a. Smart: 3 years	0.095	40
b. Smart: 5 years	0.063	26
c. Smart: 7 years	0.049	21
d. Smart: No charger	0.060	25
e. Smart: 7 years, no charger	0.034	14
f. Smart: 7 years, no charger, no top lid	0.029	12
g. Conventional: 3 years	0.002	-
h. Conventional: 7 years	0.002	-

6.5 Discussion: LCA smart vs conventional pillbox

This section presents some discussion points and limitations of the analyses. Based on the discussion and limitations, possible further research is suggested.

The results of the LCA show that the smart pillbox has a greater environmental impact compared to the conventional pillbox across all endpoint impact categories and with a substantial margin. The use of electronics and more materials led to a higher impact. The higher impact of the smart pillbox compared to the conventional pillbox is also aligned with the hypothesis that more materials and electronics lead to a higher impact, which was recognised in the beginning of the report, built on previous research.

In this chapter, the analysis goes beyond a product-level evaluation and includes a functional-level examination. The examination considers not only the potential negative effects of the electronics required for a smart pillbox but also the benefits of taking medication on time. In order to make this comparison other impact categories were put aside to focus more on the human health impact of the smart pillboxes. A limitation of this approach is that the other impact categories were not analysed in detail. This could be a point for further research.

Additionally, the results are based on assumptions and there are variations in data availability. The assumptions made regarding transport, different proxies, and other factors have already been questioned in Chapter 4.4 for the smart pillbox. No major issues with the assumptions were identified that would result in significant differences in impact.
An additional assumption was made regarding the replacement of parts in improved alternatives. A sensitivity analysis (Figure 24) was performed to assess the effects of this assumption. Only minor differences in impact were found across all impact categories. To conclude, assumptions regarding transport, proxies, replacement of parts and other factors only had minor impact on the results.

Moreover, a crucial aspect to consider is the impact of the assumptions on the results regarding medication adherence in relation to the enhancement of quality of life. Multiple sensitivity analyses (section 6.4.4) demonstrate that the outcomes are heavily dependent on the information surrounding medication adherence. The initial assumption is that the smart pillbox realises 80% medication adherence, leading to a 0.34 QALY increase compared to not using a smart pillbox (Krack et al., 2018). The second assumption is that the conventional pillbox achieves 60% adherence to medication intake, resulting in a 20% decrease in QALY improvement compared to the smart pillbox.

This assumption regarding medication adherence creates a small difference in outcomes between the smart and conventional pillboxes. However, the sensitivity analyses reveal that alternative assumptions lead to larger differences in outcomes between the two alternatives. In one of the sensitivity analysis, patients using the smart pillbox experience a negative QALY, whereas in other scenarios, a positive QALY was found. This finding highlights the significant influence of this assumption on the results of the comparison between the smart and conventional pillbox.

When not using assumptions of different medication adherence percentages and not using the QALY increase of Krack et al. (2018) a break-even point was calculated as a sensitivity analysis. This break-even point indicates how much the smart pillbox needs to improve QALY more than the conventional pillbox in order to offset its environmental impact related to human health, without using any assumptions related to medication adherence.

The sensitivity analysis was conducted to determine the break-even point without considering any assumptions related to medication adherence or the QALY increase reported by

Krack et al. (2018). The break-even point represents the amount by which the smart pillbox needs to improve QALY more than the conventional pillbox to offset its environmental impact on human health.

The break-even point calculation indicates that the current smart pillbox (alternative a) would need a QALY improvement of at least 0.095 to offset the DALY impact, while the conventional pillbox used for 3 years (alternative g) would require a minimum of 0.003 QALY. In comparison, the improved alternative *f* (smart pillbox used for 7 years, without including charger and replacement of top lid) would only need a QALY improvement that is 12 times higher than that of the conventional pillbox used for 7 years (alternative h). Additionally, the results indicate that the current smart pillbox (alternative a) needs a QALY improvement that is 40 times higher than that required by the conventional pillbox (See Table 15 for a clear overview of the alternatives and Table 21 for the break-even calculations including results as described above).

Thus, this study provides valuable insights into the trade-offs between the environmental impact and health benefits of using smart pillboxes.

Limitations of this study are the limited data availability and time constraints. The study relied solely on the bill of materials (BOM) to calculate the impact and did not consider the production processes for the assembly and part construction, as shown in Figure 12. Due to the unavailability of certain materials in the ecoinvent database, proxies had to be used. Another important limitation was the absence of precise data in the literature regarding the improvement of medication adherence with conventional and smart pillboxes, which required the use of assumptions that impacted the results.

To address the limitations of the findings in this chapter, additional research is recommended. A more comprehensive analysis could be performed by collecting more comprehensive data regarding the lifecycle of the product. Additionally, research towards certain materials used for the pillbox could provide insights into the impact of using proxies in the current study. Conducting a study to examine the effect of various pillboxes on medication adherence and QALY would provide a more robust foundation for the results, thereby eliminating the need for assumptions surrounding this topic.

6.6 Conclusion: LCA smart vs conventional pillbox

The aim of this chapter was to answer the fourth sub-question:

> *What is the comparative analysis of the environmental impact of the current smart pillbox and redesigned smart pillbox scenarios, as obtained from research question A, with a conventional pillbox used in Europe in relation to their respective benefits to the quality of life of patients?*

By only looking at the impact of the product by means of an LCA the results indicate that the smart pillbox has a higher impact than the conventional pillbox across all endpoint categories, with a noticeable difference. However, when looking at it in a wider perspective by including a functional-level examination there is a smaller difference in results. The benefits of medication adherence are also considered and not only potential negative effects of pillbox alternatives.

With literature suggesting that medication adherence of 80% or higher can improve a patient's QALY by 0.34, the impact on human health (DALY) and the improvement of quality of life (in QALY) were theoretically calculated. The results showed that the smart pillbox improved QALY by 0.245 and the conventional pillbox by 0.270, based on the assumption that the smart pillbox achieves 80% medication adherence and the conventional pillbox 60%. However, different scenarios were calculated in the sensitivity analyses which resulted in different results.

Because of the high uncertainty in data and the insignificant difference in results a conclusion based on these results could not be made.

If we exclude the assumption on medication adherence and the use of QALY improvement, the sensitivity analysis (Section 6.4.4; break-even point) reveals that the smart pillbox (a) needs to achieve a QALY improvement that is 40 times higher than the conventional pillbox (g) to offset its DALY impact. Additionally, the improved smart pillbox alternative (f) only needs a QALY 12 times higher than the conventional pillbox.

In summary, the findings indicate that a substantial improvement in QALY is required for the smart pillbox to balance out its environmental impact compared to the conventional alternatives.

Chapter 7. Discussion

This chapter addresses the main discussion points and limitations to answer the main research questions A and B. This chapter is a general discussion of the results in this research. In-depth discussion of the results of the first three sub-questions can be found in Chapter 3.2, 4.5 and 5.3 and in Chapter 6.5 the fourth sub-question is discussed.

The main research questions can be answered through the results obtained from the four sub-questions addressed in Chapters 3 till 6. To respond to the sub-questions, existing methods were used that required data, and when data was unavailable, assumptions were made, or data was obtained from the literature. The methods used to address the research questions influenced the results, and alternative methods may have produced different outcomes.

Two methods were used to analyse repairability: the Disassembly map and Recovery Assessment. Because these methods have already been compared, the results have been tested.

It is challenging to find a method that can cover as much ground as an LCA when identifying hotspots. As previously noted, LCA is a method that provides a thorough analysis, allowing the identification of environmental problems throughout a product's entire life cycle. While other methods may not be as detailed as LCA, faster versions of LCA could produce similar results in less time but with less detailed information and more uncertainty.

Likewise, the Circular Product Readiness method could potentially be replaced with the Circulytics assessment, as the Circular Product Readiness method is based on this method. The Circulytics assessment mainly considers the structure of a company, and this could potentially lead to recommendations that are not based on a product level, like alternative business models for the smart pillbox.

Additionally, the data utilized for this research was obtained from a single smart pillbox company, thus generalizing the results to other smart pillboxes is not feasible. The available data was limited and the time frame for this research was constrained to 6 months. Furthermore, some of the data found in the literature did not precisely match the smart pillbox being studied, leading to results that may not perfectly reflect reality. However, every effort was made to align the results as closely as possible with reality.

The objective of the first research question is to gain insight into the environmental sustainability of a smart pillbox and offer design suggestions based on the findings. The research was conducted using a physical smart pillbox and interviews with the manufacturer.

The redesign recommendations presented in the study are based on the findings from the analyses and are subjective in nature. Further research could be done to identify alternative solutions for the environmental challenges caused by the smart pillbox and to explore other design options based on the environmental issues identified in this study.

Redesign recommendations were given in Table 12. There is some overlap between the different methods in the use of plastic materials, particularly for the top lid. This overlap could provide a starting point for the company to improve their product.

These redesign recommendations could be used for other medical devices, especially products with a similar nature. Medical devices that are used at home, should also be easy to repair by consumers and failure of products could be eliminated by redesign to extend its lifetime, as with the battery in the smart pillbox. By taking a closer look at a product and analysing the repairability of products small redesign interventions can make a huge difference in extending the product lifetime. By looking at the impact of certain materials in the design phase this can contribute to an overall lower environmental impact. Additionally, a lifecycle perspective can help improve the end-of life of products during the design phase.

The first three sub-questions led to recommendations for redesigning the smart pillbox with the aim of improving its environmental sustainability. The outcomes of the LCA, as presented in Chapter 6, indicated that a redesigned product would improve environmental performance. Nevertheless, the LCA results comparing the smart pillbox and a conventional pillbox shows that the conventional pillbox has a significant lower environmental impact.

The issue arises whether the integration of smart technology in all products is a wise decision. Therefore, this study aimed to evaluate the benefits of the smart pillbox against its environmental impact as well as that of the conventional pillbox. However, the results showed a small difference between the alternatives, and the high level of data uncertainty did not allow drawing absolute conclusions.

The uncertainty in the data mainly arises from the assumptions made about medication adherence and the difference in QALY improvement between the smart and conventional pillbox. Multiple sensitivity analyses comparing the smart and conventional pillbox (Chapter 6.4.4) have shown that the outcomes are considerably influenced by the information surrounding medication adherence. To mitigate this uncertainty in the assumptions and QALY improvement, a break-even point analysis was conducted. The analysis shows that a substantial increase in QALY is necessary for the smart pillbox to offset its environmental impact compared to the conventional alternative.

In addition, this research compared Disability-adjusted Life Years (DALY) and Quality-adjusted Life Years (QALY), which has not been done like this before. In Chapter 1.1.2, the literature suggests that specific interventions can enhance medication adherence, leading to improved health outcomes. Similarly, smart pillboxes have the potential to improve people's lives, but concerns have been raised about their environmental impact. This motivates the question of how the environmental impact of a smart pillbox compares to its health benefits. To address this question, comparable units were searched that could allow for a fair comparison of these two aspects. The DALY metric is used to calculate the environmental impact and the QALY metric to calculate the improvement in quality of life, which are commonly used in the literature and can be compared to each other. While it was challenging to translate these two different aspects into a common unit, it is believed necessary. Medical products are brought to the market because there is a demand for them. The process of developing a product should involve analysing the potential benefits it can provide and weighing them against any potential negative impacts it may have. Ultimately, the goal is to create a product that meets the needs of consumers while also being sustainable in its lifecycle. By carefully considering the benefits and impacts of a product, companies can create products that not only help people, but also contribute to the improvement of the environment. Therefore, comparing the environmental impact and health benefits of medical products is an interesting way to understand their overall impact on human health.

The study conducted calculations for a single person using the smart pillbox. An important aspect to understand is that the calculated DALY is not solely for one person but for all those affected by environmental burdens. These burdens can result in various forms of health hazards resulting in DALY due to disease. For example, certain chemicals create a risk of cancer, leading to DALY. These health hazards do not affect only one person but for all those impacted by such chemicals.

In comprehensive research conducted by Gao et al. (2015), the use of DALY for assessing environmental health impacts was examined. The study highlighted that the level of pollutant exposure varies among populations. The negative effects of the smart pillbox are not only located to the user, but for the entire world. Specifically, as certain components of the smart pillbox are produced in different parts of the world, the connected effects of some exposure are narrowed to the particular manufacturing regions within the product lifecycle and to the rest of the world. Additionally, given that the use phase is outside the manufacture phase, the impact of

regional pollutants does not directly apply to the person using the product. Therefore, using the calculated DALY for only one individual is unrealistic and does not represent the true reality of the situation.

On the other hand, QALY benefits affect only one person. Therefore, the scope to which the DALY indicator applies does not align with that of the QALY indicator. Despite this, this study tried to understand how the impact and benefits compare regardless of where they occur even though this does not represent reality. Because, as mentioned before, it is necessary to understand the complete impact of medical products on human health, as they not only have negative effects but also offer potential benefits for people's well-being.

The study by Krack et al. (2018) evaluated the health benefits of medication adherence by measuring the negative effects using VAS-AL. They used a lineal correlation between VAS-AL and QALY. The study acknowledged that this approach had been previously used but how much this represents reality is uncertain.

While recognizing the limitations of this study, it provides an indication of the health effects for a single person. The findings reveal that in order to offset the environmental impact for one individual, the QALY benefit must be particularly high. Nevertheless, this only applies to the environmental impact on one person. Therefore, despite the many limitations, the study underlines the need to question the use of smart products and whether they genuinely enhance people's lives. Sufficient argumentation must be provided to validate how a product's benefits outweigh its environmental burdens in terms of human health.

Further research could investigate the benefits of the smart pillbox to prove if it causes any differences in the outcomes.

The assumption that the smart pillbox improves medication adherence, thus leading to a better quality of life, has a significant influence on the results. However, there remains significant uncertainty regarding the accuracy of this assumption. Further research could confirm its validity by measuring adherence levels for the pillbox alternatives to draw conclusions on medication adherence differences, if any. Such an approach would help to reduce the level of uncertainty.

Moreover, once medication adherence improvement with the smart pillbox is measured, a comparison can be made between the impact of medication non-adherence. As outlined in Chapter 1.1.2, medication non-adherence leads to hospitalization and higher costs for patients, as documented in the literature. Thus, after establishing the smart pillbox's positive effects on medication adherence, it becomes possible to compare its environmental impact to the environmental impact of medication non-adherence, such as hospitalization.

Due to the uncertainties and the small difference in outcomes between the alternatives, no definitive conclusions can be drawn, and these cannot be generalized. Nonetheless, it is possible that the difference between QALY and DALY is much bigger for more critical medical products, which could generate a clearer outcome. This is due to the fact that certain medical products have a more significant positive impact on the health of patients. An example of this could be with patients with heart disease who can benefit from a pacemaker, as it has been shown to prolong their lifespan and potentially improve their overall QALY. As done in this study, an evaluation can be made of the trade-off between the additional materials required for a smart pacemaker and the potential benefits to patients. Smart pacemakers can monitor heart health and identify early stages of heart problems without requiring a doctor's appointment, which is not possible with non-smart pacemakers (Tarakji et al., 2021). Therefore, a comparison between smart and non-smart pacemakers could be conducted to determine whether the added benefits of a smart pacemaker are worth the use of extra potential environmental impact.

Even though the limitations make it hard to generalize the findings of this research, it does suggest that the implementation of smart technology in products can lead to additional

environmental impacts. With the constant development of technology, more and more smart products are being introduced into the market, which can lead to increased e-waste. Therefore, it is essential to ensure that smart products can adapt and evolve with us, by making sure products can be repaired and updated.

Additionally, the complete lifecycle of a smart product is important to consider, from production to disposal. It is necessary to question whether a product really needs to be smart or not and to critically assess the benefits that it offers to the world.

In conclusion, the implementation of smart technology in products can bring benefits, but it can also increase environmental impact. Therefore, it is crucial to consider the complete lifecycle of the product, to assess whether it needs to be smart, and to critically evaluate its benefits to society.

The scope of this study was to examine the impact of the smart pillbox on human health. Although other categories were not explored, they are still significant and should not be overlooked. The effects of the smart pillbox on ecosystems are also relevant to human health, not only due to the potential direct effects of harmful chemicals, but also due to the impact on food availability and nature. All systems are interconnected and can have an impact on one another.

The comparison between benefits and impacts was measured using comparable units, such as QALY and DALY. This approach could potentially be applied to other industries, such as the food industry. For example, it may be possible to compare the environmental impact of certain foods to their health benefits or impact. Take avocados as an example; while they are known to be healthy and nutritious, they also have a significant environmental impact (Krosofsky, 2021) However, it may be even more necessary to critically examine the meat industry by subtracting the environmental impact from the health impact measured in QALY. By doing so, a better understanding of the overall impact of meat consumption on human health could be found.

In summary, the use of comparable units such as QALY and DALY can help in comparing benefits and impacts, not only in the medical industry but also in other sectors like the food industry. By critically assessing the complete impact of products on human health, we can make more considered decisions about their consumption and production.
In addition, there may be other comparable units, besides QALY and DALY, that can offer a more complete comparison between impacts and benefits. Further research could explore additional common ground related to this topic, to gain a more complete understanding of the overall impact of products on the world. This includes taking a much broader perspective than just looking at the environmental impact and carefully weighing all the impacts that a product can have.

Chapter 8. Conclusion and recommendation

The conclusion of the report is divided into two parts (A & B), each addressing a different aspect of the environmental sustainability of the smart pillbox. Part A of the study concentrated on the product level while Part B focused on the functional level, resulting in answers to the research questions that are indicated also as A and B.

Chapter 8.1 summarises the answers to sub-questions 1 to 3, which in turn help address main research question A. Chapter 6.6 summarises the answer to sub-question 4, in order to provide a conclusion for main research question B. Finally, Chapter 8.3 reflects on the overall answers to both research questions, and offers a recommendation based on the findings. Throughout the conclusion, the limitations and discussion points outlined in Chapter 7 are taken into consideration.

8.1 Research question A

The focus of research question A was to provide redesign recommendations for a smart pillbox in order to improve its environmental sustainability, considering both circularity and sustainability assessments. The aim was to determine what changes could be made to the product and its system to improve its overall environmental impact.

> Research question A:
> *What redesign recommendations can be given for a smart pillbox to improve the environmental sustainability of the product and its system based on circularity and sustainability assessments?*

To provide redesign recommendation that answer Research Question A, Table 13 has been included again as Table 22, which was initially presented at the end of Part A.

In Chapter 3, The Sub-question was answered by using the Disassembly Map and Recovery Assessment method. The results of these assessments showed that the priority parts of the smart pillbox, such as the PCB, battery, speaker, and bearings, could be repaired by professionals. Since the company offers free repairs, consumers are not required to repair the product themselves, except for the battery, which may sometimes detach. The recommendations based on this sub-question and the sub-question are shown in Table 22.

The answer to the second sub-question was that the environmental hotspots of the current smart pillbox were identified as (1) the adapter, (2) PCB including LEDs, (3) tray, (4) cable, (5) top lid, (6) battery, and (7) bottom lid (Chapter 4). To reduce or remove hotspots redesign recommendation were proposed shown in Table 22.

Chapter 5 used the Circular Product Readiness method to answer the third sub-question. In terms of circularity, the smart pillbox product and its system score 84% of the 100% of all design indicators, but without a comparison to another company, it is difficult to interpret the score's meaning. But the answers to the questionnaire gave insights and recommendations were given, shown in Table 22.

Table 22. Redesign recommendations devided by sub-question

Part	Recommendation	Reason	Chapter
Sub-question 1: *How can the disassembly be improved to extend the lifetime and increase repairability of the smart pillbox?*			Chapter 3
Sub-assemblies	Use screws instead of snap fits to attach the sub-assemblies	Allows consumers to easily open up the product to reattach the battery.	Chapter 3
Battery	Fixate battery in a designated spot. (See Figure 11)	The battery detaches sometimes and needs to be reconnected. Fixating it prevents repair requests and extra transport to a repair facility.	Chapter 3
Top lid	Remove silicone layer or use low impact material for the main material.	The top lid needs replacement because visual wear and tear impact the aesthetic durability.	Chapter 3
Sub-question 2: *What are the environmental hotspots of the current smart pillbox?*			Chapter 4
Power adapter	Do not include a charger or give it as an option to the consumer. Replace the existing charging port with a USB-C port that corresponds to EU standards and ensure the smart pillbox functions with chargers that use this port.	The power adapter contributes most to a larger amount of impact categories. The USB-C charger is in line with new EU regulations; therefore, the USB-C charging port is recommended.	Chapter 4
Top lid	Changing the Polycarbonate to a less impactful material. Further research is needed to understand what material functions as a better alternative.	The lid is in the top 5 of parts that contribute most to the overall impact of the smart pillbox.	Chapter 4
Sub-question 3: *How do the smart pillbox product and its system score on circularity?*			Chapter 5
All	Use Eco-Steer design approach by promoting environmentally desirable habits. For the smart pillbox, provide guidance to the user on how to prolong battery life and ask users to assess whether the product is still fulfilling their needs if it has remained unused for an extended period. If not, request the user to send the product back to the company.	- Users are not encouraged to use the product sustainably. - Active end-of-life retreatment is not considered.	Chapter 5
Plastic components	Explore the use of recycled materials in plastic components by starting a conversation with the supplier to determine the possibilities.	Recycled materials are not used.	Chapter 5
All	Collaborating with a specialized electronic product recycling facility to identify and address recycling pain points specific to the smart pillbox, thereby optimizing its recyclability.	Recycling processes are not explored.	Chapter 5
Overlap all sub-questions			
Plastic components	Change to lower impact/recyclable materials.	Top lid needs replacement, contributes to the overall impact of the smart pillbox. And recycled materials are not used.	-

Research question A on redesign recommendations for the smart pillbox aimed to improve its environmental sustainability based on circularity and sustainability assessments, as addressed in the three sub-questions in Chapters 3-5. To conclude research question A, the product can be improved by using the results given by the sub-questions and recommendations given in Table 22. There is some overlap between the different methods in the use of plastic materials, particularly for the top lid. This overlap could provide a starting point for the company to improve their product.

8.2 Research question B

The aim of research question B was to compare the redesigned smart pillbox to a non-smart pillbox in terms of its environmental impact, measured in terms of Disability-adjusted Life Years (DALY), and the benefits it offers in terms of Quality-adjusted Life Years (QALY). The aim was to determine the trade-off between the additional environmental burden and the improved health effects.

> Research question B:
> *How does the (redesigned) smart pillbox compare to a conventional non-smart pillbox considering the extra environmental burden (in DALY) and the benefits of healthier life years (QALY)?*

In Chapter 6 an LCA was used to answer the fourth sub-question: *What is the comparative analysis of the environmental impact of the current smart pillbox and redesigned smart pillbox scenarios, as obtained from research question A, with a conventional pillbox used in Europe in relation to their respective benefits to the quality of life of patients?*

The conclusion of the sub-question suggests that while the smart pillbox has a higher environmental impact than conventional alternatives, a functional-level examination shows a smaller difference. However, due to the high uncertainty in data and the sensitivity of the assumption related to medication adherence, no conclusive recommendation could be made based on the findings. Additionally, medication adherence and its potential benefits on human health were considered, and the results showed that a significant improvement in quality of life (QALY) is necessary for the smart pillbox to balance out its environmental impact compared to conventional alternatives.

Research question B aimed to compare a smart pillbox and a conventional non-smart pillbox in terms of its environmental impact and benefits. Because of the high uncertainty in data and the insignificant difference in results a conclusion based on these results could not be made. The smart pillbox requires a QALY improvement significantly higher compared to the conventional pillbox in order to offset the DALY impact.

8.3 Recommendations

This research aimed to improve the smart pillbox on both a product and functional level. Based on the findings, the following recommendation can be provided:

The results of research question B suggest that the improvement of the Quality-adjusted Life Years (QALY) needs to be much higher for the smart pillbox compared to a conventional pillbox. However, the outcomes of the improved smart pillbox show significant improvement. By improving the design of the smart pillbox to be more environmentally friendly, it can result in a lower impact on the environment and a higher QALY. Therefore, although the current results cannot create hard conclusions, there is always room for further improvement to make the product even more environmentally sustainable and therefore make the difference between the impact and the benefits higher.

This study provides a basis for comparing the environmental impact and benefits of products from a broader perspective. Rather than exclusively focusing on the environmental impact of products, a thorough evaluation of the overall impact of products could be conducted, including their benefits.

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Appendices

Appendix A. Product data

Appendix A1 (confidential): BOM

A1.1 BOM of smart pillbox

A1.2 BOM conventional pillbox

Appendix A2 (confidential): Unit processes

A2.1 Unit processes (smart)

A2.2 Unit processes (conventional)

Appendix A3 (confidential): Transport data

Appendix B. Activity Browser files

Appendix C. Results of hotspot analyses

Appendix C1 Impact assessment smart pillbox

Appendix C2 Hotspot results

Appendix C3 Pictures Hotspots

Appendix D. Circular Product Readiness

Appendix D1 Product readiness answers

Appendix D2 Product readiness overview visual

Appendix E. Results LCA

Appendix E1 Impact assessment

E1.1 Impact midpoint

E1.2 Impact Endpoint

Appendix E2 Hotspot analyses

Appendix E3 Sensitivity analyses

E3.1 Sensitivity PEF

E3.2 Sensitivity Replacing parts

E3.3 Sensitivity DALY & QALY