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Redesigning Health Devices for the Circular Economy: A Case Study on Smart Pillboxes

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***Abstract*—Like many health devices, smart pill boxes designed to enhance medication adherence often incorporate electronic components and smart sensors. However, the production and disposal of these rising numbers of electronics contribute significantly to the global e-waste crisis, exacerbating the negative climate impact of the healthcare industry. To minimize the impact of such electronic health devices, redesign based on circular economy principles is crucial. However, currently no clear circular design methodology exists to apply those principles in the healthcare domain. This paper discusses a case study in which we propose conceptual redesigns that aim to mitigate the environmental impact of smart pill boxes and help align them with circular economy principles. We employ a research-through-design approach in which we attempt to apply the well-known "10R strategies" (i.e. *refuse*, *rethink*, *reduce*, *reuse*, *repair*, *refurbish*, *remanufacture*, *repurpose*, *recycle*, and *recover*) as a design method. While doing this, we assessed their applicability in a design process and added value in making the device circular through reflective journalling, and their estimated effectiveness on minimizing environmental impacts by comparing fast-track LCAs for each design decision. In this way, we were able to provide insights into the intricacies of designing a more sustainable and circular device in this manner, and subsequently formulate recommendations for designing similar devices in the future.**

Keywords—Circular Economy, Sustainable Design, Life Cycle Assessment, Medication Adherence

I. INTRODUCTION

In 2022, the Dutch National Institute for Public Health and Environmental Protection (RIVM) calculated that the healthcare sector accounts for approximately 7% of global greenhouse gas emissions [1]. There are several causes for this high impact, one of them being the rapid digitalization of health devices. A worrying development, with electronic waste (e-waste) being one of the fastest growing waste streams in the world [2]. This not only poses immediate hazards but also undermines long-term sustainability efforts.

To ensure the long-term benefits of electronic components integrated into healthcare devices, it is imperative to mitigate the environmental impact of digitization. A possible opportunity in achieving this is embracing the principles of the circular economy, which minimize waste and environmental impact through “an economic system that replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials” [3]. However, the transition of health devices to such a system requires a fundamental shift in design practices. While literature underscores the significance of design in facilitating the circular economy transition [4], and even provides some potential “strategies for recovery of circular medical products” [5], due to mostly safety-related challenges it is currently hard to apply circular design methods in the healthcare domain.

Existing sustainable design strategies such as life cycle assessment and eco-design offer valuable guidance focused on minimizing environmental impacts [6], but may overlook critical healthcare-specific considerations, such as contamination risks, patient safety concerns, and the complex regulatory landscape. Therefore, it is vital to adapt those existing methods to the specifics of medical device design. A first attempt to this was done by [5], which categorizes and analyses existing instances of circular economy in the medical sector, identifying device criticality and sterilization requirements as key factors influencing the design.

To further contribute to the adaptation of existing circular design methodologies to the healthcare domain, we aim to build on this previous work by conducting a circular design case study on smart pill boxes. These devices represent an example of rapid digitization of healthcare and the environmental sustainability challenges associated with it. Formerly, medication storage relied solely on simple plastic containers, but today, smart pillboxes equipped with sensors and reminders are entering the medication adherence market. By exploring the circular design ‘solution space’ of such devices, we aim to extrapolate circular design recommendations that can be applied to similar electronic health devices. In this way, we contribute to future application and normalization of circular design in this context, with the aim to ultimately enhance its sustainability.

A widely recognized hierarchy of 10R-strategies outlines various approaching to enhance the sustainability and circularity of products [7]. This hierarchy encompasses the following strategies: *refuse*, *rethink*, *reduce*, *reuse*, *repair*, *refurbish*, *remanufacture*, *repurpose*, *recycle*, and *recover*. In [8], it is suggested that that the 10R strategies can be used as a starting point for circular interventions by healthcare staff. While the 10R-strategies were originally conceptualized as a framework for resource management within a circular economy, rather than specifically for product redesign, we utilize our case study to explore their potential applicability in the redesign process of an electronic health device. By considering all steps needed in the process for each R-strategy, such as e.g. cleaning methods, we aimed to adapt the R-strategies to ensure that healthcare-specific requirements are incorporated. By structuring our design iterations around this hierarchy, we assess the strategies based on the key aims of this paper:

1. Evaluate the extent to which applying the R-strategies allows us to come up with feasible and viable circular concepts in the healthcare context.
2. Ascertain that circular strategies also result in sustainable solutions by assessing their environmental impact.

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II. METHOD

A. *Research Through Design Method*

We conducted a research through design study, by deliberately introducing the R-strategies into our design method, while questioning their adaptability and effectiveness for our specific design case. The research through design method was split-up in five different stages:

1. Estimation of environmental impact hotspots of the current pillbox through a fast-track LCA.
2. Design sprints and concept development for each R-strategy separately, considering the impact hotspots.
3. For each design sprint, performing an in-between qualitative assessment of the integration of each R-strategy in the design method through reflective journalling.
4. Fast-track LCA comparison of design concepts to estimate the effectiveness of designing for each R-strategy in mitigating environmental impact.
5. Development of a final design that combines different R-strategy-based concepts and additional evaluation thereof through fast-track LCA.

Following the conclusion of the design case study, we used an inductive approach to derive circular design recommendations for similar electronic health devices.

B. *R-Strategies Utilization*

Several design sprints were performed based on the 10R-strategies. However, due to applicability of the specific strategies to our case study, we made two adaptations:

1. Refurbish and remanufacture were combined into one design sprint, as due to the high quality and safety requirements of many health devices we expect design requirements for both strategies to often be similar.
2. No design sprint was performed for the strategy of recover, as this is defined as “incineration of material for energy recovery” [7], which we argue is not a strategy we can design for, as literally anything can be incinerated..

After the two adaptations made, we came to the following list of 8 R-strategies utilized in our Research through Design approach: *refuse*, *rethink*, *reduce*, *reuse*, *repair*, *remanufacture/refurbish*, *repurpose*, and *recycle*. Table 1 displays how we defined those strategies based on [7], adapted to make them suitable for design purposes (e.g. adding examples of how product use can be intensified for *rethink*) and to make them fit the narrative of the healthcare industry (e.g. merging *remanufacturing* and *refurbishing* and including cleaning processes in *reuse*).

The design sprints resulted in eight different redesign concepts, one for each R. However, as we argue that products that address multiple R-strategies are more environmentally sustainable, we also aimed to combine the concepts. We did so by viewing the R-strategies as if they were the different product functions in a morphological chart, combining ideas while considering the hierarchical nature of the strategies. This resulted in one final concept that could subsequently be assessed on its environmental impact.

TABLE I. DEFINITIONS OF THE R-STRATEGIES

R-Strategy	Definition
Refuse	Making product redundant by eliminating its function or by offering the same function with a more sustainable, dissimilar product.
Rethink	Making product use more intensive through e.g. product sharing, device portability, standardized product architecture, and/or multifunctionality
Reduce	Use of fewer resources throughout the whole product life cycle (on product level minimize product, material, and electricity use).
(Direct) reuse	After cleaning, use of previously used product by another or the same user, while the product is still in working condition and the original functionalities are still present.
Repair	Bringing a defective product back to a working condition, so that it can be used for its original function.
Remanufacture/ Refurbish	Restoring an old product to as good as new or better than new condition, bring it up to date and if needed adding new parts in the product reassembly.
Repurpose	Use discarded product or its parts for a new function or in a new context, or use parts of the device in a new product with a different function.
Recycle	Processing materials to obtain the same or lower quality of materials (mostly done through sorting, shredding, and melting).

C. *Reflective Journalling*

After each design sprint, we wrote a reflective essay describing 1) the main design features of the concept, 2) its benefits and drawbacks, and 3) product and system changes that would enable the concept (compared to the original pill box). Additionally, we wrote a reflection on the ease of implementing each R-strategy into the design method. Finally, the writing for each R-strategy was analyzed and compared to derive useful design recommendations, considering the outcomes of the fast-track LCA comparisons.

D. *Fast-track LCA approach*

Several fast-track LCAs were performed in this study: we first assessed a smart pillbox as a baseline, and compared each design concept against that baseline. For all designs, the LCA boundaries included the production of the pillbox components (materials and manufacturing), transport, use, and end-of-life (EoL). While the device also uses a smartphone app, this was considered out of scope because we assumed users would already have a smartphone regardless of the pillbox, and the additional phone energy use from using the app would be negligible. As our research focuses on the development of health devices for the EU, EoL for everything was assumed to be incineration, or landfill when incineration data was unavailable. The functional unit was defined as a three-year average usage lifetime of a single smart pillbox, called one "use cycle". All impacts were calculated per use cycle. The impact assessment method was IPCC 2021 GWP100, listed in kg of CO_2 equivalent emissions. Impacts were calculated using the Idemat2023 database in Excel.

As the redesigns are conceptual, we had to estimate the changes in, e.g., used components, material types, or material volumes, resulting in high uncertainty ratings. For both the baseline and new estimated designs, the rule of thumb used to set uncertainties was ±10% for precise data and perfect database match, ±30% for confident estimates or plausible database substitutions, and ±100% for unsubstantiated guesses.

For the baseline design, a bill of materials was available, but to protect intellectual property confidentiality, results were aggregated into material groups. Transport was assumed to be from production in China to a geographically average center in the EU, by a mix of container ship, train, and trucking, with ±100% uncertainty. Usage energy (charging the battery) was assumed to average 125 Wh/yr, with ±50% uncertainty, based on the manufacturer's data. The assumptions we made for each new concept are explained with the results.

III. SMART PILLBOX: BASELINE LCA

For this study, we chose an existing smart pillbox currently on the market. The pillbox has several compartments that users can fill with different pills. It has a sliding lid and has electronics that register the opening of the lid to indicate medicine intake and remind the user to adhere to their prescriptions through auditive and visual cues that are enabled through a speaker and LED lights.

A. *Fast-track LCA of the current pillbox*

The fast-track LCA of the current pillbox determined environmental impact hotspots and set a baseline for later comparison. Although there were large uncertainties, the results clearly indicate the manufacturing stage has by far the largest impacts (Fig. 1). As Fig. 2 indicates, this is mostly caused by the manufacturing of the electronic components (PCB, battery, and LEDs). Again, despite the large uncertainties, the electronic components clearly cause higher impacts than all other components together, the latter having a combined impact of 1 to 2 kg CO_2-eq per use cycle. This is similar to the impact that the battery has on its own: 0.6 to 1.7 kg CO_2-eq per use cycle; it is likely slightly lower to much lower than the impact of the PCB (depending on the uncertainty), which is 0,7 to 6,1 kg CO_2-eq per use cycle (excluding the LEDs). Due to the large number of LEDs in the original pillbox, the impact of the manufacturing of the LEDs is also estimated to be relatively high, with an impact of approx. 0.2 to 1.9 CO_2-eq per use cycle.

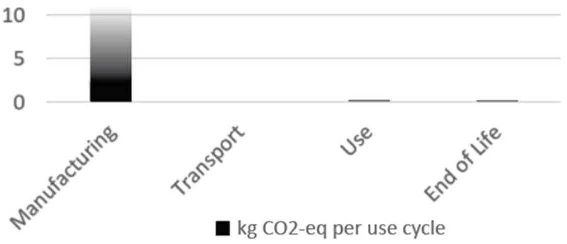

Fig. 1. Impact of smart pillbox per life cycle stage (uncertainty is displayed in gradient).

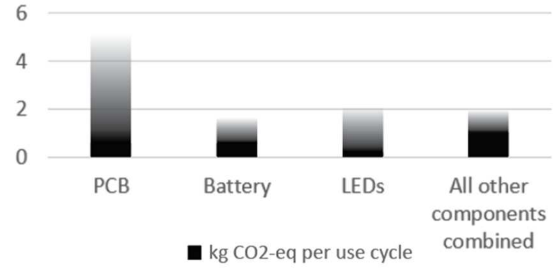

Fig. 2. Impacts by component in manufacturing (uncertainty is displayed in gradient).

Based on these outcomes, we estimated a current total impact between 2.6 and 12 kg CO_2-eq per use cycle, with the manufacturing of the electronic components (PCB, battery, and LEDs) being the main impact hotspot.

IV. RESULTS: DESIGN CONCEPTS PER R-STRATEGY

In this section, we will shortly introduce the conceptual ideas we came up with through our design brainstorming for each R-strategy, highlighting their benefits and drawbacks.

A. *Refuse Concept*

The *refuse* strategy aims to render a product redundant by abandoning its function or replacing it with a more sustainable alternative. For the pillbox, which primarily enhances medication adherence through reminders and dosing instructions, we propose integrating all functionalities into the accompanying smartphone app, removing the need for electronics in the physical pillbox. Although we cannot be certain how this change affects the medication adherence, several studies suggest that there may be no significant difference in adherence between reminder methods [9], and it has been observed that turning off alarms on pillboxes could potentially even improve adherence [10].

In this concept, users keep a simple, non-electronic pillbox for storage and portability; we assume physical presence of the pillbox will function as the reminder [11], with an app for backup reminders and/or adherence tracking. See Fig. 3 for the *refuse* concept illustration.

Fig. 3. Refuse concept

B. *Rethink Concept*

The *rethink* strategy we interpreted as a way of intensifying product use to ensure full utilization of the product functionalities. In this concept, patients receive a temporary pillbox as part of their medication purchase from the pharmacy without gaining ownership. This transformation of the ownership model requires patients to return the device to the pharmacy, which takes responsibility of refilling and medication management to prevent idle pillboxes at home. This shift encourages pillbox return, minimizing idle pillboxes at home and promoting efficient resource utilization through temporary usage. Encouraging return of the pillbox to a pharmacy may also benefit other circular strategies. Its versatile design includes a modular approach, with all electronics grouped in a separate and easily separable part, which allows attachment to various home containers, while the expanded app tracks health data and digital prescriptions, enhancing overall medication management and adherence (Fig. 4).

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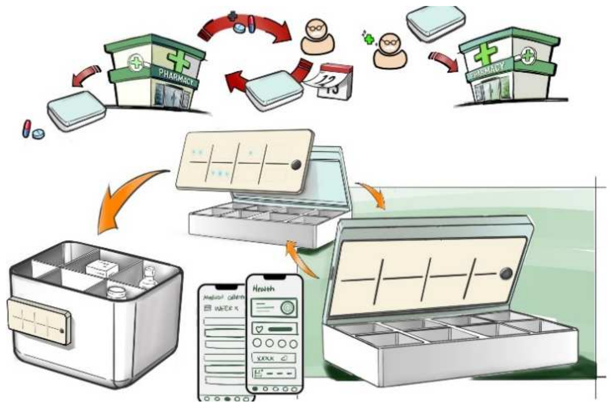

Fig. 4. Rethink concept

C. Reduce Concept

In the *reduce* concept, we aimed to minimize the need for electronics, addressing the PCB and LED impact hotspot. For the LEDs, we incorporated translucent material in the lid for light transmission, reducing LED intensity while maintaining visibility. Additionally, our concept has a modular approach, with all electronics grouped in a separate and easily separable part with snap connection that has only one LED per compartment. Additionally, standardization was enabled through integration of a USB C charging connector to be able to remove the charger from the packaging. Replacement of the speaker with a simpler, more energy efficient buzzer, and simplifying the opening mechanism with a flip design also minimized material use. Finally, to further *reduce* plastics usage and overall PCB size, since the average number of concomitant medications in the Netherlands is 4 [12], the full pillbox size is minimized by 50%, to just 4 compartments. The final *reduce* concept is displayed in Fig. 5.

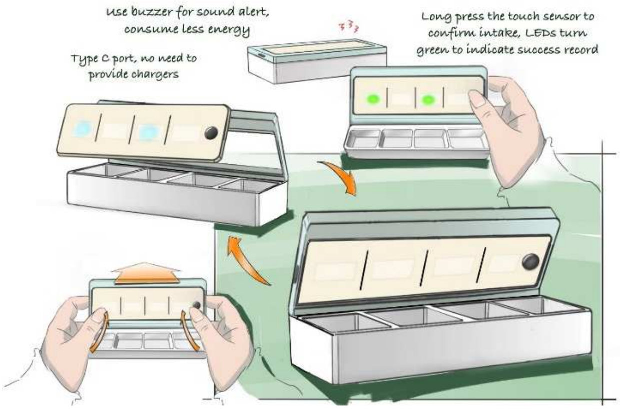

Fig. 5. Reduce concept

D. Reuse Concept

We interpret the *reuse* strategy as *direct reuse*, referring to products that are used again for their original purpose, without alteration, by a different user. For the pillbox, this entails maintenance for lifespan extension. To enable *reuse*, our concept entails a similar system as the *rethink* concept: the user obtains pills and the pillbox from the pharmacy, paying for the pills and adherence support instead of purchasing the pillbox. The pillbox design features a standard USB C charging port, with charging cable available for purchase at the pharmacy. Electronics are enclosed within a buckle lid, with waterproofing facilitated by screws and gaskets for cleaning. Materials are chosen for resistance to hot water, alcohol, and UV light, with a smooth, scratch-resistant surface to ensure device longevity. A physical reset button on the lid allows deletion of stored data. The app now generates a log of all medicines previously placed in the pillbox, aiding in decontamination. When users no longer receive pills, they can return the pillbox to the pharmacy or purchase it at low cost for *reuse* with other pills not prescribed by their doctor. Returned pillboxes are disinfected and quality-checked, receiving a 'reused' sticker if in good condition. The *reuse* concept is displayed in Fig 6.

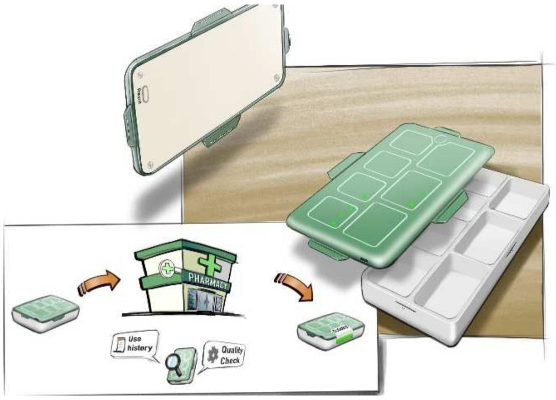

Fig. 6. Reuse concept

E. Repair Concept

Repair can be done by the user ("self-repair") or professional repairers. For our low-cost, frequently used pillbox, our focus is on enabling *self-repair.* Our new concept includes a digital diagnosis mode in the app, allowing users to find and fix problems. They can request spare parts via the app for minor problems and return broken parts for a reward. The pillbox design features a buckle lid with internal electronics, screws, gaskets, and an easily replaceable battery. The *repair* concept is displayed in **Error! Reference source not found.**.

Fig. 7. Repair concept

F. Remanufacture/Refurbish Concept

Our approach for *remanufacture/refurbish* emphasizes durability, easy disassembly, and tracking systems for efficient operation, accommodating the needs of both remanufacturing and refurbishment. It features an independent electronic bundle and a durable box, facilitating separate quality checks and simultaneous inspections.

Surfaces are hard, smooth, and suitable for disinfection, while screws secure the PCB and close the electronics bundle for repeated disassembly. The interchangeable battery and standard USB C charging port enhance longevity and compatibility, catering to the requirements of both processes. NFC tags aid in inventory management, while a digital checking program ensures functionality, benefiting both remanufacturing and refurbishment processes. To determine whether the PCB functions optimally, the engineer can write a log into the PCB to document usage history and update the NFC, enhancing component traceability. Refurbished products are identified with an embossed sign on the lid, streamlining identification and differentiation. The *remanufacture/refurbish* concept is displayed in Fig. 8.

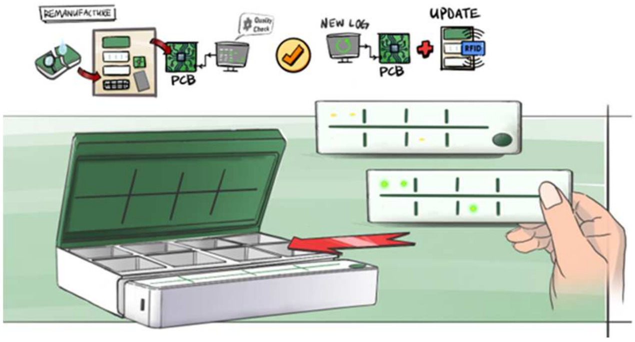

Fig. 8. Remanufacture/refurbish concept

G. Repurpose Concept

In order to *repurpose* a product or product parts, new applications would need to be found for the device after use, to use it for a new function and/or in a different context. Unfortunately, deliberately designing for repurpose (without creating a multifunctional device) has proven to be complicated, as our influence on user behavior is limited. However, as the design features of the smart pillbox are naturally close to an organizer, our concept represents a modular design with standardized components, that enables the user to explore new functions and various use environments. The modular pillbox consists of an independent electronic bundle and a "dumb organizer". Users can detach the electronic bundle to use it as an alarm clock The electronic bundle is equipped with a standard rechargeable cell battery (AA); the charger is optional. The pillbox contains flexible dividers that can help users create up to six compartments which can be customized when repurposing. In the app, a digital community function would be added in which people can share their "after-use-stories" of how they have repurposed the pillbox, to inspire others. The modular *repurpose* concept is displayed in Fig. 9.

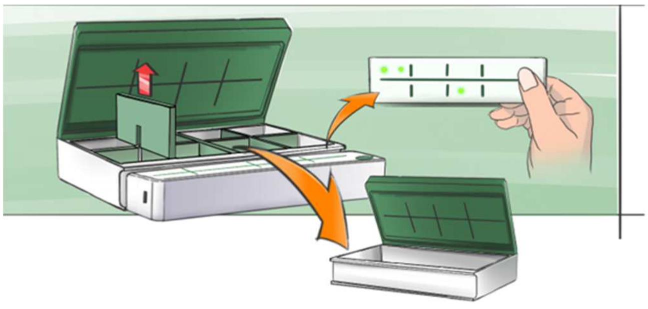

Fig. 9. Repurpose concept

H. Recycle Concept

To facilitate the *recycle* process, we focus on easy battery access, and efficient material separation. We prioritize mono-material design, disassembly ease, and avoidance of adhesives and screws for attachment. Return instructions are provided in the app, where users can also receive rewards upon product return confirmation. The product features screwless design with snap-fits in one mono-material, a USB C charging port eliminating the need for a charger (as users often do not return the charger with the product), and an interchangeable battery with a distinct cover for easy identification. Disassembly indications for the battery are printed on the pillbox, while all shell components are made of the same plastic. Lead-free soldering and conductive ink are used on the circuit board, with the original PCB color retained for machine sorting convenience. A QR code on the product provides access to its digital passport, detailing materials, recyclability, and recycling advice. The *recycle* concept is displayed in Fig. 10.

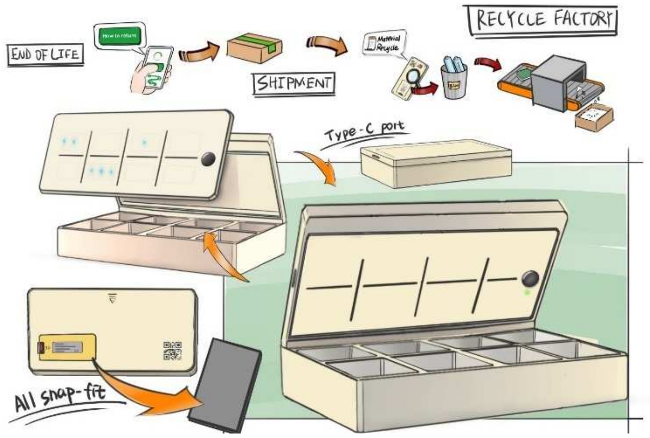

Fig. 10. Recycle concept

V. COMPARISON OF THE R-STRATEGIES

In this section, we will compare the application of each R-strategy in our design method by detailing how the R-based brainstorms influenced circularity (through reflective journaling) and sustainability (via fast-track LCA comparisons). For the fast-track LCA comparison, we will also explain based on which concept-based adaptations and assumptions we made the calculations.

A. Reflective Journalling

For each R-strategy, we reflected on the benefits, drawbacks, and the ease of implementation. The benefits and drawbacks of the R-strategy-based design concepts compared to the original pillbox can be found in Table II. When reflecting on the designs, we surmised that all R strategies have both benefits and drawbacks. Table 2 lists a number of these, without claiming to be complete. For instance, *refuse* can significantly reduce waste, but ensuring product functionality is essential. In the case of our *refuse* concept, it is crucial to examine how our design affects medication adherence. Additionally, while *reuse* shows much promise as a simplified method for extending product life cycles, concerns persist regarding the perceived value of second-hand products and the potential increase in labor intensity within the healthcare system, as the pharmacy becomes responsible for cleaning devices. Another strategy with potential benefits

TABLE II. POTENTIAL BENEFITS AND DRAWBACKS FOR EACH DESIGN CONCEPT, BASED ON REFLECTIVE JOURNALLING

Benefits	**Design sprint concepts it applies to**							
	Refuse	***Rethink***	***Reduce***	***Reuse***	***Repair***	***Repurpose***	***Reman/refurb***	***Recycle***
Simplified logistics during manufacturing (less shipping)	▨	▨	▨	▨	▨	▨	▨	▨
Reduction of incinerated/landfilled waste	▨	▨	▨	▨	▨	▨	▨	▨
Enables disinfection, quality check, sorting	▨	▨	▨	▨	▨	▨	▨	
Reduced consumption of raw materials in production and conservative use of resources	▨		▨	▨		▨	▨	▨
Easy disassembly (easy separation between different materials, interchangeable battery)	▨				▨	▨		▨
Higher work efficiency in EoL system operation	▨			▨			▨	▨
Lower labor intensity in manufacturing (easy assembly)	▨			▨	▨			
Decreased energy consumption during use	▨		▨			▨		
Extended product life cycle		▨	▨	▨	▨	▨	▨	
Encourage continuous use (add value)		▨				▨		
Prevention of idle usage at home (motivate return)		▨		▨				
Simplified reverse logistics		▨		▨				
Assured safety and quality of the product during use							▨	▨
Drawbacks								
Diminished sense of product value, no ownership (may lead to careless treatment or disposal)	▨	▨		▨				▨
Potentially shorter life cycle (higher learning curve, less durable, safety concerns in repair)	▨		▨		▨			▨
Potentially affect functionalities negatively	▨		▨			▨		▨
Increased labour intensity in manufacturing (complex assembly, more connections)		▨				▨	▨	
Higher resource consumption during manufacturing (more moulds for different components)		▨				▨		
Increased labor intensity in healthcare system (more functions at pharmacy)		▨		▨				
May increase initial manufacturing costs			▨	▨	▨	▨	▨	
Minimal influence on whether strategy will actually take place					▨	▨		▨
Potential poor waste collection (broken parts, shift in user perception of the product)					▨	▨		
Inventory management pressure					▨		▨	
Resource intensity of EoL process (complex system: log writing, NFC updating)							▨	

seems to be *repurpose*. It is, however, quite challenging to design a product for *repurpose* without compromising its original functionality, and there is usually no way to ensure that the product is indeed repurposed by the user.

Strategies that seem more promising than *repurpose* are *reduce*, *rethink*, and *remanufacture/refurbish*. By *reducing* the materials and energy used, we easily obtain sustainability benefits with minimal drawbacks. Our *rethink* concept does the same thing, but on a system rather than a product level, aiming to intensify use, which often leads to new business models or value chain collaboration. Therefore, it seems to be important to retain supply chain efficiency. We believe *rethink* to be a crucial strategy that could enable other strategies to work. Also *remanufacture/refurbish* seems to hold promise. The benefit of this strategy is that it enables the manufacturers to ensure patient safety during the use phase as they retain their influence on product quality.

Despite showing less benefits in our overview, we argue that designing for *repair* is vital in all instances, as other strategies such as *reuse* and *remanufacture/refurbish* also benefit from the easier disassembly, modularity, and standardization caused by designing for repairability. However, as we focused our design sprint on self-repair, the success of our specific concept was dependent on the behavior of the user. Also, the adaptations to the design might complicate the manufacturing processes. Therefore, we expect *repair* would have had more benefits if we had designed the pillbox for professional *repair*, as it might be easier to ensure that users let their device get repaired under warranty.

Finally, the recycle strategy is the least environmentally sustainable, and it does not maintain product integrity. Nonetheless, it is crucial to incorporate it into product designs to address the inevitable EoL stage, regardless of the previously applied R-strategy.

1) Circularity Evaluation

We evaluated the R-strategies on their potential to enhance product circularity. We categorized strategies into three groups:

- *Refuse* and *reduce* minimize resource use but do not inherently facilitate the circular flow of materials.
- *Rethink*, while not directly a circular strategy, could enable circularity by promoting continuous use and extending product lifecycles.
- *Reuse, repair, repurpose, remanufacture,* and *recycle* are clear circular strategies. They extend product lifecycles and optimize EoL processes, closing the loop on resource utilization. However, prioritizing tighter circularity loops over recycling is crucial for optimal circularity.

Overall, these evaluations highlight the importance of combining diverse strategies to achieve comprehensive circularity in product systems.

B. Fast-track LCA comparison

In addition to reflective journaling, we conducted quantitative comparisons of design sprint outcomes using estimated fast-track LCAs. Our primary goal was to compare the CO_2 impact of each design concept relative to the original pillbox and to each other. Details on these comparisons are provided later in this section. Fig. 11 illustrates the estimated impact of each concept compared to the original pillbox, with the uncertainty of each impact displayed in a gradient. It assumes only one use cycle for each design, even the ones designed for multiple life cycles. Notably, strategies like *refuse* and *reduce* show sustainability benefits by minimizing resource use in production and use stages. Other R-based concepts have CO_2 impacts well within the uncertainties of the original pillbox for one cycle; some may lower impacts slightly, but it is far from guaranteed if they only have one use cycle.

However, if the circular designs achieve five use cycles, as shown in Fig. 12, the relative CO_2 impact of *reuse* and *remanufacture/refurbish* improve significantly, with *repair* showing a lesser improvement. The relative impacts of *refuse*, *reduce*, *rethink*, and *recycle* strategies remain consistent, because they still have only one use cycle. These findings align with our journalling about circularity: *refuse* and *reduce* improve sustainability, not circularity, *rethink* enables circularity but does not guarantee it, and the R-strategies of *reuse*, *repair*, and *remanufacture/refurbish* are clearly circular strategies. *Recycle*, though a circular strategy, may not fully reflect its circularity in our fast-track LCA. This is because the *recycle* concept mostly focused on recycling of plastic components, while the electronics, which have the highest impact, did not get recycled.

Further sections will detail how calculations for each R-strategy were derived, including adaptations from design concepts and additional assumptions in the fast-track LCA. As the calculations solely serve as an estimated comparison of the concepts with the original pillbox, we only provide estimates of how much better or worse they are than the original pillbox.

1) Explanation of Refuse Calculations

In the *refuse* concept, we remove all electronics from the fast-track LCA calculations. This includes the battery, PCB, speaker, and LED. As we still advise users to use the smartphone app with their own simple plastic pillbox, we kept all plastics for the tray and lid and the transportation thereof in the calculation. However, as most simple plastic pillboxes do not have a sliding lid, we also excluded the sliding mechanisms and the magnets. Additionally, we deleted the product-related electricity used in the use phase. Although electricity is still used through the smartphone app, these impacts were already out of scope for the original pillbox. As was to be expected, these adaptations decrease the CO_2 impact of the pillbox by 30 – 90% per use cycle. However, in this we do not consider possible influence of these adjustments on medication adherence. For the five use cycles scenario, its impacts per use are unchanged.

2) Explanation of Rethink Calculations

To enable the *rethink* concept, due to the strong system focus, not much product changes are needed. The same electronics are utilized, but an additional compartment needs to be produced in the same plastic, which was estimated to have a weight of 20% of the pillbox tray, with 20% uncertainty. Due to the lid being hinged instead of sliding, all components of the sliding mechanism are eliminated. The concept also eliminates the automatic recording or medication intake,

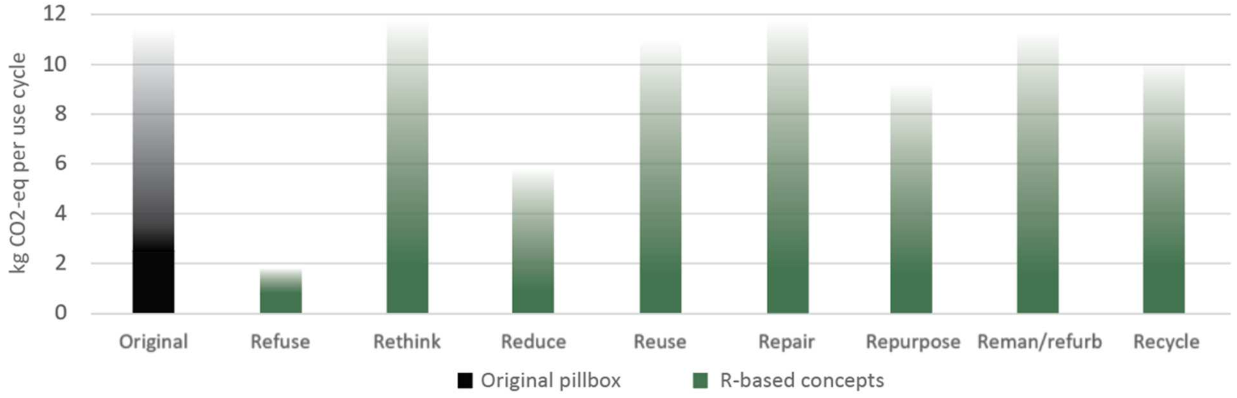

Fig. 11. Comparison of total estimated CO_2-eq per R-based concepts with only one use cycle (3 years).

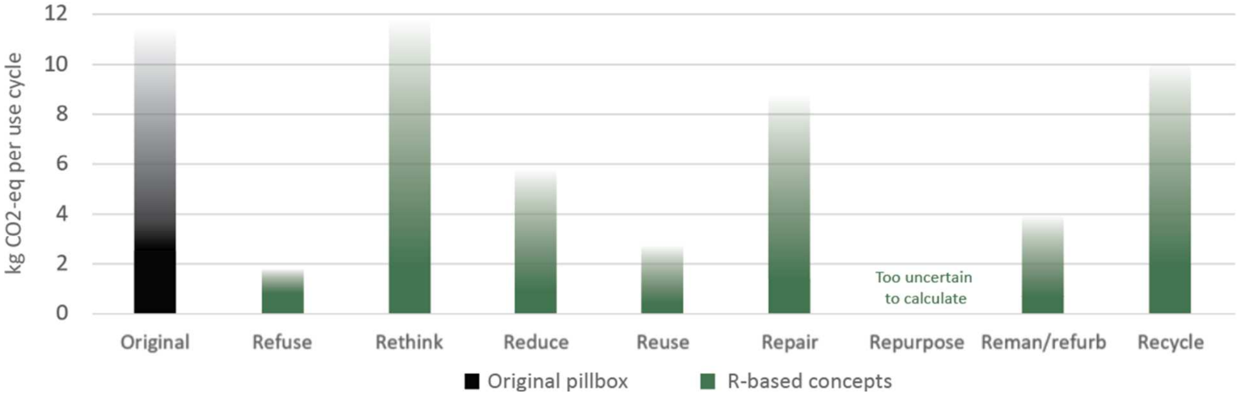

Fig. 12. Comparison of total estimated CO_2-eq per R-based concept for five use cycles (15 years).

replacing the recording sensor and magnet with a simple press button. We made the assumption that this would not alter the PCB weight used to calculate the PCB impact, but we did adapt the uncertainty of the PCB weight to 100%. The increase in the CO_2 impact caused by the user's travel to the pharmacy, which we estimated to be 470 km over three years, is so negligible that this is not visible in the final total impacts per use cycle. Taking into account the device changes and adding them in the fast-track LCA made for the original pillbox, this results in an estimated impact similar to the original pillbox's impact. Although the *rethink* concept might enable the *reuse* scenario, this concept does not necessarily assure long-term *reuse* beyond the initial use cycle. Therefore, for the five use cycles scenario, its impacts per use are unchanged.

3) Explanation of Reduce Calculations

For the concept, changes are implemented to eliminate combined materials in the lid for LED diffusion, switching to opaque PMMA material. Material mass is estimated by transferring mass and density from the original lid materials, with a 50% uncertainty. This inadvertently prevents the 2K injection molding used for the original lid. The reduce concept also reduces the overall pillbox size, halving plastic materials in the lid and tray. The PCB mass is also reduced by 50% (with 100% uncertainty), given the elimination of the sensor. LED count is reduced to four, one per compartment, and the speaker is replaced with a buzzer, assumed to have similar impact. We also assumed this would minimize energy use during the use stage by 40%, with 100% uncertainty. Sliding mechanisms, charger, and additional packaging are removed from the calculation. Based on these adjustments, we estimate the *Reduce* is likely to yield a significant improvement, perhaps cutting impacts in half. For the five use cycles scenario, its impacts per use are unchanged.

4) Explanation of Reuse Calculations

For the *reuse* concept, adjustments are made to eliminate the rubbery material materials in the lid, replacing it with the same durable material used in other parts of the original pillbox, and which is known for its longevity and resistance to water, heat, and scratches. Material weight calculations are based on the density and mass of the original pillbox's rubber material, with a 60% uncertainty. The sensor is removed by reducing PCB mass with 0.11 grams, which is the estimated weight of the sensor, with an increased uncertainty of 100%. Slider mechanisms and the need for a charger are also eliminated, assuming users possess a USB-C charger at home. However, four tiny stainless-steel screws and one gasket are added to the calculations. Due to reusability, the scenario of the user travelling to the pharmacy was copied from the *rethink* calculations. Accounting for these changes, the estimated impact is perhaps a bit lower than the original pillbox, but well within uncertainty ranges when only accounting for one use cycle. For the five use cycles scenario of *reuse*, we count the original transport, manufacturing in only the first of the five cycles; EoL impacts are only counted in the last cycle; impacts of the use stage, including user travel to the pharmacy, are counted in all five life cycles. With five life cycles, impacts are likely reduced by 10% - 85% less than baseline.

5) Explanation of Repair Calculations

To enable the *repair* concept we developed, a similar design is needed as the *reuse* concept. This means that we eliminated the sensor by minimizing the PCB mass with 0.11 grams, increasing the uncertainty to 100%, and removing all slider mechanisms as the lid was replaced with a buckle lid. Also, just as with the *reuse* concept, 4 stainless-steel screws and one gasket were added. As we do not expect the removable battery lid to change the design composition much, all other features of the pillbox remained the same, including the transport, use, and EoL stages. By adapting the fast-track LCA calculations based on this, this results in an estimated impact of the *repair* concept is perhaps slightly lower than the original pillbox, but well within uncertainty ranges. For the five use cycles scenario, we assumed with 100% uncertainly that the repair strategy would prolong each use cycle by one year, making one use cycle 4 years instead of 3. The impacts of replacement parts manufacturing, transport, and EoL were assumed to be included in this, as the product's life might be extended beyond 4 years but the impacts of replacement parts would make total impacts equivalent to a 4 year lifetime with no new parts. Therefore, we multiplied the impacts per use cycle by 75%.

6) Explanation of Remanufacture/Refurbish Calculations

Changes to enable the *remanufacture/refurbish* concept are similar to those of the *reuse* concept: the rubbery material was again removed in a similar way, but in this case not only for durability, but also to enable cleaning. Also, in the same way as the *reuse* concept, all sliding mechanisms and the need for a charger were eliminated while four tiny stainless-steel screws were added, in this case to ensure ease of disassembly. However, instead of minimizing the PCB mass to reduce the sensor, the PCB mass remained the same, as the *remanufacture/refurbish* concept would also need an NFC sensor to be added. Naturally, this mass comes with 100% uncertainty. This results in an estimated impact which is perhaps slightly lower than the original pillbox, but well within uncertainty ranges. In the five-use cycle scenario, we assumed critical components like the battery and LEDs are replaced half the time, calculating one full manufacturing impact for the first use cycle and half of the impacts for LEDs and the battery for the following four use cycles. EoL impacts are only counted in the last cycle. The use stage is counted for all five use cycles. The full transport is counted for the first use cycle, then the following four use cycles only count transport to a *remanufacturing/refurbishment* facility (1/3 of the full transport, ±100%). The resulting total impacts have enough uncertainty that in their worst case, they might potentially be worse than the best-case baseline, but in their best case, they might reduce impacts by 70% from the baseline worst case.

7) Explanation of Repurpose Calculations

For our *repurpose* concept, alterations to the original pillbox transition it into a modular design while abandoning the sliding mechanism. Symmetric design is crucial to facilitate modularity and minimize pill compartments, resulting in a 13% reduction in LED lights. Due to this, we also expect a reduction of energy use in the use stage of 5% ±100% uncertainty. Flexible compartments require separate production, with the pillbox tray using 20% less material, as this material will be used to produce five modular units via injection molding. Similar to the *rethink* concept, the pillbox features a separate electronics compartment. Simplifying repurposing, the battery is replaced with two standard rechargeable cells (AA), and assuming only half of the users will make use of the optional charger, the charge volumes are reduced by 50%, with ±100% uncertainty. Accounting for these changes, the repurpose concept yields an estimated impact that might be slightly lower than the concepts of e.g., *reuse* and *remanufacturing*. This reduction is primarily due to the change of battery and nonintentional reduction of LED lights. Since the outcome and duration of *repurposing* are highly uncertain, we excluded it from the five use cycles scenario calculations.

8) Explanation of Recycle Calculations

To enable our *recycle* concept, we first minimize the number of different materials by eliminating all sliding mechanisms again. Additionally, charging is eliminated. However, the most important change for this concept is that all plastic parts are changed into one recyclable material. In this case, we chose to use amorphous PET and calculated the mass of this material based on the mass and density of the materials used in the original pillbox. For the EoL stage, for all plastic components, we substituted landfilling and incineration practices with recycling for plastic and metal components. However, we assumed that the electronic components are not recycled, due to their small size and specialized composition, which can make them difficult to separate and process efficiently in typical recycling facilities. This results in an estimated impact which is perhaps slightly lower than the original pillbox, but well within uncertainty ranges, because the plastics are a miniscule percentage of total impacts. For the five use cycles scenario of *recycle*, we calculated the full manufacturing impact for the first use cycle, and impact of manufacturing with recycled plastics for the other four use cycles. The use and transport stages were the same for all five use cycles. EoL was assumed to be recycling in four life cycles, and incineration in the final EoL.

VI. COMBINING R-STRATEGIES IN ONE CONCEPT

The final step in our study was aimed at combining different strategies in a single design, to surface any trade-offs among strategies and determine the added value of this combination in terms of improving the sustainability and circularity of the product.

A. Ease of Combining R-Strategies in One Product

Overall, we believe that most R-strategies can be combined in a single product, while there may arise some drawbacks. Firstly, as *refuse* has a close alignment with the functional definition, this significantly influences the scope in the design phase (e.g., we cannot *reuse* or recycle a product after completely abandoning it), making *refuse* hard to combine. However, all other R-strategies can be combined with varying levels of ease. For *rethink*, combinations can mostly be made when addressing this strategy from a service and system design perspective. Although this concept so far seems to not necessarily improve sustainability or circularity by itself, it can play a crucial role in enabling other strategies (e.g. by intensifying the use, we can enable strategies such as *reuse*). Most easy to combine are the strategies of *reuse*, *repair*, *repurpose*, and *remanufacture*/*refurbish*. This is because most of them serve overlapping considerations, such as product and material durability, cleanability, and ease of disassembly. Additionally, for *reduce*, we could adhere to similar considerations but with minimized consumption of materials and resources where possible but aiming to maintain product durability and reliability. However, *recycle* prioritizes the system operation of the EoL process, which limits the choices in material and connections, possibly jeopardizing some design considerations (e.g. some recyclable materials might be less durable or harder to clean), making *recycle* less easy to combine to the full extent.

B. Final Combined Concept

Based on the reflections in section *A*, we developed a combined concept based on the strategies of *rethink*, *reduce*, *repair, reuse, repurpose, remanufacture/refurbish*, and partially *recycle* (Fig. 13). To create the combined concept, compared to the original design, we make the following design adaptations based on the R-based design concepts:

- Service subscription without product ownership, with a distribution and collection role of the pharmacy (based on *rethink* and *reuse*).
- Minimize the size by 50% with just four pillbox compartments, four LEDs, without a charger and with a buzzer instead of a speaker (based on *reduce*).
- Add four screws and one gasket to benefit durability, disassembly, and daily cleaning (based on *reuse*, *repair*, and *remanufacture*/*refurbish*)
- Add four screws and one gasket to benefit durability, disassembly, and cleaning (based on *reuse*, *repair*, and *remanufacture*/*refurbish*)
- Change plastics into recycled, water- and scratch resistant ABS (based on *reuse*, *repair*, *repurpose*, and *remanufacture/refurbish*), recyclable (based on *recycle*), and translucent (based on *reduce*).
- The app provides a medication log (based on *reuse*) and a self-repair service (based on *repair*).
- Make sure the battery is a standard rechargeable cell battery (based on *repurpose*) and that it is easily interchangeable (based on *repair*).
- Create a modular box with independent electronic bundle and flexible dividers (based on *repurpose*).
- Add a QR-code to enable a digital product passport (based on *remanufacture/refurbish*) without adding an NFC (based on *recycle*).
- Add an embossed sign on the lid for refurbished products (based on *remanufacture/refurbish*).
- Add a colored disassembly indicator to simplify battery removal (based on *recycle*).

Based on these adaptations, we performed another fast-track LCA. The design choices were calculated in the same way as they were calculated for the R-based strategy concepts. While still being within uncertainty ranges, the calculations showed that for only one use cycle this concept may yield an estimated reduction of up to 95% compared to baseline. This improvement percentage for one use cycle is less than that of *refuse*, but much better than that of all other strategies.

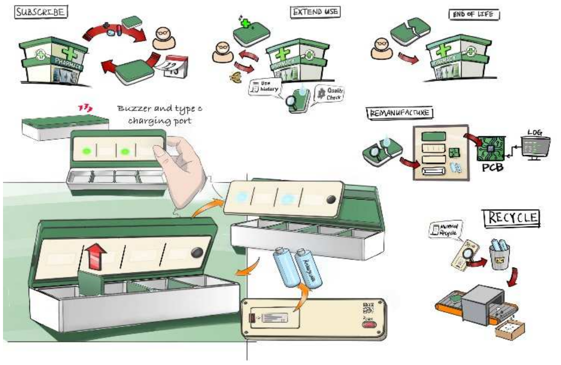

Fig. 13 Concept combining 7 R-strategy designs

Although we did not design the circular supply chain, we did try to calculate what would happen if the pillbox were produced from recycled materials and used for one use cycle of three years, after which it is reused twice (for six years in total), repaired once (extending the second *reuse* cycle by one year), remanufactured once, and then recycled upon EoL (after two years). We calculated this 15 years of use scenario in a similar way as we calculated the five use cycle scenarios for the R-based concepts. As this scenario still entails only one manufacturing and one EoL stage, and since the transport and use stage impacts are negligible, the estimated impacts of the 15 year scenario for the combined concept are similar to those of the 3 year scenario, resulting in an estimated relative impact per use cycle which is 65 – 95% lower than baseline.

VII. DESIGN RECOMMENDATIONS

The main aim of this paper was to determine to what extent R-strategies can be utilized as a design method. Overall, we do believe that the utilization of R-strategies in a design method has added value. In this section we will explain which aspects should be considered for each R-strategy when designing an electronic health device for circularity/-sustainability based on a discussion of our findings. The considerations can be found in Table III, ordered based on their importance, following the hierarchical order of the R-strategies.

For many reasons, product and system standardization can be beneficial: for example, using the same charging port for many different devices will abandon the need for production and purchase of many different ones. Simultaneously, we would like to recommend resource efficiency; make sure that we are not using unnecessary amounts of materials, resources, and electricity in the product life cycle (*reduce*). For the materials and parts that we do use, we need to ensure durability to make the device suitable for *reuse*, *repurpose*, or *remanufacture/refurbish* after the first use cycle. Depending on the level of needed decontamination (e.g. using a simple alcohol wipe versus high temperature steam sterilization), the product needs to be able to withstand necessary chemicals, temperatures, handling, and liquids. When a product is defective, it is preferable to first enable either self-repair or serviced repair to avoid product disposal and elongate repeated cycles of *reuse¸ repurpose and remanufacture/refurbish*. In some cases, it is important that the product is easy to disassemble. For example, to test product parts separately or to remove hazardous materials (such as batteries) prior to the *recycle* process. To enable the testing and assure product quality for any next use, we would also need to ensure that authorized parties are enabled to perform the needed quality assessments. This may include e.g. indicators of contamination and the possibility to test fragile product parts on strength. For this, we also need to provide access to product information about e.g. the number of *reuse* cycles a product has already been gone through, because of which we will need to ensure product traceability. In case a product is planned for recycling, we also need to ensure material separation to ensure homogenous recyclable waste streams. This goes further than enabling disassembly, e.g. 2K injection molding, mixed plastics and flame retardants need to be avoided and the use of a standardized PCB color would allow it to be recognized by the separation equipment of the recycling facilities.

VIII. DISCUSSION

Overall, using the R-strategies in our design methodologies has helped generate ideas, and seems to have improved the sustainability and circularity of the smart pillbox concept overall, especially when integrating multiple strategies into a single concept. Only the strategy of *rethink* seemed to have zero positive impact on product level sustainability, as this strategy mostly focused on developing system level design interventions. However, it is likely that a circular business model could be enabled through this strategy, which would improve the adoptability of most other R-strategies. *Reuse* and *remanufacture/refurbish* provided the most sustainability benefit when accounting for multiple use cycles.

TABLE III. MAIN CONSIDERATIONS FOR EACH DESIGN CONCEPT

R-Strategy	**Main consideration**	**Important requirements that apply**										
		Functionality	***Utilization***	***Standardization***	***Resource efficiency***	***Durability***	***Cleanability***	***Repairability***	***Disassembly***	***Quality assessment***	***Traceability***	***Material separation***
Refuse	Only design, develop, and market products that address unmet needs.	▨										
Rethink	Design products that promote full utilisation of functionalities.		▨	▨								
Reduce	Minimize use materials and resources in production and use stage.				▨							
Reuse	Maintain uniform product quality during multiple use cycles.			▨		▨	▨	▨		▨	▨	
Repair	Ensure authorized parties can access and replace critical product parts.			▨		▨	▨	▨			▨	
Reman/refurb	Ensure authorized parties can effectively recover the product to as-new state.			▨		▨	▨	▨	▨	▨	▨	
Repurpose	Ensure product modularity to enable use for different purposes.			▨		▨	▨	▨	▨		▨	
Recycle	Ensure product materials are easily separable and recyclable.			▨					▨		▨	▨

Especially the *reuse*, *repair*, *remanufacture*/*refurbish*, and *recycle* strategies were easy to implement in the design process. However, it was in some cases hard to get a grip on the definitions of some strategies. This was especially the case for *refuse*, *rethink*, and *reduce*, due to their abstract nature. Based on a trial-and-error design process, we now feel confident to recommend addressing *refuse* from the perspective of product functionality, *rethink* from the system and service design perspective, and *reduce* from the product architecture perspective. The hardest strategy to design for was *repurpose*, as designing a function to be used after the initial function comes with a lot of uncertainty, as we cannot assure repurposing behavior of the user.

Especially since *refuse* is on top of the R-strategies hierarchy and is clearly the best option in terms of sustainability, we recommend to always start design processes by asking the following question: *do we really need this functionality and if yes, is this specific product really the most effective and most sustainable way of addressing the need?* It is, however, also important to consider the drawbacks of this R-strategy. For example, *refusing* a previously profitable product may lead to serious business trade-offs for any product category; but in the case of health devices, it may also pose serious safety risks. Although in our fast-track LCA we only compared concepts based on kg CO_2-eq, we recommend to also measure the impacts of the product redesigns on the product effectiveness. In the smart pillbox, for example, it would be crucial to determine whether the addition of electronics would improve medication adherence, and if so, whether this increase in adherence would pay back the higher environmental impact, which is a variable we would advise to consider in future assessments of similar products.

We concluded that *refuse* is hard to combine with other R-strategies, since in its ideal scenario there would not be any product. Thus, for cases where *refuse* is not favorable or only partially an option, we advise looking into the other R-strategies. In this, we advise brainstorming on all strategies, while putting more effort on R-strategies higher in the hierarchy, starting with optimizing the service systems surrounding the product to enable the other R-strategies (*rethink*) and minimizing unnecessary use of materials and resources in the manufacturing and use stages (*reduce*). Overall, we would advise always aiming to combine as many R-strategies as possible.

Therefore, although we now looked at each R-strategy separately, it is important to acknowledge the extensive overlap among them. For example, *repair, repurpose, remanufacture/refurbish* and *recycle* could all benefit from easily separable components and materials, and to enable *reuse*, *repair*, *repurpose,* as well as *remanufacture/refurbish*, part longevity is essential. While combining the different strategies, we would suggest only considering *recycling* to the extent that it does not unacceptably jeopardize the viability of any other R-strategy, adding it into the process only after designing for others, e.g. *reuse*.

Lastly, despite not being a sustainable or circular principle, an additional important consideration in the healthcare context is to put safety first. Not doing this can tremendously jeopardize the success rate: e.g., we cannot *refuse* functionalities that are vital to patient survival or *reuse* smart devices without first removing sensitive data from the previous patient. To ensure sustainability, it is however important to only design products that answer a user or patient need and will actually be used.

A. Limitations and Future Work

In the discussion we have already highlighted some specific limitations related to the implementation of the R-strategies in the design process and the assessment thereof. However, it is important to also acknowledge the limitations of our overall study method; most importantly the analysis which is based on a single case study. Despite valuable insights, we highlight the need for further research to validate our findings across diverse contexts in the healthcare domain. Additionally, our sustainability assessment was currently solely based on a mostly product-level fast-track LCA comparison of CO_2 impacts alone. This represents a clear limitation, as sustainability encompasses a broader range of environmental, social, and economic factors that warrant exploration in future investigations. The large uncertainties in LCAs could also be tightened by finding more precise data after further specifying exact designs, though this would cost time and money that may not be worth it for design strategies that do not show obvious potential for significant improvement.

Furthermore, while our study has focused on the R-strategies framework [7], it is essential to recognize that this framework may not encompass all aspects of sustainability, particularly in terms of the bio cycle as defined in the circular economy Butterfly Diagram [13]. Future studies could explore the integration of additional sustainability frameworks to provide a more holistic assessment of product design impacts.

While our study has provided valuable insights into the application of R-strategies in healthcare design, there remains ample room for further exploration and refinement. By addressing the limitations outlined and continuing to advance our understanding of sustainable design principles, we can work towards creating more resilient and environmentally conscious healthcare systems for the future.

IX. CONCLUSION

In this paper, we aimed to assess whether the 10R-strategies framework could successfully be implemented in a design method for creating a more environmentally sustainable redesign of an electronic health device. To do so, we performed a design case study on a smart pillbox, including separate design sprints for each R-strategy, and combining those concepts into one redesign suggestion. For each design sprint, we assessed the quality of the integration of the R-strategy and the extent to which the R-strategy-based design concept had improved the sustainability and/or circularity of the product.

Overall, the R-strategies were easy to use as goals in normal design brainstorms. Especially the strategies of *reuse*, *repair*, *remanufacture/refurbish*, and *recycle* were easy to design for. For *refuse, rethink,* and *reduce*, some terminology confusion arose, which was solved by determining points of focus: we addressed *refuse* from a product functionality perspective, *rethink* from a system design perspective, and *reduce* from a product level perspective. *Repurpose* was the hardest strategy to design for, as it seemed impossible to assure the *repurpose* process would actually take place and in which way the product would be repurposed.

To assess the environmental effectiveness of the R-strategies, we performed fast-track LCAs for each design concept. *Refuse* ensured the most improvement in CO_2-emissions, and *reuse* is similar if systems are in place for the product to actually be reused several times. *Reduce* is very likely an improvement, perhaps cutting impacts by half. However, the other R-strategies scored within uncertainty of the original product, so they may or may not provide improvements, depending on implementation specifics. Combining strategies can multiply benefits. We therefore advise designers to always combine *rethink* with one of the technical strategies (e.g. *reuse* or *remanufacture / refurbish*) and to only consider recycling after the other R-strategies have been utilized.

In our discussion on fostering environmentally sustainable electronic health devices using the R-strategies framework, we highlighted key considerations. These include maintaining product functionality in *refuse*, maximizing product functionalities in *rethink*, and prioritizing standardization, resource efficiency, durability, and cleanability across R-strategies. We also emphasized the significance of repairability, quality assessment, traceability, and material separation in recycling concepts.

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REFERENCES

[1] M. Steenmeijer, L. Pieters, N. Warmenhoven, E. Huiberts, and M. Stoelinga, "Het effect van de Nederlandse zorg op het milieu. Methode voor milieuvoetafdruk en voorbeelden voor een goede zorgomgeving," [object Object], 2022. doi: 10.21945/RIVM-2022-0127.

[2] "Tackling informality in e-waste management: The potential of cooperative enterprises," Working paper, Oct. 2014. Accessed: Mar. 04, 2024. [Online]. Available: http://www.ilo.org/sector/Resources/publications/WCMS_315228/lang--en/index.htm

[3] J. Kirchherr, D. Reike, and M. Hekkert, "Conceptualizing the Circular Economy: An Analysis of 114 Definitions." Rochester, NY, Sep. 15, 2017. doi: 10.2139/ssrn.3037579.

[4] J. D. Sherman *et al.*, "The Green Print: Advancement of Environmental Sustainability in Healthcare," *Resources, Conservation and Recycling*, vol. 161, p. 104882, Oct. 2020, doi: 10.1016/j.resconrec.2020.104882.

[5] G. M. Kane, C. A. Bakker, and A. R. Balkenende, "Towards design strategies for circular medical products," *Resources, Conservation and Recycling*, vol. 135, pp. 38–47, Aug. 2018, doi: 10.1016/j.resconrec.2017.07.030.

[6] A. Navajas, L. Uriarte, and L. M. Gandía, "Application of Eco-Design and Life Cycle Assessment Standards for Environmental Impact Reduction of an Industrial Product," *Sustainability*, vol. 9, no. 10, Art. no. 10, Oct. 2017, doi: 10.3390/su9101724.

[7] S. Bag, S. Gupta, and S. Kumar, "Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development," *International Journal of Production Economics*, vol. 231, p. 107844, Jan. 2021, doi: 10.1016/j.ijpe.2020.107844.

[8] J. C. Diehl, "The Green Intensive Care: From Environmental Hotspot to Action," 2023.

[9] S. C. Kalichman, D. Cain, C. Cherry, M. Kalichman, and H. Pope, "Pillboxes and Antiretroviral Adherence: Prevalence of Use, Perceived Benefits, and Implications for Electronic Medication Monitoring Devices," https://home.liebertpub.com/apc. Accessed: Mar. 22, 2024. [Online]. Available: https://www.liebertpub.com/doi/10.1089/apc.2005.19.833

[10] E. S. Spratt *et al.*, "Using Technology to Improve Adherence to HIV Medications in Transitional Age Youth: Research Reviewed, Methods Tried, Lessons Learned," *J Gen Med (Dover)*, vol. 1, no. 1, p. 1002, 2017.

[11] R. J. B. Ellis, M. R. Knisely, K. Boyer, and C. Pike, "Pillbox intervention fidelity in medication adherence research: A systematic review," *Nursing Outlook*, vol. 65, no. 4, pp. 464–476, Jul. 2017, doi: 10.1016/j.outlook.2016.12.011.

[12] B. Visscher, *Towards tailored medication self-management: needs of and support for patients with limited health literacy*. Maastricht: Maastricht University, 2023. doi: 10.26481/dis.20230417bv.

[13] Ellen MacArthur Foundation, "The butterfly diagram: visualising the circular economy." Accessed: Aug. 04, 2023. [Online]. Available: https://ellenmacarthurfoundation.org/circular-economy-diagram

[14] E. Hoobroeckx, "Assessing environmental sustainability of digital health devices at a product and functional level: A smart pillbox case study," 2023, Accessed: Apr. 04, 2024. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3A53b23311-dc41-4ce7-9857-3498f5c6091f

[15] Y. Mao, "Improving the return rate of a smart pillbox in a circular economy: From product redesign to comprehensive guidelines," 2023, Accessed: Apr. 04, 2024. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3A8bf84519-e935-4cf8-89e0-490abad49ef7