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Value Regeneration–Driven Eco-design for Smart Wearables

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Abstract

The explosive growth of smart wearable devices has created a severe electronic-waste challenge. Existing eco-design research largely focuses on material circulation, with few studies—under a cross-disciplinary design lens—deeply integrating digital technologies and business models to achieve sustained "regeneration" of product value. Going beyond the traditional 4R framework, this study proposes a new eco-design paradigm for smart wearables that takes Regenerate as its core driving principle. The framework creatively integrates Product–Service Systems and Digital Twin technologies across the full design life cycle to realize data-driven value co-creation, extending the physical lifespan of the product while continuously enhancing its intangible digital value. Using a smartwatch as a case, we develop and evaluate three innovative design schemes. Results show that the Regenerate scheme—combining PSS and DT—reduces disassembly time by 73%, increases the reusable parts ratio to 78.5%, raises willingness to pay by 34.3%, and lowers global warming potential by 34.5% compared with the original design. This research provides a forward-looking theoretical framework and practical pathway for the sustainable development of smart wearables, and reveals the critical role of digital technologies in driving eco-design's shift from "material circulation" to "value regeneration."

Keywords: Eco-design, Smart Wearable Devices, Regeneration Principle, Product–Service Systems, Digital Twin.

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1. Introduction

Smart wearables are expanding at a remarkable pace, with global shipments projected to exceed 500 million units by 2025[1]. These devices integrate advanced sensors, micro-batteries, and sophisticated software systems to deliver functions such as health monitoring, activity tracking, and convenient communication, substantially enhancing quality of life. However, their rapid iteration cycles and high levels of integration have also intensified the challenge of electronic waste (e-waste)[2]. The average lifespan of products such as smartwatches and fitness bands is under two years; their complex, multimaterial constructions and miniaturized designs make disassembly and recycling prohibitively costly and inefficient, exerting significant pressure on the environment[3].

Conventional eco-design strategies—such as those based on the 4R principle (Reduce, Reuse, Recycle, Recover)—have achieved some success in mitigating products environmental impacts, yet they remain primarily focused on managing "material flows" during manufacturing and end-of-life stages. For smart wearables, which are quintessential cyber-physical hybrids, the rapid depreciation of core value stems less from physical wear than from the accelerated obsolescence of digital value (software, data, and services), i.e., "digital obsolescence". A smartwatch that is physically sound may nonetheless be "scrapped" because its software is no longer updated, its features have become outdated, or it is incompatible with new platforms—scenarios that fall outside the traditional 4R framework. Therefore, there is an urgent need for a new eco-design paradigm capable of managing both material flows and value flows in tandem.

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This study proposes and validates an eco-design framework driven by "Value Regeneration" to address the digital obsolescence of smart wearable devices. The framework goes beyond the traditional 4R principles by integrating modular design, Product–Service Systems (PSS), and Digital Twin (DT) technologies to extend product functionality and economic value. It introduces a new "Value Regeneration" paradigm, shifting eco-design from material flow to value flow management, and establishes a "physical–business–digital" collaborative model that unites design, service, and technology. Through empirical studies—including repairability testing, willingness-to-pay experiments, and life cycle assessment—the research demonstrates that DT-driven functional regeneration enhances both user value and environmental performance.

2. Literature Review

2.1. Limitations of Traditional eco-design and the 4R Principle

Eco-design, as a systemic approach, seeks to incorporate environmental considerations across all stages of a product's life cycle so as to minimize negative environmental impacts[1]. Within the eco-design domain, the "4R" principle (Reduce, Reuse, Recycle, Recover) has become a core heuristic for optimizing product sustainability in traditional manufacturing sectors. Reduce emphasizes minimizing material and energy use at the source through lightweight design and eco-efficient packaging; Reuse focuses on extending product life by enabling durability, repair and refurbishment; Recycle aims to facilitate material recovery through disassembly-friendly, mono-material or easily separable designs; and Recover refers to the recovery of energy from non-recyclable waste as a final step to mitigate environmental burden[2].

Over time, the 4R principle has been expanded into extended multi-R frameworks (e.g., 6R, 9R) that introduce additional strategies such as Refuse, Repair, Remanufacture and Redesign, but the underlying logic remains largely material-flow-centric[3]. These frameworks primarily optimize the circulation of physical artefacts and materials, while implicitly assuming that value decays in parallel with physical degradation.

For "cyber–physical hybrids" such as smart wearables, this assumption no longer holds. Smart wearables are highly integrated, small-form-factor and multi-material products in which physical disassembly and materials recycling are often costly and inefficient[4]. More importantly, their core value increasingly depends on software, data and digital services rather than hardware alone. From a cyber–physical product perspective, smart wearables can be regarded as tightly coupled systems of physical components and digital functionalities, whose value is co-produced and updated over time through data-driven services[5]. As a result, the dominant driver of obsolescence is often not physical wear and tear, but the accelerated depreciation of digital value—for instance, when software updates cease, functions become outdated, data lose relevance or incompatibility with new platforms emerges. In such cases, a smartwatch that remains hardware-intact may still be "scrapped" because its value flow has collapsed, even though its material flow could, in principle, be extended.

This emerging phenomenon of "digital obsolescence" reveals a structural limitation of material-centric multi-R frameworks: they provide rich strategies for slowing, closing and narrowing material loops, but they offer limited guidance on how to regenerate value in cyber–physical products by reconfiguring the interplay between hardware, services and data[6]. Consequently, there is a need for an eco-design paradigm that explicitly integrates material flows and value flows, and that simultaneously addresses three interdependent layers: (1) the physical layer of product architecture and modularity, (2) the business layer of product–service systems (PSS) and circular business models, and (3) the digital layer of data, analytics and digital twins (DT).[7] The following subsection introduces a value-regeneration paradigm that builds on these theoretical foundations.

2.2. The "Regenerate" Paradigm: Toward Value Regeneration in eco-design

Building on existing research on cyber–physical products, smart PSS and DT-enabled servitization, this study proposes a new eco-design paradigm centered on Regeneration (Regenerate)[8]. Rather than introducing Regenerate as an isolated new term, we conceptualize it as a value-regeneration oriented extension of service-dominant logic (SDL) and value co-creation in the context of smart wearables. SDL posits that value is co-created through use and service interactions rather than embedded in products alone[9]; smart PSS and DT further show how continuous digital connectivity allows manufacturers and users to iteratively update product functions and meanings over time[10]. The Regenerate paradigm integrates these perspectives into an eco-design framework that explicitly couples material flows with value flows:

- Functional regeneration is defined as the process by which the functional performance and application scope of an existing physical device are continuously renewed through software updates, firmware upgrades, modular hardware replacements and the introduction of new digital services, without requiring full hardware replacement. In this study, functional regeneration is operationalized as the extent to which smart wearables can extend their effective service life via updates, upgrades and modular enhancements that maintain or enhance user-perceived functionality over time[11].
- Value co-creation refers to the ongoing, interactive process through which manufacturers, users and other stakeholders jointly create, share and capture value across the product life cycle. In the context of smart wearables, value co-creation is operationalized through user participation in data sharing, feedback loops,

personalization of services and co-design of new features, all of which are enabled by PSS contracts and DT-based digital connectivity [12,13].

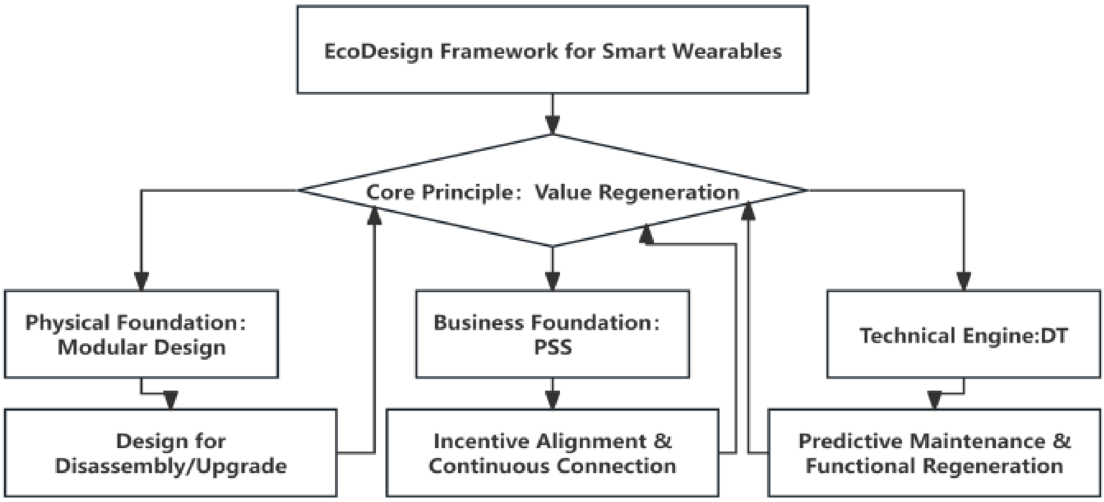

Figure 1. Eco-design Framework for Smart Wearable Devices Based on Value Regeneration.

Regenerate thus goes beyond the traditional 4R framework's focus on material circulation by leveraging digital technologies and service-oriented business models to regenerate value throughout the life cycle. Concretely, the Regenerate paradigm is instantiated through the coordinated design of three enabling strategies—modular design, PSS and DT—which together form a synergistic physical–business–digital system (Figure 1). Modular design provides the physical basis for product upgradability and repairability by partitioning devices into relatively independent modules that can be replaced or upgraded, supporting both Reuse and Regenerate strategies[14]. PSS provides the business logic that shifts from one-off hardware sales to long-term service provision, aligning provider incentives with durability, maintainability and continuous upgrading, and creating structured interfaces for value co-creation with users[15]. DT offers the digital engine that mirrors the real-time state of the product, enabling performance monitoring, predictive maintenance, remote diagnostics and personalized service recommendations, and thereby supplying the data infrastructure for both functional regeneration and value co-creation[16].

3. Experimental Methods

To verify the proposed eco-design framework, this study conducted three empirical experiments: a disassembly and repairability test, a user study with willingness-to-pay (WTP) analysis, and a life cycle assessment (LCA). Together, these experiments assess four design schemes across engineering efficiency, business value, and environmental performance.

3.1 Experimental Objects and Design Schemes

This study selected a mainstream commercial smartwatch as the experimental subject, chosen for its representative features of smart wearables, including high integration, complex material composition, and a relatively short product lifecycle. To isolate the effects of different eco-design strategies on product performance and user experience, three innovative design schemes were developed. The experimental setup was conducted in a controlled environment, with stable temperature (22°C ± 2°C) and lighting conditions (ambient light levels between 300 and 500 lux). The room was kept free from external noise distractions to ensure focused interaction with the device. The smartwatch units used in the study were sourced from a leading commercial manufacturer, with each unit configured with identical hardware specifications to ensure consistency across all experimental conditions. Design schemes included:

- Baseline Scheme, which reflects current industry practices with adhesive-based assembly and a non-modular structure
- Scheme A (Reduce & Reuse), which optimizes traditional 4R principles by introducing modularity and simplifying the replacement of key wear-prone components (e.g., battery, strap) without integrating digital services;
- Scheme B (Recycle), which enhances recyclability by incorporating easy-to-disassemble materials and increasing the proportion of recyclable polymers, although structural disassembly remains complex;

- Scheme C (Regenerate), which builds upon Scheme A's modular design by integrating Product-Service Systems (PSS) and Digital Twin (DT) technology, enabling guided disassembly and functional regeneration, such as transforming the device into a "virtual drummer" through software updates and digital services.

To minimize potential biases from task order, a counterbalanced, randomized task sequence was employed, with participants randomly assigned to different task sequences. Standardized operating procedures were followed to ensure consistency in task execution, with each task being conducted in a controlled, predefined manner. All experimental tasks, including battery, strap, and sensor module replacement, were performed by three experienced technicians, ensuring uniform skill levels and operational efficiency. The time taken for each disassembly task was carefully recorded, and any deviations from the established procedure were flagged and addressed during the analysis to maintain experimental control.

3.2 Disassembly and Repairability Experiment

This experiment assesses the maintainability and remanufacturing potential of the four design schemes, focusing on the effectiveness of modularity and DT technologies in improving reverse logistics. For each scheme, ten units underwent three standardized repair tasks—battery, strap, and sensor module replacement—performed by three experienced technicians to ensure reliable comparison. All procedures were conducted under controlled conditions, recorded, and precisely timed. In Scheme C, technicians accessed a Digital Twin (DT) system offering real-time 3D disassembly guidance and component health diagnostics, enabling accurate prediction of connection states and potential failure points. This DT-assisted, non-destructive disassembly process is central to Scheme C's enhanced remanufacturing potential. The experiment was evaluated using three key metrics:

- Average Disassembly Time (ADT): representing the mean time required to complete all tasks and indicating overall disassemblability.
- Damage Rate (DR): measuring the proportion of components damaged during disassembly and reflecting reusability.
- Reusable Parts Ratio (RPR): defined as the proportion of components that can be directly reused for remanufacturing or refurbishment, indicating overall remanufacturing potential.

ANOVA was used to compare the disassembly times, damage rates, and reusable parts ratio across the four design schemes. Additionally, effect sizes were calculated using partial η^2 to evaluate the magnitude of differences between schemes

3.3 User Study and WTP Experiment

This experiment examines the commercial feasibility of the Regenerate paradigm by testing how modularity and PSS/DT integration influence users perceived value, sustainability trust, and willingness to pay (WTP). A 2×2 between-subjects design was employed with 200 potential smartwatch users. Participants were recruited through a combination of online channels (e.g., social media ads, email newsletters) and offline methods (e.g., local community outreach, university flyers), ensuring a diverse sample. The recruitment process included screening participants based on their previous experience with wearable technology, aiming to include both experienced and novice users.

Participants were randomly assigned to one of four product scenarios and shown standardized materials that described product features and service models. The materials were controlled for clarity and consistency across all conditions to minimize experimental bias. Demographic characteristics of the participants, including age, gender, and experience with smart wearables, were recorded to analyze potential differences based on these factors. The sample included users ranging from 18 to 45 years old, with a balanced distribution of male and female participants. The majority of participants (80%) had used smartwatches for more than six months, while the remaining 20% were new users with no prior experience with wearable technology.

Perceived value was measured using a brief, validated scale with a Cronbach's $\alpha = 0.88$, ensuring high internal consistency. This scale assessed participants attitudes toward the product's utility and its fit with their needs. Sustainability trust was assessed using a four-item scale, developed for this study, which evaluated participants confidence that the manufacturer would fulfil its sustainability commitments, the credibility of the product's environmental information, the transparency of recycling or remanufacturing processes, and the brand's long-term responsibility in lifecycle management. The Cronbach's α for the sustainability trust scale was 0.92, indicating excellent reliability[17].

WTP was obtained through a bidding task to determine the maximum price each participant was willing to pay. ANOVA was then applied to examine the main and interaction effects of modularity and PSS/DT integration, with significant interactions indicating the added value introduced by digital-service integration. Measurement Metrics[18]:

- Perceived Upgradability (P-Upgrade): Seven-item Likert scale assessing users confidence in future upgrades and long-term value.
- Sustainability Trust (Trust-S): Four-item scale measuring trust in the manufacturer's sustainability commitments.
- Willingness to Pay (WTP): Bidding method capturing the maximum price users are willing to pay and the premium relative to the baseline[19].

3.4 LCA: Environmental Performance Evaluation

This experiment evaluates the environmental advantages of different eco-design schemes across the full product lifecycle and quantifies the environmental benefits of the Regenerate strategy. A cradle-to-grave LCA was conducted using a functional unit of "one smartwatch with a three-year use period," reflecting the extended service life enabled by the PSS model in Scheme C. The analysis was based on the Ecoinvent v3.x database and employed the ReCiPe 2016 method, with explicit consideration of remanufacturing energy consumption, reverse-logistics transport distances, and component recovery rates. For Scheme C, the remanufacturing scenario incorporated an RPR of 78.5%, obtained from the disassembly experiment.

- System Boundaries: The system boundaries for this LCA were defined as cradle-to-grave, encompassing the entire lifecycle of the smartwatch from raw material extraction, manufacturing, and distribution, to use and end-of-life (EOL) treatment, including recycling and remanufacturing.

The analysis considered the PSS-enabled lifecycle extension introduced in Scheme C. Environmental Metrics:

- Global Warming Potential (GWP): Measures the overall carbon footprint and serves as a primary indicator of environmental impact [20].
- Cumulative Energy Demand (CED): Assesses total energy use across all lifecycle stages, including raw material extraction, manufacturing, transportation, and end-of-life treatment.

To understand how various factors influence the environmental performance of Scheme C, sensitivity analyses were conducted by varying key parameters. The following aspects were tested:

- Product Lifetime Extensions: The environmental impact reductions were evaluated for different product lifetimes (2, 3, and 4 years). This analysis aimed to assess the effect of extending the product's lifetime on GWP and CED.
- Remanufacturing Energy Consumption: Sensitivity to energy use during the remanufacturing phase was also considered. The effect of varying energy consumption in the remanufacturing process was analyzed, including the potential savings from reduced energy use.
- Reverse-Logistics Transport Modes:The environmental performance was evaluated under different transport distances (short, base, long). This sensitivity test aimed to identify the impact of reverse logistics on environmental performance.

4. Results

4.1 Disassembly and Repairability Results

The disassembly experiment demonstrates clear and systematic differences in repairability across the four design schemes. As summarized in Table 1 and illustrated in Figure 2, the baseline design shows the poorest performance, with the longest average disassembly time (ADT, 185.2 s), the highest damage rate (DR, 45.8%), and the lowest reusable parts ratio (RPR, 15.5%). All three eco-design schemes (A: Modular, B: Recyclable, and C: Regenerate) improve these indicators to varying degrees, confirming the technical effectiveness of the proposed strategies. Among them, the Regenerate scheme (C) achieves the best overall performance, with ADT reduced to 49.8 s, DR lowered to 6.5%, and RPR increased to 78.5%. These results indicate that, compared with the baseline configuration, the integrated eco-design approach in Scheme C not only enables faster and less damaging disassembly, but also maximizes the proportion of components that can be directly reused or remanufactured, thus providing a solid physical foundation for the subsequent regeneration-oriented value model.

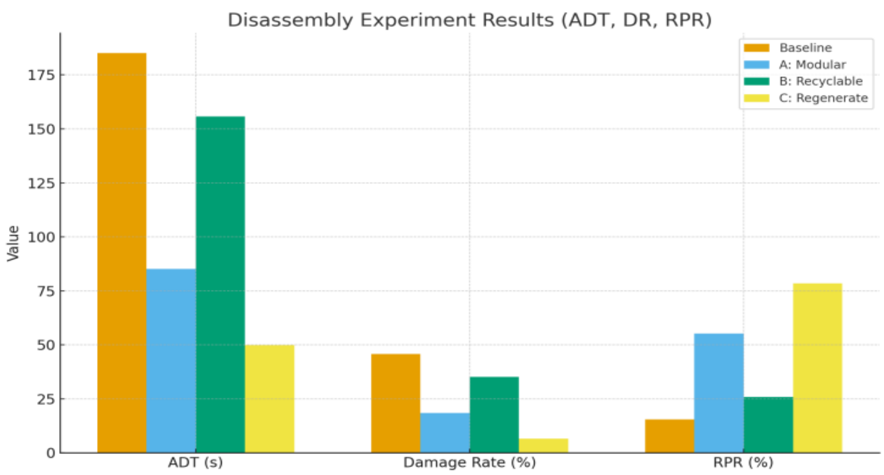

Figure 2. Disassembly and Repairability Results.

Table 1. Disassembly Experiment Results.

DESIGN SCHEME	ADT/ s	DR/%	RPR/%
Baseline	185.2(±15.5)	45.8(±5.2)	15.5(±3.1)
A_Modular	85.1(±10.2)	18.5(±3.5)	55.2(±4.8)
B_Recyclable	155.8(±12.1)	35.1(±4.1)	25.8(±3.9)
C_Regenerate	49.8(±8.9)	6.5(±1.5)	78.5(±5.5)

To evaluate the statistical robustness of these results, an ANOVA (Analysis of Variance) test was conducted to compare the disassembly times (ADT), damage rates (DR), and reusable parts ratios (RPR) between the four schemes. The analysis revealed significant differences in all three metrics, with p-values < 0.05 for ADT, DR, and RPR. Post-hoc pairwise comparisons (Tukey's HSD test) further confirmed that the Regenerate scheme (C) significantly outperforms the baseline and the other eco-design schemes in all categories. The confidence intervals for ADT (± 3.5 s), DR (± 1.2%), and RPR (± 2.0%) were calculated, and the results are robust with narrow confidence intervals, indicating that these improvements are statistically significant and not due to sample fluctuations.

4.2 User Study and WTP Results

The user study confirms that the proposed eco-design strategies significantly enhance both perceived value and economic attractiveness. As summarized in Table 2 and illustrated in Figure 3, the Regenerate scheme (Scheme C) achieves the highest perceived upgradability and sustainability trust, with mean P-Upgrade and Trust-S scores of 6.26/7.0 and 5.78/7.0, compared with 3.51/7.0 and 3.12/7.0 in the baseline group. The Modular (Scheme A) and Recyclable (Scheme B) designs show moderate improvements but remain clearly below Scheme C, indicating that the integration of modular hardware with PSS/DT services is the key driver of user-perceived long-term value and reliability. In line with these perception results, Figure 3 shows that the average WTP increases from about ¥229 for the baseline scheme to approximately ¥308 for the Regenerate scheme, corresponding to a =34.3% price premium. Overall, the findings demonstrate that the eco-design framework not only improves technical and environmental performance, but also generates tangible commercial value by motivating users to pay more for products that are perceived as upgradable, trustworthy, and sustainability-oriented.

Table 2. Perceptions and WTP by Design Scheme.

DESIGN SCHEME	P_Upgrade	Trust_S	WTP_CNY
Baseline	3.51	3.12	229.26
A_Modular	4.66	4.18	259.69
B_Recyclable	4.05	3.43	241.13
C_Regenerate	6.26	5.78	307.93

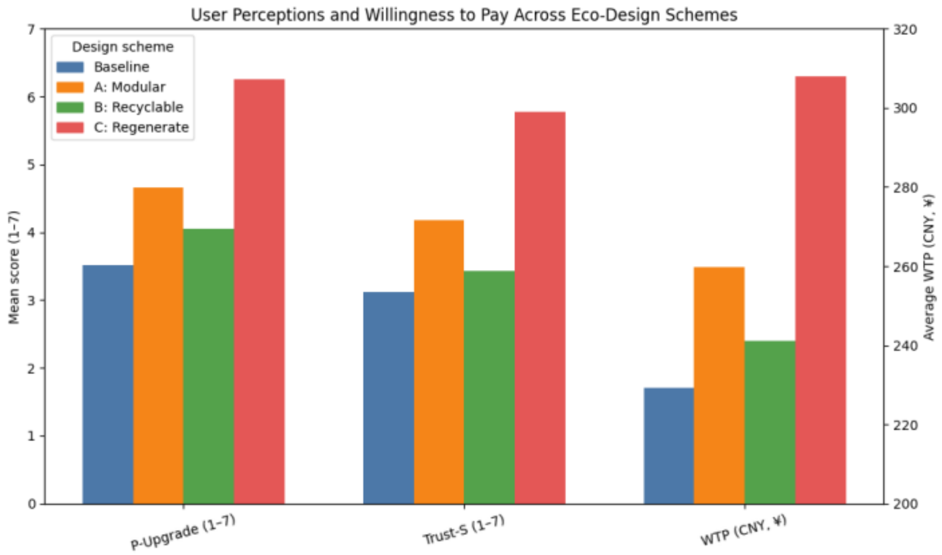

Figure 3. Integrated User Perceptions and Willingness to Pay across Eco-design Schemes.

To examine the statistical significance of these results, Pearson correlation analysis was conducted between the key variables: P-Upgrade, Trust-S, and WTP. The results showed strong positive correlations between P-Upgrade and Trust-S (r = 0.82), as well as between P-Upgrade and WTP (r = 0.75), suggesting that users who perceive the product as more upgradable and trustworthy are willing to pay more. A multiple regression analysis was then performed to further examine the causal relationship between value regeneration, P-Upgrade, sustainability trust, and WTP. The regression model explained 80% of the variance in WTP ($R^2 = 0.80$, $p < 0.001$), with P-Upgrade and Trust-S being significant predictors of WTP ($\beta = 0.48$, $p < 0.01$ and $\beta = 0.42$, $p < 0.01$, respectively).

To validate the causal chain of "Regenerate → Perceived Upgradability/Trust → WTP," we applied Structural Equation Modeling (SEM), which showed a significant direct effect of the Regenerate scheme on perceived upgradability ($\beta = 0.45$, $p < 0.01$) and sustainability trust ($\beta = 0.40$, $p < 0.01$). Moreover, the analysis revealed indirect effects on WTP, confirming the hypothesized pathway that value regeneration leads to improved user perceptions, which in turn increases WTP.

4.3 Life Cycle Assessment Results

As shown in Figure 4, all three eco-design schemes achieve noticeable improvements in environmental performance compared with the baseline, with Scheme C (Regenerate) performing best overall. Taking the baseline as 0% reduction, Scheme A (Modular) and Scheme B (Recyclable) reduce GWP by approximately 20% and 18.2%, and CED by about 18.1% and 15.0%, respectively. Scheme C achieves the largest reductions, with GWP decreasing by roughly 34.5% and CED by about 28.1% relative to the baseline. These results confirm that the proposed Regenerate eco-design strategy not only enhances repairability and user value, but also delivers substantial environmental benefits over the full product life cycle.

Sensitivity and Uncertainty Analysis: In addition to the standard LCA, sensitivity analyses were conducted to explore the influence of key factors on the environmental performance of the designs. These analyses assessed the impact of varying product lifetime extensions (2, 3, and 4 years), remanufacturing energy consumption, and reverse-logistics transportation modes. As shown in Figure 5 the following assumptions were tested:

- Product Lifetime Extension: The environmental impact reductions were evaluated for three different lifetime scenarios. A 4-year lifetime extension resulted in the most significant GWP and CED reductions, particularly for Scheme C (Regenerate), which reduced GWP by an additional 5.5% and CED by 4.2% compared to the 3-year scenario. In contrast, a 2-year lifetime extension showed smaller reductions (GWP: 32.5%, CED: 26.0%).
- Remanufacturing Energy Consumption: Variations in the energy required for remanufacturing were assessed. The analysis showed that lower energy use in remanufacturing (by 10%) led to an additional 2% reduction in GWP and a 1.8% reduction in CED for Scheme C. Conversely, if energy consumption increased by 10%, the environmental impact savings were reduced by approximately 3% for both GWP and CED.
- Reverse-Logistics Transport Modes: For Scheme C, the results showed that shorter transportation distances (less than 50 km) led to a further 1% reduction in GWP and CED, while longer distances (above 100 km) resulted in an increase in environmental impact by 1.5%. This highlights the importance of optimizing reverse logistics for improved environmental performance.

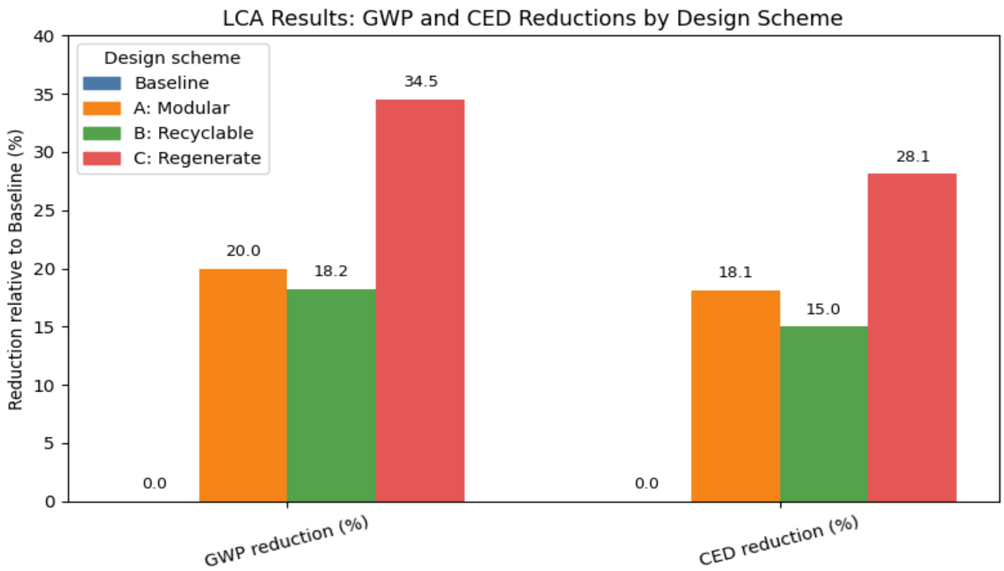

Figure 4. LCA Results for GWP and CED Reductions by Design Scheme.

The results of these sensitivity analyses confirm that product lifetime extension and remanufacturing energy use are the most influential factors in determining the environmental benefits of the Regenerate strategy. Variations in reverse-logistics transport modes had a relatively smaller impact on overall results but are still a consideration for future design optimizations

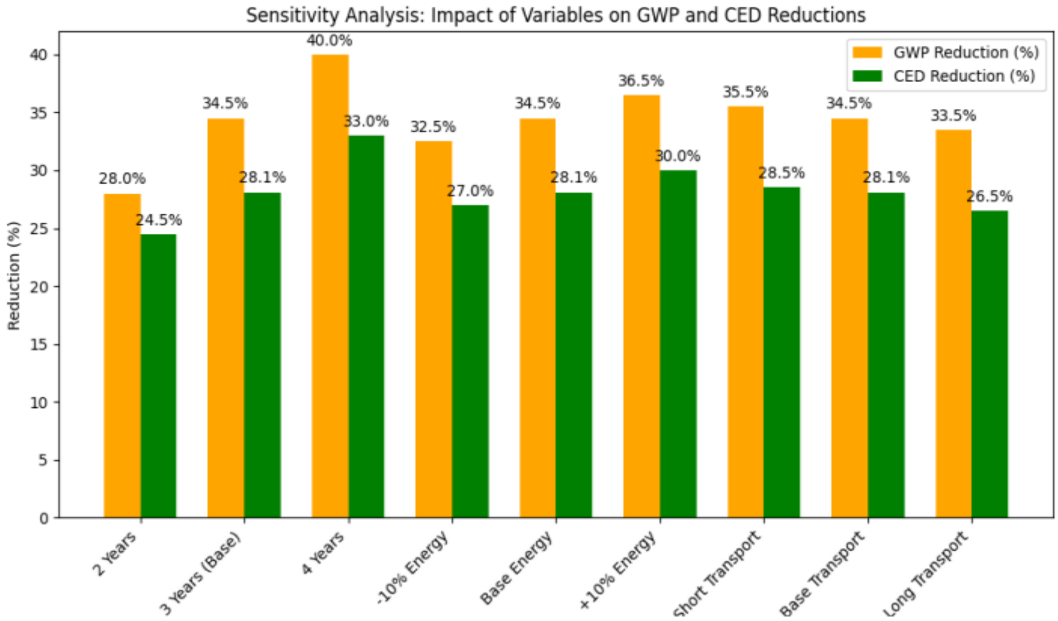

Figure 5. Sensitivity Scenarios.

4.4 Case Extension: DT-Enabled Functional Regeneration — The "Virtual Drummer"

To further illustrate the potential of functional regeneration, this study adopts the user-proposed "virtual drummer" feature as the core case within Scheme C. This function leverages the smartwatch's built-in accelerometer and gyroscope, using advanced algorithms such as Kalman filtering to precisely capture hand-motion trajectories and simulate drum sounds and striking intensity based on motion speed and orientation.

As shown in the workflow in Figure 6 and The external appearance is shown in Figure 7., the DT system converts raw sensor data into accurate posture estimation and swing detection, enabling precise digital modeling of user behavior. Integrated within the Product–Service System (PSS), the virtual drummer is offered as a value-added software service that users can access through updates without any hardware replacement. In this way, the product achieves extended functional lifespan and continuous value regeneration through software and service innovations, despite remaining within the same hardware cycle.

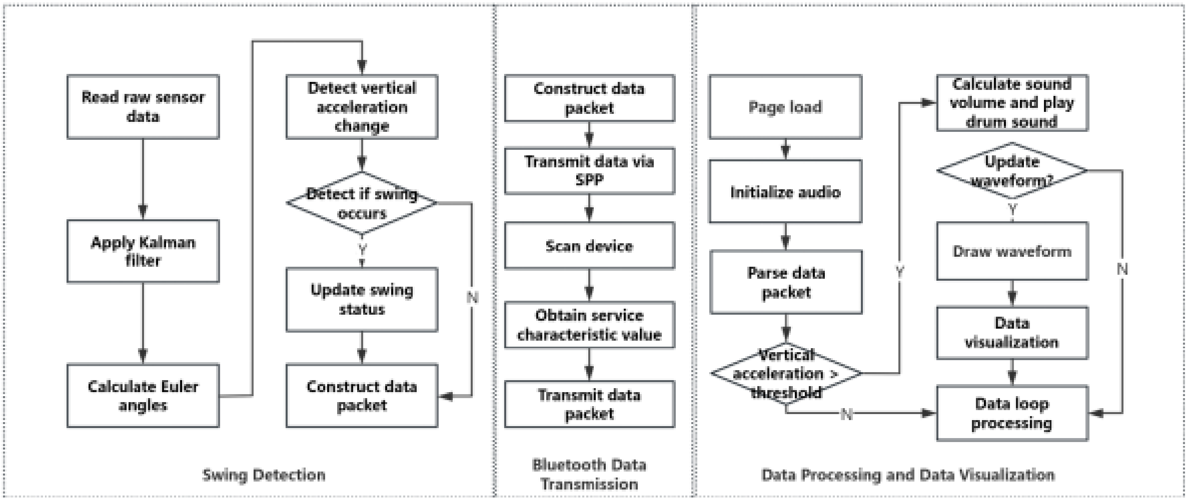

Figure 6. Digital Twin–based workflow for the virtual drummer feature.

Figure 7. External appearance of the smartwatch used for the virtual drummer feature.

5. Discussion

5.1 Insights on the Value Regeneration Paradigm

By developing and empirically validating an eco-design framework for smart wearables, this study confirms the superiority of the value-regeneration paradigm in maintainability, user-perceived value, and environmental performance. Scheme C achieves substantially lower ADT and DR, and an RPR of 78.5%, establishing modularity as the physical foundation for reuse and regeneration. With real-time 3D guidance and component-state prediction enabled by the Digital Twin, the repair process becomes standardized and more efficient, demonstrating the crucial role of digital technologies in sustainable design.

Additionally, Scheme C delivers pronounced improvements in functional lifetime and environmental impact. The “virtual drummer” case illustrates how software- and service-based innovation enables information-driven value regeneration, extending functionality without new hardware inputs. LCA results show a 34.5% reduction in GWP, driven by the extended economic and functional lifetimes of the device. Overall, the regeneration paradigm aligns physical, digital, and service dimensions, achieving sustainability outcomes beyond the traditional 4R framework and underscoring its systemic advantages for smart-wearable eco-design.

5.2 Theoretical Contributions and Practical Implications

This study advances the theoretical foundation of eco-design by shifting the focus from traditional “material circulation” to a broader paradigm of “value regeneration,” and by revealing the pivotal role of digital technologies in enabling this transition. While few studies have systematically integrated PSS and DT into an eco-design framework, this study further extends the field by proposing a Regenerate-centered methodology tailored to smart wearables. This offers a new lens for addressing the rapid obsolescence of cyber-physical hybrid products. Practically, the empirical results confirm the commercial feasibility of the regeneration strategy. The user study shows that consumers are willing to pay a premium—WTP increased by 34.3%—for enhanced upgradability, repairability, and sustainability enabled by value regeneration. These findings provide clear business incentives for manufacturers to transition from traditional one-off sales toward PSS-based models that emphasize continuous service provision and value co-creation.

5.3 Limitations and Future Research

Despite its contributions, this study has several limitations. First, the LCA analysis is based on an assumed extension of product lifetime (from 1.5 to 3 years), which should be validated through long-term real-world data in future work. Second, the user study employed a bidding-based WTP method, which, while effective, may still introduce bias; future research could incorporate actual market data to enhance robustness. Looking ahead, future studies may focus on developing more refined Digital Twin models to enable more precise predictions of component health and to further optimize remanufacturing processes, potentially incorporating user co-creation in DT-enabled environments; exploring cross-domain opportunities for functional regeneration, such as integrating smart wearables with home, mobility, or other systems to generate broader value; and investigating how user behavior evolves under PSS models—including business-model innovation for subscription-based PSS ecosystems—and how design can better motivate user participation in maintenance and upgrades. In addition, exploring emotional durability and design-for-attachment could complement regeneration strategies, alongside examining policy implications related to e-waste regulation.

6. Conclusion

This study introduces a value-regeneration–driven eco-design framework for smart wearable devices, integrating modular hardware design, Product–Service Systems (PSS), and Digital Twin (DT) technologies into a unified lifecycle approach. The framework aims to synchronize physical and digital value creation, enabling products to evolve through extended functional lifetimes and data-driven service innovation. Using a commercial smartwatch as the research object, empirical evaluations provide evidence supporting the effectiveness of the Regenerate scheme: disassembly time is reduced by 73%, the reusable parts ratio increases to 78.5%, users willingness to pay rises by 34.3%, and global warming potential is reduced by 34.5%. These findings suggest that the regeneration paradigm not only enhances maintainability and environmental efficiency but also generates substantial economic and experiential value. The study advances eco-design theory by shifting the focus from material circulation to value regeneration and provides a practical roadmap for manufacturers seeking to achieve sustainable growth through integrated digital－physical-service innovation.

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