

Lightweight Design and Sustainability Assessment of Age-Friendly Smart Wearable Devices Under the Framework of Circular Design

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Abstract:

Circular design emphasizes product disassemblability, repairability, and recyclability. Its logic of ‘extending service life’ aligns with the goals of age-friendly design, which prioritizes physical compatibility, emotional attachment, and continuity of use. Drawing on circular design theory, this paper examines the lightweight design language of age-friendly smart wearable devices and its sustainability assessment framework. The study proposes a dual framework encompassing physical lightness and perceptual lightness, and analyses lightweight design approaches across three dimensions: material sensory properties, modular structure, and interactive interface. A sustainability assessment framework is then constructed across ecological, social, and cultural dimensions. The findings suggest that circular design can extend product lifespan and reduce environmental burden while improving older users’ comprehension, maintainability, and emotional acceptance of devices, thereby offering an integrated approach to the design of age-friendly smart wearables.

Keywords:

Circular Design, Age-Friendly Design, Smart Wearable Devices, Lightweight Design, Sustainability Assessment

1. Introduction

The prevailing design paradigm for contemporary smart wearable devices takes young, healthy users as the default target, typically manifesting as slim form factors, feature-dense interfaces, and integrated enclosures. In older adult use contexts, these characteristics often translate into operational confusion, discomfort during wear, and an inability to seek repairs. A fundamental conflict exists between the ‘planned obsolescence’ culture of consumer electronics and the psychological attachment older adults form with familiar objects. Older people are reluctant to replace objects they have come to know well, yet existing device designs leave virtually no room for ‘repair’ or ‘continuation’. The physical characteristics, cognitive styles, and emotional needs of older adults are consistently marginalised in design consideration.

Circular Design requires that disassemblability, repairability, and material recyclability be integrated into the core logic of design, advocating a philosophy of ‘extending life’

rather than ‘replacing’. This resonates with older users’ emotional relationship with objects. The Global E-Waste Monitor reports that e-waste has become the fastest-growing category of solid waste: in 2019 alone, 53.6 million tonnes were generated worldwide. Due to the highly integrated structure of smart wearable devices, their recovery and disassembly is significantly more difficult than that of ordinary consumer products [1]. This paper takes circular design theory as its theoretical foundation to examine the construction of a lightweight design language for age-friendly smart wearable devices and to develop a multi-dimensional sustainability assessment framework. The central concern is how design can simultaneously respond to human fragility and the finite nature of objects in an era of concurrent demographic ageing and ecological crisis.

2. The Value Logic of Circular Design and Its Foundation for Age-Friendly Application

2.1. Intellectual Genealogy: From Design Critique to Circular Design

Circular design emerged as a distinct design concept in the sustainable design movement of the early twenty-first century, though its intellectual roots can be traced to an earlier tradition of design critique. In the 1970s, Victor Papanek argued in *Design for the Real World* that much industrial design was fundamentally engaged in manufacturing ‘planned obsolescence’—products were deliberately designed to be non-durable and difficult to repair in order to sustain consumption cycles [2]. This critique identified a core ethical problem: designers bear responsibility for the social and ecological consequences of what they create.

In contrast to the linear economic logic of ‘extract–manufacture–discard’, circular economy theory advocates redesigning material flows so that products, components, and materials retain their use value for as long as possible. William McDonough and Michael Braungart translated this vision into actionable design principles in *Cradle to Cradle*, proposing that all materials be kept within either biological or technical cycles [3]. Circular design applies these principles at the product level through three operational tiers: extending service life through repairability and modular upgrading; enabling remanufacturing and reuse at the component level; and ensuring high-quality material recovery [4].

This logic resonates with traditional Chinese material culture. The Kaogongji emphasises the appropriate use of materials and the durability of craftsmanship [5]; folk object culture is characterised by widespread practices of repair, transformation, and intergenerational transmission that constitute a vernacular tradition of circular making. Circular design and Chinese indigenous craft ethics are not disconnected—they represent expressions of the same value orientation in different contexts.

2.2. Formal, Temporal, and Relational Values of Circular Design

The significance of circular design should not be reduced to metrics such as recycling rates and carbon emissions. It is better understood as a multi-dimensional value system comprising three levels: formal value, temporal value, and relational value.

Formal value points towards structural honesty. The emphasis on disassemblability in circular design requires that a product’s external form honestly represent its internal logic of composition, such that component boundaries, connection methods, and

modular divisions are visually and tactilely legible. This goes beyond requiring that form follow function: it requires that form communicate the message that 'this object can be understood, operated upon, and disassembled'. Clear modular boundaries and intuitive connection mechanisms can reduce older users' cognitive resistance to unfamiliar objects at the visual level.

Temporal value points towards design's engagement with the full product lifecycle. Conventional product design tends to define the moment of completion as product delivery; circular design requires designers' attention to span the entire temporal arc from raw material selection through manufacture, use, maintenance, end-of-life, and material regeneration. For age-friendly wearable devices, this means design must continuously support older people's dignified use and maintenance of a device throughout its entire service life, not merely optimise the first-wear experience. The WHO World Report on Ageing and Health identifies maintaining functional capacity as the core of healthy ageing, and design intervention is identified as a key enabler of this goal [6].

Relational value points towards repair as a means of rebuilding emotional bonds between people and objects. Richard Sennett argues in *The Craftsman* that repair is grounded in familiarity with material properties and fabrication logic, and involves a deep understanding of and respect for objects [7]. For older adults, continuing to use a familiar, repaired object is not merely economical—it sustains a stable material order of life. By endowing products with repairability, circular design preserves for older users the emotional possibility of sustained companionship with objects.

2.3. Intrinsic Alignment Between Circular Design and Age-Friendly Design

The intrinsic alignment between circular design's three values and age-friendly design derives from a shared ethical point of departure: acknowledgement of and response to vulnerability. Age-friendly design acknowledges that human bodies age with time, requiring design premises based on people's actual capacities; circular design acknowledges that material quality degrades with time, requiring design that accounts for the true lifecycle of products. Both orientations confront the traces that time leaves on people and objects alike.

From the perspective of user psychology, older adults typically form strong emotional bonds with objects they have used over time, and these bonds serve an important psychological stabilising function. Circular design provides structural assurance of long-term accompaniment through repairability and modular upgrading. From a practical standpoint, the structural transparency and operational accessibility demanded by circular design closely overlap with the core requirements of age-friendly design for ease of comprehension and operation; clear modular boundaries and intuitive disassembly reinforce older users' sense of control over their devices.

The meeting of circular design and age-friendly design is a natural convergence of two value orientations that both point towards design's humanistic responsibilities, rather than a forced integration driven by policy discourse.

3. Lightweight Design Pathways for Age-Friendly Smart Wearable Devices

3.1. Dual Dimensions of Lightness: Physical Burden and Perceptual Burden

Lightness is conventionally understood as an engineering proposition: reducing material weight and structural volume. For older users, however, this proposition acquires considerably more complex dimensions. Older adults' perception of 'lightness' is not wholly determined by physical weight. A 20-gram device with a dense interface, cumbersome operation, and friction between its wearing structure and the wrist curve will still feel heavy to its user. A 30-gram device with well-distributed weight, a warm tactile quality, and clear operational logic may produce the sensation that the wearer has 'almost forgotten it is there'.

Lightweight design for age-friendly wearables must therefore distinguish between physical lightweighting and perceptual lightweighting. Physical lightweighting focuses on material and structural strategies: selecting high specific-strength, low-density materials; eliminating redundant mass; positioning the device's centre of gravity close to the wrist to avoid the sustained fatigue caused by weight offset. Perceptual lightweighting encompasses visual lightness, tactile comfort, cognitive low-load, and emotional security—dimensions that cannot be measured in grams but directly determine whether older users are willing to wear a device continuously. Both dimensions must advance in parallel and be mutually calibrated throughout the design process for genuinely age-friendly lightweight design to be achieved.

3.2. Material Lightweighting: Sensory Adaptation and Trust Building

Materials constitute the most direct interface between a device and the human body. Older adults' skin sensitivity increases with age, making them more responsive to material temperature, hardness, and surface texture; material selection is therefore simultaneously a proposition of physiological compatibility and sensory expression. The dominant materials in mainstream wearable devices—metals and rigid engineering plastics—communicate a sensory language of cold hardness and detachment, serving technological aesthetics rather than user comfort and psychological trust. This sensory language often reinforces older users' sense of unfamiliarity with technological products and impedes the formation of emotional bonds.

Circular design's ecological requirements for materials offer an alternative pathway. Bio-based polymers such as modified polylactic acid (PLA) are lightweight, present a fine matte surface texture, have lower thermal conductivity than metals, and produce no pronounced cold sensation on contact; thermoplastic elastomers (TPE) combine flexibility with recyclability and, when used in skin-contact areas, provide a soft, textile-like tactile quality that reduces friction irritation during extended wear [8]. These materials communicate warmth and trustworthiness—qualities with higher compatibility with older users' psychological expectations.

The internal tensions of material strategy cannot be ignored. Carbon-fibre composites offer exceptional specific strength and are ideal for physical lightweighting, but remain difficult to recycle under current technological conditions and their hard, cold surface properties are ill-suited to age-friendly contexts. Material selection requires continuous trade-offs among lightweighting performance, circular sustainability, and sensory age-friendliness—there is no single optimal solution.

3.3. Structural Lightweighting: Modular Division and Repairability Semantics

Modular design is circular design's core structural strategy. Dividing a device into a sensor core module, a wearable contact module (strap and housing), and an energy module (battery unit), and equipping each with non-permanent connection mechanisms, is the structural prerequisite for achieving disassemblability and

repairability. Modular design is not only a structural strategy but also a choice of formal language and an expression of design semantics.

Arnheim noted in *Art and Visual Perception* that the visual system has an innate tendency to actively seek order and holistic structure [9]. When a device's modular divisions are visually legible—with a rhythmically articulated boundary between strap and watch face, connections that honestly display their interlocking logic, and different material modules distinguished by subtle colour or texture differences—users can establish a preliminary understanding of the product's structure through visual perception, gaining an implicit sense of psychological security: this object can be understood and controlled. Connection mechanisms are the detail most capable of conveying design semantics. Adhesives and heat-welded joints communicate 'do not disassemble'; magnetic interfaces, push-fit clips, and rotary-lock structures communicate that the device can be opened and engagement is invited. For older users, the latter means not only the possibility of repair but also the sense of being anticipated and respected by the designer.

Modular design faces practical challenges: overly complex module divisions and connection mechanisms may create new operational difficulties. As older adults' fine motor ability declines with age, the granularity of modularisation and connection design must be calibrated against older users' actual operational capacities. Where necessary, 'professionally maintainable' is a more realistic goal than 'user self-repairable'.

3.4. Interaction Lightweighting: Information Reduction and Multi-Sensory Feedback

A common misconception in age-friendly interface design is that it is equivalent to reducing features, enlarging fonts, and simplifying menus. The core task of interface design is not feature reduction but the reconstruction of information priority hierarchies, so that the most important information is presented in the clearest way at the most appropriate moment. The Bauhaus principle of 'less is more' and the aesthetic of *ma* (negative space) in Japanese design both point towards a formal philosophy of strengthening core expression through restraint and white space [10]. Every pixel on screen, every haptic feedback, every audio prompt must pass a necessity test. Redundant information not only occupies visual space but consumes cognitive resources; for older users already challenged by slower cognitive processing, any unnecessary information load constitutes tangible harm to the use experience.

Reducing always-on screen time and high-frequency interaction demands directly lowers device energy consumption, extends battery life, and reduces replacement frequency—a rare convergence point where perceptual lightweighting and ecological sustainability reinforce each other.

Non-visual feedback channels equally deserve attention. Haptic, auditory, and thermal feedback constitute a multi-sensory expressive dimension beyond visual display. For older users with declining vision, an accurately timed haptic response is often more immediately perceptible than on-screen text. Rhythmically distinct vibration patterns and tonally clear audio alerts constitute a sensory language system that older users can interpret, and their design warrants the same level of attention as visual interface design.

4. Sustainability Assessment of Age-Friendly Smart Wearable Devices Under Circular Design

4.1. Assessment Framework: From Environmental Indicators to Multi-Dimensional Value

Sustainability assessment in engineering contexts is typically centred on quantifiable indicators such as carbon equivalent emissions, material recovery rates, and energy consumption data. The ISO 14040 series of standards established by the International Organisation for Standardization provides a systematic analytical tool for assessing the environmental impacts of products across their full lifecycle [11]. These indicators possess objectivity and comparability, but their limitations are equally evident: they can tell us how much carbon a device emits but cannot tell us whether its design genuinely serves the dignity of older users; they can calculate material recovery efficiency but cannot measure whether design has established a sustainable emotional bond between older adults and the material world.

Taking the formal, temporal, and relational values identified above as evaluative benchmarks and conducting a value review across ecological, social, and cultural dimensions constitutes a more complete assessment pathway. The goal is not to assign a composite score but to objectively represent the degree of realisation of circular design principles in age-friendly wearables, along with their internal tensions and practical limitations.

4.2. Ecological Dimension: Achievements and Limitations of Environmental Responsibility

Circular design's core ecological commitment is to reduce the full lifecycle environmental burden by extending product lifespan and ensuring material circulation. Substituting modified PLA and TPE for conventional metals and engineering plastics offers visible ecological advantages at both ends: the bio-based origins of raw materials and the post-disposal degradation potential. The full lifecycle carbon footprint of bio-based materials is typically lower than that of petroleum-based polymers, and their degradability under appropriate conditions offers an end-of-life disposal pathway alternative to landfill and incineration [12].

However, the ecological benefits of material strategies depend on stringent preconditions. The degradability of bio-based materials requires industrial composting conditions and cannot occur naturally in standard waste management streams; the recycling and reuse of TPE equally depends on well-developed sorting and collection infrastructure. When these conditions cannot be guaranteed, the ecological potential of materials remains at the level of design intent. Ecological sustainability is a systemic goal requiring coordinated action from product design, recovery infrastructure, and consumer behaviour alike; design strategies can create the conditions but cannot alone guarantee their realisation.

Modular structural design contributes ecologically on two levels: independently replaceable modules extend the overall product lifespan, so that localised damage need not result in whole-device disposal, directly reducing e-waste generation; non-permanent connections improve disassembly efficiency at end of life, supporting higher-quality material recovery. Yet modular design presents an internal paradox: detachable connections require a considerable number of clips, rails, seals, and magnetic elements whose varied materials are difficult to sort uniformly and which,

due to their small size, are readily missed by sorting equipment—adding complexity to end-of-life processing. How to balance the benefits of extended lifespan against the recovery costs of connector proliferation remains an open problem in the ecological dimension of circular design.

4.3. Social Dimension: The Promise and Gap of Intergenerational Equity

The social dimension of sustainability asks whether a design equitably serves the groups it claims to address. The social value of repairability, as advocated by circular design, lies in granting users a sense of autonomous agency over objects. For older adults, however, this promise faces a practical gap. As fine motor ability declines with age, to what extent can repairability genuinely translate into operations that older people can perform independently? If repair work can only be performed by professionals or younger family members, repairability undergoes a shift in meaning at the level of social practice: it retains ecological value in reducing whole-device disposal, but the social value of granting older users autonomous agency is substantially diminished under real-world conditions. This contradiction suggests that age-friendly sustainable design should not treat ‘older adults being able to repair independently’ as the sole pathway to social value realisation, but should simultaneously consider building complementary social support infrastructure, including community repair service networks, household assistance guidance, and manufacturer periodic maintenance services. Social sustainability in design is sometimes expressed not only in product form but also in the social ecology of product use and maintenance.

Intergenerational equity is another issue worth examining. Smart wearables situate older adults within a technical system underpinned by digital infrastructure; when interface design takes young users’ digital literacy as the default baseline, the technology threshold becomes a mechanism of implicit social exclusion. The WHO notes that the roll-out of digital technologies must be adapted to the actual capacities of different age groups to avoid exacerbating intergenerational health inequality [6]. The substantive significance of subtractive aesthetics and information hierarchy reconstruction is to refuse ‘accommodating’ older users through feature reduction and instead to reorganise information order through design intelligence, enabling older adults to access health management experiences on equal terms without being condescended to.

4.4. Cultural Dimension: The Dignity of Objects and Humanistic Reflection

Many age-friendly wearable devices on the current market exhibit a tendency towards ‘medicalised aesthetics’: white or grey housings, bulky and heavy forms, and interface design dominated by visual symbols such as ‘fall prevention’ and ‘emergency call’. This design language defines older adults as subjects of monitoring and protection rather than as whole individuals with aesthetic preferences and self-awareness. It reinforces older adults’ negative self-perception at a cultural level while creating psychological distance between user and device at an emotional level. A product that makes its user feel diminished, regardless of how favourable its ecological indicators may be, cannot establish a durable emotional relationship between user and object—its cultural sustainability is fragile.

A design orientation that uses gentle materials to convey approachability, restrained form to convey respect, and function concentration rather than feature reduction to convey confidence in older users’ capacities points, at the cultural level, towards

acknowledgement of older adults' full subjecthood: they are not merely subjects requiring care, but subjects with the right to possess a beautiful object that can accompany them over time. A repairable, continuable age-friendly wearable device extends not only the physical lifespan of the product but also the emotional narrative between an older person and their object. The sustainability of this narrative is a humanistic value that no carbon footprint data can capture, yet it is genuinely present.

5. Conclusions

Framing the research question as a move 'from replacement to repair', this paper introduces circular design into the study of age-friendly smart wearable devices. A dual framework of physical and perceptual lightweighting is proposed, and a lightweight design language is constructed across three dimensions: material sensory language, modular structural semantics, and interface subtractive aesthetics. A three-dimensional sustainability assessment framework encompassing ecological, social, and cultural dimensions is also established. The findings confirm that circular design holds significant value in extending product lifespan and responding to the dignity needs of older adults, while its social accessibility and end-of-life recovery efficiency face unavoidable practical tensions.

Future research on age-friendly wearable design under circular design principles may advance in two directions. First, at the material and structural level, developing bio-composite materials that combine degradability with high recyclability, and simplifying modular connection mechanisms to reduce end-of-life disassembly and sorting costs. Second, extending repairability from a product attribute into a social service, and constructing a social ecology supporting full product lifecycles through community repair networks, distributed recovery stations, and intergenerational technology transfer mechanisms.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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