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Integrating Life Cycle Assessment, Monetised Externalities and Value Alignment for Strategic Reconfiguration of Circular Business Models: The Case of Smartphones

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ABSTRACT

The smartphone industry faces sustainability challenges from greenhouse gas emissions and resource depletion to growing e-waste volumes. Circular business models have been proposed as a pathway to address these issues, yet their adoption remains limited, lacking integrative assessment frameworks that connect environmental performance with business viability. This study develops and applies such a framework combining life cycle assessment, monetisation of externalities via the eco-cost method and a structured value alignment score. Using primary data from Fairphone 5 as a case study, four scenarios with increasing levels of circularity are analysed: (S0) a linear business-as-usual baseline, (S1) extended use with moderate user-led repairs, (S2) long-life use with intensified user-led repairs and (S3) a product-as-a-service model based on manufacturer-led refurbishment. The results demonstrate that all circular business models outperform the linear baseline in terms of both environmental impacts and monetised externalities. Incremental models that extend product lifespans through user-led repair (S1, S2) yield significant reductions in greenhouse gas emissions (up to −46%) and eco-costs (−36%). However, their strategic alignment is constrained by weakened consumer value propositions and original equipment manufacturing profitability. In contrast, a product-as-a-service model (S3) achieves superior outcomes by internalising life cycle responsibility and aligning incentives with longevity and service quality, reflecting systemic reconfiguration of value logics. The study contributes theoretically by operationalising an integrated framework that bridges environmental metrics with strategic value dimensions to evaluate circular business models. Practically, it provides firms a structured tool for evaluating trade-offs and advancing scalable pathways towards a sustainable circular economy.

1 | Introduction

The rapid proliferation of mobile phones has transformed modern communication, social interaction and facilitated unprecedented digital access. Yet, their life cycle is characterised by globally dispersed supply chains that deplete finite resources, generate significant emissions and externalise social and environmental costs. This prevailing linear

This study addresses the challenge of designing effective circular business models (CBM) by developing and applying a novel integrated assessment framework to the smartphone industry. This framework synthesises quantitative life cycle assessment and monetised externalities and a semi-quantitative value alignment score to comprehensively assess the strategic viability and holistic sustainability performance of distinct CBMs. The findings reveal critical trade-offs between product longevity and CBM viability, demonstrating that systemic product-as-a-service models, which align environmental stewardship with continuous value delivery, offer a more robust pathway to a circular economy than simpler repair-focused models. Consequently, this research provides actionable insights for designing and evaluating CBMs that balance environmental, economic and strategic objectives, contributing to the development of genuinely sustainable business strategy.

'take–make–dispose' production and consumption model dominant in the mobile phone industry is emblematic of the inherent tensions between technological advancement, economic growth and environmental sustainability. With over 7.2 billion smartphones in use globally and 1.23 billion units sold in 2024 alone (Popal and Reith 2024; TechTarget Inc. 2025), this sector represents both a driver of socio-economic activity and a significant contributor to environmental degradation. Manufacturing alone generates approximately 60–65 Mt CO_2e (Kamiya and Moore 2025), whereas short product lifespans (Nøjgaard et al. 2020) and frequent new releases (Ylä-Mella et al. 2022) accelerate e-waste generation. In 2022, global e-waste reached 62 Mt, with projections suggesting 82 Mt by 2030 (Baldé et al. 2024). Despite containing valuable critical (e.g., tantalum and cobalt) and precious materials (e.g., gold and copper), only around 20% of global e-waste is properly recycled (Rizos et al. 2019; Baldé et al. 2024). The remainder is often discarded, landfilled or exported illegally, leading to severe environmental and social consequences, including hazardous substance leaching (Baldé et al. 2024).

As a response to these concerns, policymakers have introduced a range of measures such as extended producer responsibility (EPR), eco-design requirements and data transparency mandates (e.g., EU's circular economy directive, Ecodesign for Sustainable Products Regulation [ESPR], Digital Product Passport [DPP] and right-to-repair [RtR]) (Ren and Albrecht 2023; Cao et al. 2024; CircuLaw 2024; Jugend et al. 2024). Yet, the smartphone sector remains constrained by a narrow focus on end-of-life (EoL) strategies, particularly recycling while overlooking value retention strategies such as reuse, repair and refurbishment (Guo et al. 2023; Mayers et al. 2023). By adopting these strategies, circular business models (CBMs) aim to reconfigure the way in which firms create, deliver and capture value while addressing environmental, social and economic risks (Sjödin et al. 2020; Geissdoerfer et al. 2023). In practice, however, CBMs often remain abstract and detached from robust performance data, limiting their diffusion and impact (Santa-Maria et al. 2022; Geissdoerfer et al. 2023).

Established methods like life cycle assessment (LCA) and true cost accounting (TCA) can evaluate sustainability performance and provide critical data, but they are rarely incorporated into business model design or evaluation (de Giacomo and Bleischwitz 2020). Although these methods suit a product-focused linear economy, a circular economy (CE) requires LCA to analyse environmental trade-offs across the entire product life cycle, linking to value creation and capture dynamics to enable strategic decision-making (Goffetti et al. 2022). TCA, by monetising hidden environmental and social costs, makes externalities visible but similarly remains disconnected from firm-level value creation and capture logics (Michalke et al. 2025). This disconnect highlights a persistent gap—although the CE concept is conceptually appealing, it lacks integrated, holistic assessment frameworks that can bridge environmental performance, monetised externalities and strategic viability (Tura et al. 2019; Vermunt et al. 2019). Consequently, there is an urgent need for integrated assessment frameworks combining environmental, economic and potentially social dimensions, supported by robust, standardised metrics (Corona et al. 2019; Centobelli et al. 2020; van Loon et al. 2021; Jerome et al. 2022).

Therefore, the objective of this study is to address this gap by developing and applying an integrated assessment to systematically evaluate the environmental performance, monetised externalities and strategic viability of different CBMs in the smartphone sector. This approach integrates LCA and TCA within the circular business model innovation (CBMI) process using a multi-criteria scenario analysis that surfaces strategic trade-offs and guides value reconfiguration. The assessment framework is applied to the Fairphone 5, a device designed for circularity (e.g., through longevity and repairability) and aligned with policy mandates (e.g., the EU's RtR and ESPR). As the Fairphone 5 overcomes common linear product challenges, it serves as an ideal case for evaluating CBM potential while minimising hypothetical assumptions that could skew results (Hazelwood and Pecht 2021; Jugend et al. 2024). In doing so, this study makes three key contributions:

1. Firstly, it advances the literature on sustainability and circularity by integrating LCA and TCA into CBM design, showing how quantitative environmental and economic metrics can inform value creation, delivery, proposition and capture.
2. Secondly, it highlights structural misalignments between current business practices and sustainability goals, comparing four distinct CBM scenarios under harmonised functional conditions.
3. Finally, it provides empirical evidence on the trade-offs of circular strategies, demonstrating why systemic, service-based models outperform user-led initiatives in aligning environmental performance with long-term value creation.

The paper proceeds as follows. Section 2 reviews relevant literature on smartphone life cycle impacts, TCA and CBMs. Section 3 presents the conceptual framework that integrates these strands. Section 4 applies this framework to scenario-based analysis using LCA and TCA data for smartphones. Section 5 discusses strategic implications for CBM design and acknowledges the study's limitations, and Section 6 concludes by outlining the main contributions and suggesting directions for future research.

2 | Literature Review

This section outlines the conceptual foundations of CBMI and its relevance to the smartphone sector. Section 2.1 examines LCA as a diagnostic tool for identifying the environmental performance of developed CBMs. Section 2.2 introduces eco-cost accounting to monetise externalities. Section 2.3 then explores how CBMI can reconfigure value creation to operationalise circularity and sustainability.

2.1 | LCA of Smartphones: Environmental Hotspots and Limitations for Business Model Innovation

LCAs provide a granular breakdown of the environmental performance of products and services, particularly in resource-intensive sectors such as consumer electronics. Its strength lies in systematically accounting for impacts across the entire life cycle stages and highlighting environmental hotspots in resource extraction, component manufacturing, assembly, transport, use phase and EoL (Goffetti et al. 2022). In the case of smartphones, numerous studies identify upstream processes, particularly the extraction of raw materials and the energy-intensive manufacturing of components, to dominate the overall product footprint (Clément et al. 2020; Cordella et al. 2021). These studies also highlight the significant energy consumption, resource depletion (particularly critical raw materials like cobalt, tantalum, lithium and rare earth elements) (Gómez et al. 2023) and water use associated with component production and assembly (Madaka et al. 2022). The use phase, primarily driven by electricity consumption for charging and data usage, constitutes a secondary but substantial impact, heavily influenced by the local energy grid mix. Finally, although EoL management is crucial for resource recovery and for mitigating hazardous emissions such as landfill leachate (Forti et al. 2020), it generally contributes only a relatively small proportion to the total life cycle impact compared to the manufacturing stage (He et al. 2020; Bruno et al. 2022).

LCA studies further highlight the influence of product lifespan in determining cumulative environmental burdens. In the smartphone market, the prevailing trend of short lifespans, driven by rapid technological obsolescence, perceived obsolescence and limited repairability (Welfens et al. 2016; Proske and Jaeger-Erben 2019), substantially increases the per-unit footprint when impacts are amortised over time. Furthermore, studies also reveal the limitations of a narrow focus on recycling efficiency alone (Makov and Fitzpatrick 2021; Proske 2022). Although improving recycling rates is necessary, studies demonstrate that prolonging the active use phase through strategies like reuse, repair and refurbishment can deliver greater environmental benefits by avoiding the carbon- and resource-intensive manufacturing of new devices (Pamminger et al. 2021).

However, the application and interpretation of LCA in the electronics sector also reveal important methodological challenges and uncertainties. Data sources remain fragmented, with foreground data (e.g., bill of materials and energy use) sourced from OEMs, whereas background data for complex supply chains rely on generic databases, which may lack temporal or geographical representativeness (Elias Mota et al. 2020). Inconsistent system boundaries further complicate cross-study comparisons, as some LCAs focus solely on production and use phases and others include EoL or infrastructure impacts (Prado et al. 2017). Choices in life cycle impact assessment (LCIA) methods, such as regional versus global datasets, and reliance on industry average life cycle inventory (LCI) data can introduce uncertainty, with studies demonstrating that different LCA software and databases can yield significant disparities in results (Bicalho et al. 2017; Elias Mota et al. 2020). Furthermore, the complexity, time and cost of conducting LCAs, as well as difficulties in interpreting and communicating the multifaceted results, limit their integration in corporate sustainability reporting, often reducing the scope to simplified metrics like carbon footprint (Stewart et al. 2018). Most critically, for business strategy, conventional LCA is not well suited to assess business models, as it neglects economic and socio-technical factors, such as monetary flows and value-chain dynamics, essential to corporate strategy (Goffetti et al. 2022). These limitations underscore the need for standardised methodologies, enhanced data quality and expanded frameworks to improve LCA's strategic utility in the electronics sector.

Despite LCA's robustness in revealing environmental hotspots, its integration into business model innovation (BMI) is limited, especially in the fast-paced smartphone sector where innovation cycles and profit motives impede the adoption and implementation of circular strategies (Rittershaus et al. 2025). Although some manufacturers have begun to explore product life extension (PLE)–oriented interventions such as refurbishing schemes or take-back programmes, such efforts often remain inadequate, failing to enable true value retention through modularity, reuse and prolonged lifespan (Schischke et al. 2019; Kim et al. 2022).

This integration gap stems partly from LCA's product–system focus, which abstracts away from the actor-specific dynamics of value creation, delivery and capture that characterise CBMs (Bocken et al. 2014). Although LCAs quantify the merits of strategies extending the product's life cycle (Proske 2022), they offer little guidance on operational restructuring, such as shifting from product sales to service models or redistributing revenues and risks in product-as-a-service (PaaS) setups. Complementary methods in the literature address this by incorporating economic and social dimensions. This disconnect has spurred the development of integrated assessment frameworks. The most prominent one, Life Cycle Sustainability Assessment (LCSA), aims to integrate the environmental, social and economic dimensions to evaluate triple-bottom-line impacts (Stewart et al. 2018). However, the practical application of such comprehensive frameworks for guiding BMI faces its own hurdles, including exceptional complexity, data intensity and disaggregated results that are difficult for managers to transfer into strategic decisions (Elias Mota et al. 2020). This is because these broader frameworks still inherit the limitations of a conventional, product-focused LCA, failing to bridge the gap to the strategic and socio-economic drivers of a business model (Böckin et al. 2022; Goffetti et al. 2022).

Addressing this gap requires the development of integrated assessment frameworks that can align environmental insights from LCA with the strategic and organisational insights of BMI, particularly in sectors where sustainability transitions hinge on both technical redesign and operational reconfiguration.

2.2 | Eco-Costs Assessment of Smartphones: Internalising Externalities

Although LCA effectively identifies environmental burdens, it does not translate these into monetary terms. TCA offers a complementary perspective by translating environmental and social externalities into monetary terms, thereby revealing the hidden costs of production and consumption systems (Michalke et al. 2025). Rooted in ecological economics, TCA quantifies the economic costs of greenhouse gas emissions, ecosystem degradation, resource depletion, pollution or adverse social impacts that are typically excluded from traditional economic assessment and accounting practices (Bithas 2011).

Various TCA methodologies exist, ranging from damage cost approaches (estimating repair costs for environmental damages) to abatement cost approaches (estimating the cost of preventing environmental damage) (Arendt et al. 2020). Among abatement cost methods, the eco-cost-to-value ratio (EVR) has gained traction (Vogtländer et al. 2019). The strength of the EVR metrics in strategic decision-making lies in its ability to benchmark the economic value generated by a product (reflected in its market price) against the eco-costs embedded in its production and use. A lower EVR signifies a more sustainable product that delivers high economic value with relatively lower hidden environmental liabilities. Eco-costs quantify the prevention expenditure required to keep total pressures within planetary boundaries, aggregating climate change, resource scarcity, toxicity, biodiversity loss and other midpoint indicators into a single monetary metric. This prevention-oriented logic aligns well with the CE principles, emphasising proactive harm avoidance over reactive remediation. Moreover, eco-costs' reliance on publicly available characterisation factors makes the method readily comparable across products (Vogtländer 2025).

The EU and affiliated organisations have operationalised this concept by developing shadow prices for major environmental impacts such as the social cost of carbon (€/tonne CO_2) and health damages from air pollution (€/DALY). For instance, CE Delft (de Vries et al. 2025) and the European Commission reports provide monetisation guidelines for a wide range of impact categories, which can be aligned with LCA results to produce composite eco-cost profiles for products like smartphones.

Despite increasing attention to sustainable production and consumption, the integration of environmental and eco-cost assessments remains underdeveloped in the smartphone sector. Most existing studies adopt either an environmental perspective quantifying impacts through LCA or a market-oriented approach focused on direct financial costs and revenues. Rarely are these combined to reveal the full spectrum (from raw material extraction to e-waste generation) of externalised costs and potential value opportunities embedded in smartphone life cycles (Nguyen et al. 2016). Consequently, the strategic trade-offs involved in CBMs, where a reduction in environmental externalities is weighed against implementation costs or changes in revenue models, are seldom quantified in an integrated manner. This omission has two implications—firstly, it obscures the true socio-environmental burden of smartphones; secondly, it prevents firms from recognising opportunities for cost savings, resource efficiency and new revenue streams. Life cycle–extending strategies such as repair, refurbishment, leasing or component harvesting can partially offset declining sales by generating after-sales revenues while simultaneously lowering manufacturing expenditures through reduced demand for new units and components (Geissdoerfer et al. 2020). When assessed alongside the avoided external costs revealed by TCA, these internal gains offer a more comprehensive perspective on the total value proposition of CBMs.

However, eco-cost assessment is not a substitute for conventional financial analysis. Rather, it serves as a normative and strategic lens. While acknowledging the inherent ethical and methodological debates surrounding the monetisation of natural resources, its primary purpose is not to reflect firm-level profitability but to reveal distortions in market prices that systematically undervalue environmental degradation and social harm (Centemeri 2009). Making these hidden costs explicit is particularly important for CBMs, which aim to reconfigure value creation and capture around the minimisation or avoidance of systemic harms (Bocken et al. 2022). Their integration within sustainability research reflects a growing recognition that assessing environmental impacts without accounting for their broader socio-economic consequences is both analytically incomplete and ethically inadequate. By making external costs visible, eco-cost assessment provides a comprehensive basis for designing CBMs that create value by actively designing out environmental liabilities, turning sustainability from a compliance issue into a strategic value driver of innovation.

2.3 | CBMs: Reconfiguring Value Dimensions for Circularity and Sustainability

CE seeks to enhance resource productivity by narrowing (enhancing efficiency), slowing them (extending use) and closing them (reclaiming resources) material and energy loops (Kirchherr et al. 2017; Konietzko et al. 2020). However, interconnected barriers spanning financial, market, operational, organisational, policy, technological and intrinsic domains pose substantial systemic inertia, impeding CE implementation (Tura et al. 2019; Vermunt et al. 2019; Rizos and Bryhn 2022). Emerging from a technical perspective (Ferasso et al. 2020; Ahmad et al. 2023), challenges such as cost and profit uncertainty (Junge 2024), inadequate reverse logistics infrastructure (Evans and Vermeulen 2021; Thapa et al. 2023), organisational resistance to change (Makov and Fitzpatrick 2021; Ylä-Mella et al. 2022) and consumer reluctance towards non-linear consumption (Tunn et al. 2020; van der Velden et al. 2023) demand a more fundamental redesign of prevailing business models' underlying value framework rather than incremental adjustments (Tabas et al. 2025). Instead, they necessitate a fundamental redesign of the underlying business logic (Méndez-León et al. 2022), aligning with Schumpeter's concept of 'creative destruction', where disruptive innovation supplants entrenched paradigms.

CBMI serves as a critical strategic lever for this transformation, reconfiguring value creation, delivery and capture to align with CE principles (Geissdoerfer et al. 2023). To sharpen the analytical focus, this section adopts a structured typology of value dimensions drawn from business model literature and adapted for sustainability contexts (Osterwalder and Pigneur 2010; Geissdoerfer et al. 2017). We conceptualise value multidimensionally, encompassing economic (e.g., profitability and revenue streams), environmental (e.g., reduced externalities and resource efficiency) and social (e.g., stakeholder equity) aspects (Attanasio et al. 2022). These are systematically unpacked through four core business model dimensions, that is, value proposition, creation, delivery and capture, thereby illustrating how CBMI reshapes them to promote circularity.

A CBM's value proposition redefines: 'What value is provided and to whom?' (Islam et al. 2024). Unlike linear models, a circular value proposition is built on solutions that often shift away from ownership-based sales to durable, service-oriented solutions that extend product life cycles (PLC). For smartphones, this might involve modular designs enabling upgrades, paired with take-back programmes, thereby addressing environmental burdens (e.g., e-waste reduction) while creating economic value through recurring service revenues, efficiency gains and modest social benefits. Hence, developing a successful value proposition requires a deep understanding of consumer behaviour and stakeholder needs to ensure the offer is attractive (Kunz et al. 2018; Cao et al. 2024).

In this regard, value creation is the continuous process of generating this value across the entire PLC, far beyond the initial sale (Chesbrough et al. 2018; Sjödin et al. 2020). It relies on a collaborative approach where providers and customers jointly create value based on a product's ongoing value-in-use rather than its one-time value-in-exchange (Da Fernandes et al. 2020; Hunger et al. 2024). This process is driven by internal factors like enhanced managerial practices and external factors like ecosystem orchestration to facilitate value co-creation. This dimension enhances environmental outcomes (e.g., slowing loops via repairability) and social equity (e.g., inclusive innovation) while economically leveraging shared knowledge for cost efficiencies.

Value delivery involves the mechanisms and systems that transmit and maintain this value to the user throughout the PLC (Shevchenko et al. 2019). This is achieved through consistent, value-added services such as maintenance and repairs that adapt to evolving customer needs (Jaeger-Erben et al. 2021; Makov and Fitzpatrick 2021). Its success is critically dependent on factors such as durable product design, robust reverse logistics and effective PLE strategies (Achterberg et al. 2017).

Finally, value capture refers to the mechanisms a company uses to secure a return from the value it creates while redistributing CE benefits. It is the capacity of an entity to claim a share of the value generated at different points in the PLC (Chesbrough et al. 2018). This necessitates designing effective governance structures and long-term agreements to ensure the value created exceeds the cost of its delivery (Da Fernandes et al. 2020; Rizos and Bryhn 2022). Given that the roles of consumers and providers can shift, value capture strategies must also determine how the benefits of CE practices are distributed to encourage more sustainable consumption (Lopes de Sousa Jabbour et al. 2019). In CE contexts, this involves novel streams like leasing or resale royalties, balancing economic viability with environmental mitigation.

CBMI thus links product-level innovations (e.g., recyclability for closing loops) with organisational and ecosystem transformations, enabling systemic impact where linear models fall short (Boons and Lüdeke-Freund 2013; Geissdoerfer et al. 2020). To guide the transition, literature offers a wide array of CBM frameworks and typologies, often categorised into three interconnected streams: frameworks focused on CBMI, on CBM adoption and implementation and on circular supply chains (Islam et al. 2024). Whereas some innovations like enhanced recyclability (closing loops) or material efficiency (narrowing loops) might offer partial benefits within linear structures, key leverage points for slowing consumption (e.g., modularity, repairability and traceability) cannot achieve systemic impact without corresponding innovations in the underlying value framework itself (Magnier and Mugge 2022; Ylä-Mella et al. 2022).

To guide the transition towards a CE, a wide array of conceptual frameworks has emerged, which can be clustered into three main streams of research (Islam et al. 2024). The CBMI stream, focusing on the design and conceptualisation of new models, is the most developed. Its contributions range from foundational models, such as CBM archetypes and classifications, to practical applications, including a variety of adaptations of established tools like the business model canvas (Woldeyes et al. 2025). It also includes process-oriented tools offering barrier mitigation strategies, developing digitalisation and technology pathways and creating circularity assessment metrics. Furthermore, scholars have focused on categorising the distinct strategic pathways of innovation, with sector-specific variants for start-ups versus incumbent firms (OECD 2019).

In contrast, CBM adoption and implementation research investigates the organisational capabilities and ecosystem conditions required to operationalise CBMs, emphasising managerial processes, product–service transitions and ecosystem coordination (Rizos and Bryhn 2022). Specifically, it explores organisational enablers, such as capability-building for PSS (Tukker 2015) and ecosystem transitions, addressing practical hurdles like PLC management and strategic shifts towards servitisation.

Finally, circular supply chains stream, though emerging, highlights the critical inter-firm coordination and infrastructure required for circularity (Brown and Bajada 2018). It underscores the need for new forms of cooperation along the value chain, the establishment of effective reverse logistics systems and policies and the use of information technology to ensure traceability. As a result, it often functions as a supporting measure for both the major branches (Govindan et al. 2015; Islam et al. 2024).

Despite these advances on CBMs, research remains fragmented, with CBMI and implementation often being treated as distinct and isolated domains, and a significant research gap with two critical characteristics manifests. On one hand, innovation frameworks frequently assume environmental benefits based on circularity principles yet rarely subject these assumptions to quantitative validation through methods such as LCA or TCA. On the other hand, adoption-focused studies highlight contextual enablers of CBMs but offer limited analytical tools for evaluating the trade-offs that arise across economic, environmental and social value dimensions. Meanwhile, research on supply chain contributions tends to emphasise infrastructural coordination, often in isolation from broader questions of both strategic and ecological viability. This fragmentation has left the field with few integrative frameworks capable of simultaneously addressing environmental performance, monetised externalities and strategic value reconfiguration.

The framework developed in this study addresses this gap by proposing an integrated assessment that synthesises three often-siloed domains: quantitative environmental performance, monetised externalities and strategic value alignment. By bridging the divide between conceptual CBM innovation and data-driven analysis, this approach offers a rigorous tool to evaluate the real-world viability of different circular strategies in smartphones, accounting for both their environmental impacts and their strategic coherence.

3 | Methodological Framework

This study develops and applies an integrated assessment framework that systematically links environmental LCA, monetised externalities and CBM evaluation within a coherent analytical structure. The framework (depicted in Figure 1) is applied to four distinct smartphone business model scenarios. An overview of these scenarios is provided in Section 3.1.3.

The assessment framework unfolds through three cumulative and analytically interlinked layers. Layer 1 (environmental impact assessment) entails a conventional LCA based on primary data provided by the original equipment manufacturer (OEM) Fairphone B.V. This foundational stage generates detailed environmental performance metrics (greenhouse gas emissions, resource depletion, water use, etc.) and identifies critical impacts and hotspots across the PLC. Layer 2 (monetised externalities) builds upon these LCA results by translating midpoint impact indicators into monetised external costs using the eco-costs method, thus yielding a scenario-specific Eco Cost Index (ECI). Layer 3 (strategic value reconfiguration) qualitatively evaluates the extent to which each business model scenario reconfigures its underlying value framework's logic in response to environmental and economic externalities. This results in a value alignment score (VAS), which reflects the model's degree of alignment with CE principles and societal value retention. VAS incorporates multidimensional considerations, including economic feasibility (e.g., revenue streams), environmental mitigation (e.g., loop slowing/closing) and social equity (e.g., inclusive access). See Table S1–S4 for the scoring rubric.

Together, the ECI and VAS constitute a two-dimensional performance space that informs the comparative assessment of the four business model scenarios. This integrated approach provides the necessary structure to move beyond description towards empirically grounded, actionable guidance for fostering genuinely sustainable consumption patterns in the smartphone industry (Corona et al. 2019; Centobelli et al. 2020). The subsequent sections detail the specific implementation of each stage within this framework, beginning with the description of the case study design.

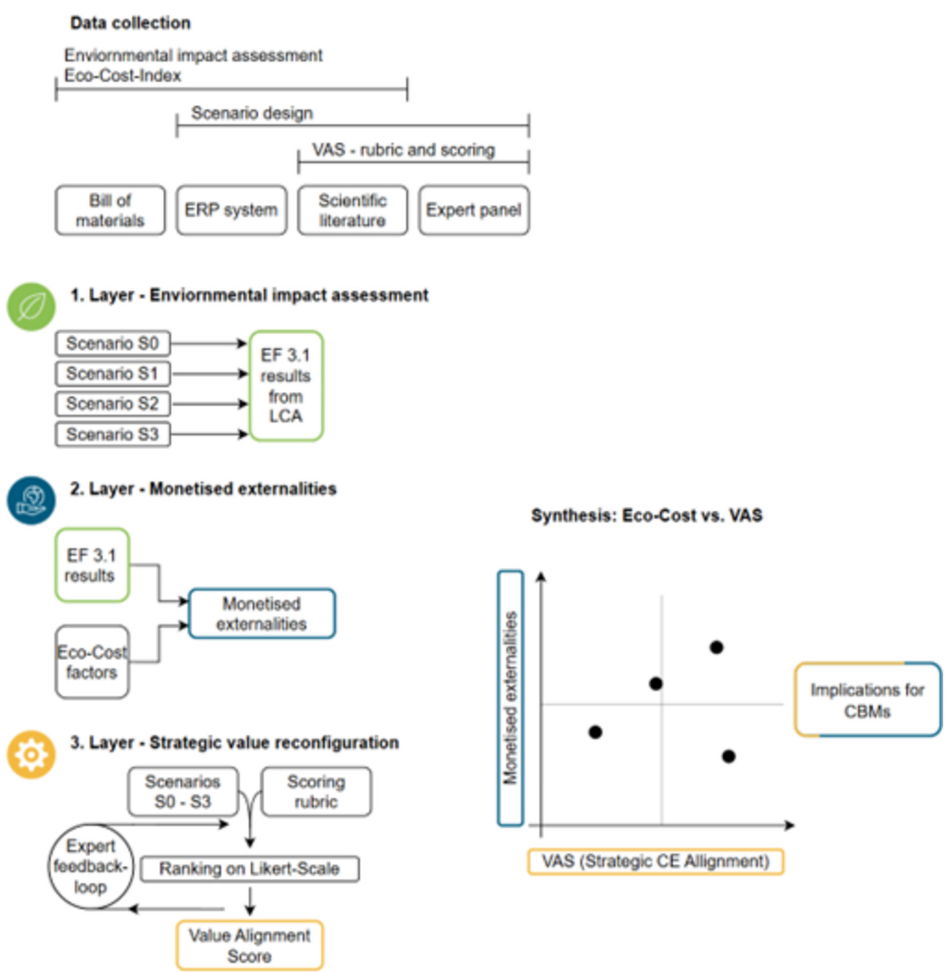

FIGURE 1 | Integrated assessment framework.

3.1 | Case Study Design

3.1.1 | Case Selection

This study employs an in-depth single-case analysis to move beyond theoretical propositions and provide robust empirical evidence on the performance of CBMs. We intentionally selected the Fairphone 5 as an exemplary case because it embeds circular principles throughout its life cycle. The company actively fosters circularity from ethical material sourcing and modular production to the end-of-use reclamation. Crucially, the device is designed for a long life and easy repair, and the company provides the complete underlying infrastructure, including spare parts, manuals and repair services. This ecosystem not only enables circular value flows (creation, delivery and capture) but also empowers diverse stakeholders, from users to recyclers, to participate actively.

This case thus provides a benchmark for what is possible under optimal conditions, enabling focused analysis of CBMs without the confounding effects of product design limitations or hypothetical assumptions. The primary goal of this approach is to offer a clear, evidence-based case study that can inform and inspire other stakeholders to adopt and pursue similar circular efforts.

3.1.2 | Scope, Assumptions and Data Sources

To provide a robust quantitative basis for the analysis, an LCA was conducted in accordance with ISO 14040 and 14044 standards. The following sections detail the methodological design choices, assumptions and data sources used.

The goal of the LCA is a cradle-to-grave comparison of four business model scenarios for the Fairphone 5. The system boundary encompasses all relevant life cycle stages, from raw material extraction and component manufacturing to device assembly, distribution, use and EoL management. Key exclusions from the system boundary include peripheral accessories (e.g., chargers, screen protectors and cases) and supporting digital infrastructure (e.g., mobile networks). This is justified on the basis that these are assumed to be consistently used across all scenarios, thereby not affecting the comparative outcome.

Primary data are drawn from Fairphone B.V.'s enterprise resource planning (ERP) system, supplemented by secondary sources like ecoinvent v3.10 for upstream processes. Assumptions on energy use, transport modes and EoL recovery rates are conservatively parameterised based on Fairphone's operational data and EU averages. Table 1 summarises all data sources and the life LCI is elaborated in the SI ‘Life cycle inventory (LCI)’ data.

3.1.3 | Scenarios Under Investigation

The scenarios investigated in this study are deliberately constructed from the perspective of the OEM. This choice reflects

TABLE 1 | Data sources for the integrated assessment.

		Scientific literature	LCA databases	Fairphone primary data	Fairphone representative	Researchers in the field of sustainability
Scenarios	Data for CBM scenarios	X		X	X	X
	Data on user patterns	X		X	X	
Environmental impact assessment	Inventory data on Fair Phone 5		X	X		
	Inventory data on distribution		X	X		
	Inventory data on use phase	X	X	X		
	Inventory data on repair efforts		X	X	X	
	Inventory data on end of life	X	X	X	X	
Monetised externalities	Eco-cost factors	X				
	Minerals, metal and fossils demand	X		X	X	
Value alignment score	Scoring rubric	X			X	
	Scoring					X

OEMs' decisive control over product design features and supporting service infrastructure, both of which are critical enablers of circularity (Rittershaus et al. 2025). The scenarios draw on ERP data, which reflect real-world practices and are also informed by forward-looking strategies for circular transitions. This OEM-centric lens facilitates a direct examination of strategic choices and operational levers available for CBM implementation, aligning with recent calls for more practice-oriented CBM research (Santa-Maria et al. 2022; Geissdoerfer et al. 2023). Moreover, regulatory frameworks such as EPR and RtR place clear obligations on OEMs, reinforcing their central role in circular transitions (Rizos and Bryhn 2022). Although CBM success depends on ecosystem-wide participation, the consumer perspective is excluded at this stage to maintain focus on the strategic levers within OEM control; its significance will be acknowledged in future analysis.

The four scenarios presented represent progressively more CBMs, differentiated by product lifespan, repair strategies and value propositions (see Table 2).

- S0 (Baseline linear sales) reflects a conventional linear sales model with a 3-year lifespan and no formalised repairs, mirroring conventional smartphone disposability.
- S1 (Extended use) is an extended-use model relying on user-led repairs to achieve a 5-year product lifespan. This emphasises slowing loops via accessible OEM provided DIY kits.
- S2 (Long life) is a maintenance-oriented model achieving a 7-year lifespan through extensive user-led repairs, including an additional DIY battery replacement. This scenario enhances durability and resource retention.
- S3 (Product-as-a-service) is a PaaS leasing model enabling a 9-year lifespan, which integrates professional maintenance and modular upgrades to ensure the device remains up-to-date.

3.2 | Framework in Detail

3.3 | LCA

In the first step, to provide a robust quantitative basis for comparing CBM scenarios, an LCA was conducted in accordance with ISO 14040 and 14044 standards (ISO 2006a, 2006b). The assessment evaluates each scenario's potential environmental impacts relative to the baseline. The functional unit (FU) is defined as 3 years of smartphone use, which allows for a fair comparison across scenarios with differing product lifespans. In LCA, the FU represents a quantified description of the performance a product, service or product system fulfils. In this study, the FU, which serves as the reference basis for all calculations, is defined as the use of one Fairphone 5 device by an end-user over a 3-year lifespan. The system boundaries are cradle-to-grave, encompassing raw material extraction, manufacturing, distribution, use, repair and EoL treatment. For scenarios involving repair, refurbishment and product–service systems, the boundary is extended to include second-life usage and associated logistics. Primary data were drawn from Fairphone's

TABLE 2 | Scenarios investigated.

	S0: Baseline	S1: Extended use	S2: Long life	S3: Product–service system
Lifespan per device	**3 years**	**5 years**	**7 years**	**9 years**
Repairs/ replacements	None assumed	1× average repair efforts—**DIY**[a]	1× average repair efforts—**DIY**[a] 1× battery—**DIY**[a]	2× average repair efforts—**as Service**[b] 1x refurbishment (battery, display, back cover and camera)—as **Service**[b]
Modularity utilisation	Not utilised by average user	Primarily leveraged for repair by users	Primarily leveraged for longevity through repair/ maintenance by users	Leveraged for repair, functional upgrading and aesthetics by service provider
End-of-life potential	Characterised by fragmented EoL pathways, low formal collection rates, and a high propensity for device hoarding or informal disposal, resulting in minimal material value recovery and significant potential for resource loss	EoL management relies on conventional processing routes, though increased user engagement from DIY repairs may marginally improve responsible disposal practices for the device and replaced components	Enhanced user commitment to the device's longevity might foster more conscious EoL decisions, potentially increasing participation in formal collection and recycling schemes	Significant EoL advantages through OEM-controlled or incentivised take-back inherent in the PaaS model, leading to potentially high collection rates for both the main device and replaced/upgraded modules; counter-effect: increased EoL burden from more frequent cosmetic component replacements

[a]Parts are being sent to consumer, who engages in **Do-It-Yourself** repair using the manuals provided.
[b]PPS allows for extended **Service**; consumer sends device to repair centre.

comprehensive bill of materials for the Fairphone 5, comprising over 6700 components.

Although the study covers a comprehensive set of 16 environmental impact indicators, nine impact categories emerge as more critical owing to their relevance to the environmental profile of smartphones (Clément et al. 2020; Sánchez et al. 2024). These are acidification, climate change, resource use, human toxicity, ozone depletion, particulate matter, freshwater ecotoxicity and water use. For example, climate change is critical due to the high-energy demand during manufacturing and use (Sánchez et al. 2024). Resource use reflects the dependence on scarce and critical materials. Human and freshwater ecotoxicity account for harmful emissions from mining, component manufacturing and improper EoL treatment (Baldé et al. 2024). Cumulative energy demand provides an overarching measure of energy throughput, capturing both direct and embedded energy flows. Finally, water use reflects the burdens from mining.

3.3.1 | Eco-Cost Assessment Monetising Externalities

In the second step, to enable the integration of environmental performance of the investigated scenarios into broader economic evaluations, this study employs eco-cost analysis to monetise environmental impacts derived from LCA results. The eco-cost methodology is grounded in the principle of prevention costs, whereby environmental burdens are expressed as marginal costs of mitigating emissions and resource depletion to levels that remain within the Earth's ecological carrying capacity (Vogtländer 2025). These costs are based on the investments required to implement best available technologies for pollution prevention, remediation and resource conservation. The eco-cost factors used in this study are provided in Supporting Information S3 and S4.

For each impact category, the eco-cost per smartphone scenario C_i is calculated:

$$C_i = I_i * P_i$$

where

I_i is the LCA derived impact (e.g., kg CO_2e),

P_i is the corresponding eco-cost price (€/kg CO_2e),

C_i is the resulting external cost in euros.

This produces an eco-cost profile per scenario, allowing direct comparison of the monetised environmental burden of each business model configuration. These data are then aggregated and weighted into a composite ECI:

$$ECI_s = \sum_{i=0}^{3} w_i * C_{i,s}$$

where w_i represents weightings based on business model priorities or policy relevance and $C_{i,s}$ is the cost of impact i for a scenario s. This output facilitates direct comparison of hidden environmental cost and serves as a crucial input for the subsequent synthesis. In the presented study, w_i is set to 1 for all indicators and therefore not considered.

3.3.2 | Circular Value Logic Alignment Score

To complement the quantitative assessment results, this study introduces the VAS, a semi-qualitative metric that evaluates to what extent each CBM scenario aligns with broader CE objectives. In achieving that, the VAS assesses each scenario for its capacity to structurally reconfigure the four value dimensions of creation, proposition, delivery and capture to align with circularity principles (Evans et al. 2017; Méndez-León et al. 2022).

The applied scoring rubric is not arbitrary, but based on 20 sector-specific indicators, developed and weighted through a multi-step process that included:

1. An extensive literature review (Rittershaus et al. 2025) to identify the frequently identified barriers and enablers for circular transitions in the electronics sector.
2. An analysis of empirical data from the case company to ground the indicators defined in operational realities.
3. Iterative feedback by, industry experts, OEM representatives and researchers to validate and refine the relative importance of each indicator. The final weightage represents an average of all responses. Although this validation process adds rigour, it is important to acknowledge that the final scoring still involves a degree of expert judgement.

$$VAS_s = \sum_{D=1}^{4} w_{D^*}\left(\sum_{i=1}^{5} w_{i|D} * S_{i|D,s}\right)$$

Each scenario was evaluated against every indicator by an expert panel, using a 0–5 Likert scale (0 = *no alignment*; 5 = *optimal alignment*), with scores substantiated by scenario-specific attributes (e.g., design for longevity an repair infrastructure). The VAS for a given scenario is calculated as follows:where

D denotes the four value dimensions,

w_D is the weight of dimension D,

$w_{i|D}$ is the weight of indicator, within dimension D,

$S_{i|D,s}$ is the score for scenario s for indicator in dimension D,

In the presented study w_D set to 1 for all dimensions to ensure neutrality and comparability between the scenarios. However, depending on the stakeholder's inherent motivation, role or field of influence within the value chain, these weightings can be adjusted to better reflect their specific perspective.

Table 3 presents the full set of indicators used in the VAS assessment. In the concluding step, VAS results are plotted against the monetised environmental externalities (ECI) to visualise trade-offs across scenarios. This matrix (ECI vs. VAS) identifies CBM configurations that achieve high strategic CE alignment at comparatively lower societal environmental cost, offering a robust basis for guiding scenario selection and informed BMI in the smartphone sector.

Although the VAS allows for weightings to be applied the four value dimensions, for this initial study, a deliberate choice was made to weight them equally ($w_D = 1$). This approach ensures a balanced, baseline comparison without pre-judging the strategic priority of one dimension over another (Méndez-León et al. 2022; Tapaninaho and Heikkinen 2022). Furthermore, it reflects the highly interconnected nature of CBMs, which involve complex reverse loops and a multitude of shifting stakeholder roles (Norris et al. 2021; Civera et al. 2025).

Because the relative strategic importance of these dimensions ultimately depends on the priorities of the OEM or the specific business context, this study deliberately refrained from imposing differentiated weights ex ante. Equal weighting thus preserves neutrality and comparability across scenarios while acknowledging that in practice firms may adapt the weighting logic to reflect their chosen strategic orientation. Future applications of the framework could integrate such context-specific weighting through stakeholder or expert consultation.

A detailed description of the methodology, including the full list of indicators and their corresponding weights, is provided in Supporting Information S12 and S13.

TABLE 3 | Indicators applied in the VAS assessment, structured by value framework dimensions.

Value dimension	Indicators				
Value creation	**Enhanced design for CE**	**Stakeholder ecosystem enablement**	**Resource use reduction potential**	**End-of-life value recovery potential**	**Rebound effect mitigation strategy**
Value delivery	Prioritisation of higher R-strategies	Transparency and information flow	Reverse logistics and take-back optimisation	Repair and service ecosystem facilitation	Integration of third-party actors
Value capture	Active consumer role enablement	Alignment with regulatory framework	Economic viability assurance	Potential for value re-capture at EoLs	Cost/benefit sharing potential
Value proposition	Promotion of sufficiency	Technological relevance and competitiveness	Price competitiveness and value communication	Building consumer trust and overcoming stigma	Enhanced service offerings

3.3.3 | Case Context and Methodological Transferability

Although the VAS provides a structured means of evaluating how business model scenarios align with circular value logic, few limitations and methodological choices must be acknowledged. Firstly, the assignment of scores on a 0–5 scale involves qualitative judgement and thus carries an element of subjectivity. To mitigate this, scoring was guided by a structured rubric derived from sector-specific CE literature and scenario attributes (Rittershaus et al. 2025) and was further subjected to expert review. An Excel-based scoring sheet was circulated among domain experts, who provided independent ratings and feedback, which were subsequently integrated to refine the scoring rubric. This step improved consistency and reduced evaluator bias, though more formal inter-rater reliability testing could strengthen future applications.

Secondly, although the framework allows for a hierarchical weighting structure, equal weights were applied across all value dimensions (creation, delivery, proposition and capture). This decision ensures a balanced, baseline comparison without prejudging the strategic priority of one dimension over another (Méndez-León et al. 2022; Tapaninaho and Heikkinen 2022) while reflecting the interdependencies of CBMs that involve reverse flows and shifting stakeholder roles (Norris et al. 2021; Civera et al. 2025). Each dimension represents a distinct but equally critical lever of circular transformation—creation (e.g., reuse and modular design), delivery (reverse logistics and extended life cycles), proposition (durability, ethical sourcing and sufficiency) and capture (service models and avoided externalities). In practice, firms or policymakers may prioritise dimensions differently; future applications could therefore adopt context-specific weighting through stakeholder or expert consultation.

Finally, although the indicators used here were tailored to the smartphone sector to capture contextual barriers and enablers of circularity, the overall structure of the framework is generalisable. Application to other industries would, however, requires sector-specific adaptation of indicators and potential recalibration of weighting schemes. Broader validation, including stakeholder workshops or triangulation with empirical performance data, would further enhance the external validity and practical relevance of the VAS.

4 | Analysis of Results

This chapter presents the results from the application of the integrated assessment framework. The findings are presented sequentially: first, the LCA outcomes (Section 4.1); second, their monetisation into eco-costs (Section 4.2); and third, the strategic circularity alignment quantified by VAS (Section 4.3). The chapter concludes with a comparative synthesis of these metrics through an eco-cost versus VAS matrix (Section 4.4) to illustrate how CBM configurations perform in direct comparison.

4.1 | Comparative LCA Results: Environmental Impact Profiles of the Investigated Scenarios

The LCA quantified the cradle-to-grave environmental burdens of the baseline scenario (S0: Business-as-usual) and three distinct CBM scenarios (S1, S2 and S3) across sixteen EF 3.1 impact categories (Table 4) (Zampori and Pant 2019). Results for nine categories that are of particular relevance (Zink et al. 2014; Ercan et al. 2016; Clément et al. 2020) to smartphone manufacturing and resource extraction are summarised in 4. Disaggregated LCA results for all remaining impact categories are detailed in Supporting Information S1 and S2.

Across all scenarios, the manufacturing and resource-extraction phases dominate the life cycle impacts. However, extending the PLC through circular strategies (CBMs) yields substantial reductions in environmental burdens. For the impact category climate change, scenario S0 exhibits the highest greenhouse gas emissions (GHGs), whereas S1–S3 achieve progressively lower burdens. S1 reduces GHGs by 32% relative to S0, and S2 and S3 by 46% and 48%, respectively (see Figure 2). When exploring other impact categories (4), scenarios S2 and S3 are the most favourable. Both scenarios achieve the lowest total impacts, with particularly pronounced reductions in 'freshwater ecotoxicity', 'fossil resource use' and 'water use'. Furthermore, they demonstrate substantial improvements in other key impact categories, reducing impacts for 'acidification' and 'particulate matter' by over 50% and for 'ozone depletion' by an even greater margin of 60%.

Notably, although S3 entails more extensive refurbishment and achieves a longer operational lifetime, its slightly higher upstream resource and energy demands largely offset the anticipated benefits of the extended use phase. In contrast, S2's more limited repair interventions deliver comparable life cycle improvements with lower refurbishment intensity. This suggests that the anticipated environmental benefits of S3's extended lifespan are largely counterbalanced by the higher resource and energy intensity associated with its comprehensive refurbishment activities, including cosmetic elements and extensive service offerings, compared to the limited repair interventions in S2. Nonetheless, the analysis of the results for both scenarios indicates a consistent and significant trend of

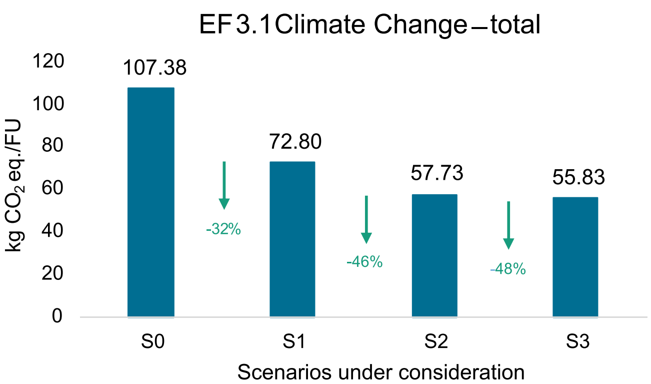

FIGURE 2 | Carbon footprint profiles of the investigated scenarios.

TABLE 4 | EF 3.1 results for scenarios under consideration.

	Scenarios under consideration			
Impact categories	**S0**	**S1**	**S2**	**S3**
EF 3.1 Acidification [mole of H + eq.]	0.45	0.29	0.22	0.22
EF 3.1 Climate change—total [kg CO_2 eq.]	107.38	72.80	57.73	55.83
EF 3.1 Ecotoxicity, freshwater—total [CTUe]	605.35	406.23	318.95	316.05
EF 3.1 Human toxicity, cancer—total [CTUh]	2.38E-05	1.75E-05	2.00E-05	1.90E-05
EF 3.1 Ozone depletion [kg CFC-11 eq.]	3.14E-06	1.91E-06	1.38E-06	1.15E-06
EF 3.1 Particulate matter [disease incidences]	4.91E-06	3.14E-06	2.38E-06	2.34E-06
EF 3.1 Resource use, fossils [MJ]	1662.40	1152.53	930.49	906.10
EF 3.1 Resource use, mineral and metals [kg Sb eq.]	0.004	0.002	0.002	0.001
EF 3.1 Water use [m^3 world equiv.]	23.67	15.95	12.92	13.13

improved environmental performance with the adoption of circular strategies and more efficient resource utilisation over an extended PLC.

Although the LCA findings provide critical insights into the relative performance of the assessed CBMs, they do not capture environmental externalities or strategic alignment within a broader CE framework. To address these gaps, the life cycle impact assessment results presented here will be combined with an eco-cost monetisation analysis in the next stage, yielding a more holistic evaluation of the CBM scenarios.

4.2 | Integration of Eco-Cost Metrics

To complement the LCA, the scenario-specific impacts were translated into monetary values using an eco-cost assessment. While standard conversion factors from the Eco-Cost V3.0 database (Vogtländer et al. 2019) were directly applicable for most EF 3.1 impact categories, depletion indicators for fossil resources and for minerals and metals required custom factor derivation owing to the lack of universally accepted unit costs.

For fossil resource depletion, this involved accounting for polymers (using the bill of materials [BoM] of 6700 components) as well as fuel consumption for transportation. Transport impacts were differentiated for DIY and PSS repair models, accounting for initial production, spare parts and service-related transport. For mineral and metal depletion, the device's material composition, derived from the FMD, was used to identify more than 50 distinct elements.

A key finding from the eco-cost assessment is the pronounced divergence between material mass contribution and monetised environmental burden. For example, aluminium, the primary contributor by weight (~37 wt%), has a relatively modest eco-cost (~1.9%). In contrast, gold, present in trace amounts (~0.03 wt%), overwhelmingly accounts for 45.6% material-related eco-costs. This is primarily due to the high-energy intensity, extensive ore processing and significant pollution associated with extracting and refining such precious metals from low-grade ores. Similar, though less pronounced, observations were made for cobalt, terbium, silver and palladium—elements crucial for electronic functionalities but associated with substantial environmental prevention costs relative to their mass.

A detailed listing of all minerals and metals, by weight and eco-cost, is provided in the Supporting Information S5. Analysed material flows are further visualised in the Sankey diagram located in the Supporting Information S6. The aggregated eco-cost results for the baseline S0 and CBM scenarios S1–S3 are summarised in Table 5, and a disaggregated version is available in Supporting Information S7.

The results indicate that the total eco-cost (ECI_s) decreases markedly with increasing circularity. Scenario S0 incurs the highest eco-cost of €66.17. The circular scenarios offer substantial reductions, with S1 at €45.49 (−31%), S2 at €41.42 (−36%) and S3 achieving the lowest total eco-cost at €41.01 (−38%). Across all scenarios, the largest monetary burdens stem from human toxicity, climate change, water use and mineral and metal resource depletion. The progressive decline in eco-costs from S0 through S3 reflects the benefits of CBMs.

TABLE 5 | Total eco-cost per scenario.

Eco-cost category using EF 3.1 (I_i)	Scenarios under consideration $C_{i,0}$	$C_{i,1}$	$C_{i,2}$	$C_{i,3}$
Acidification	€3.47	€2.24	€1.71	€1.66
Climate change—total	€16.11	€10.92	€8.66	€8.37
Ecotoxicity, freshwater—total	€1.75	€1.17	€0.92	€0.91
Human toxicity, cancer—total	€21.86	€16.12	€18.40	€17.52
Particulate matter	€0.72	€0.46	€0.35	€0.34
Resource use, fossils	€0.27	€0.18	€0.14	€0.18
Resource use, mineral and metals	€6.11	€3.88	€3.60	€3.54
Water use	€10.42	€7.02	€5.68	€5.78
Others[a]	€ 5.46	€ 8.23	€ 5.54	€ 4.34
Total eco-Cost (***ECI****s*)	€66.17	€45.59	€42.26	€41.01

[a]Other represents the sum of monetised impacts from the remaining EF 3.1 categories not explicitly listed.

Although S3 achieves the lowest overall eco-cost, its €1.25 advantage over S2 is marginal despite two extra years of service life. This narrow gap arises due to S3's comprehensive refurbishment under the product-service system model, which includes cosmetic replacements, repairs and upgrades. These carry higher resource intensity and environmental prevention costs that partly offset the use-phase gains. In contrast, S2's more targeted repair interventions deliver nearly equivalent environmental benefits at a lower refurbishment burden.

It should be noted that the primary source of uncertainty in the eco-cost assessment lies in the device's material composition, rather than the eco-cost factors themselves. The latter are derived from prevention-based abatement costs, which are deemed to be more stable than market-based commodity prices and therefore less sensitive to short-term pricing volatility. Nevertheless, due to complex alloys and the proprietary nature of supplier data, approximately 1 wt% of the device's mass is unspecified. While numerically minor, this missing fraction's potential impact is significant, as trace materials like gold carry disproportionately high eco-cost. However, this risk is partially mitigated as the entire mineral and metal depletion category accounts for only about 10% of the total eco-cost in the baseline scenario (S0). Consequently, any underestimated eco-cost would affect linear scenarios more heavily, thereby strengthening the findings that favour CBMs.

Additional uncertainties arise in the derivation of custom eco-cost factors for fossil and mineral resource depletion. Here, assumptions regarding average ore grades, processing intensities and substitution potentials may affect the precision of absolute values. Similarly, although transportation distances, repair frequencies and device failure rates were obtained from Fairphone's ERP system and are thus highly reliable, these operational parameters may not be fully generalisable beyond the case context.

To address such limitations, the eco-cost results should be interpreted as indicative magnitudes and comparative trends rather than exact economic values. The strength of the method lies in its capacity to consistently monetise diverse environmental burdens into a unified metric, thereby enabling systematic scenario comparison. To summarise, whereas uncertainties in input data and cost factor derivation remain, CBMs consistently reduce eco-costs relative to the linear baseline, even under conservative assumptions.

4.3 | Value Alignment Score

This section presents the findings of the value alignment score (VAS) assessment. The VAS provides a qualitative appraisal of each scenario's strategic alignment with core CE principles, specifically its capacity to create, deliver and capture value in a closed-loop system. Table 6 reports the aggregated VAS for each scenario, with criterion-level breakdowns available in Supporting Information S8–S11 and summarised in Supporting Information S13.

Scenario S0 (VAS: 6.75) exhibits the weakest CE alignment. As a conventional sales model with a 3-year lifespan and no repair options, its score reflects minimal engagement with circular value creation, delivery, proposition or capture.

Introducing DIY repairs and extending product lifespan in scenario S1 (VAS to 11.50), with increases across all four value dimensions, highlighting the initial strategic value in enabling PLE. The most significant gains occur in value creation (through product longevity and repairability), value delivery (via more accessible repair options) and value capture (through modest improvements in economic viability). By contrast, value proposition shows only marginal improvement, indicating that extending lifespan through DIY repair enhances operational and structural aspects of circularity more than it strengthens the perceived attractiveness of the offering. Overall, S1 highlights the strategic potential of enabling PLE while also revealing the limits of such interventions in reshaping the value proposition.

Scenario S2 (VAS: 11.15) extends the lifespan further to 7 years, but its VAS is marginally lower than S1. This stems from weaker performance in value capture and value proposition. Specifically, the longer span of 7 years undermines 'economic viability assurance' for the OEM and reduces 'technological relevance and competitiveness' for consumers. These trade-offs illustrate that merely extending PLC through user initiative, without concurrent business model innovations that sustain both consumer value and OEM returns, may yield diminishing returns in strategic CE alignment.

Whereas environmental performance improves, business viability and consumer appeal can weaken, thereby constraining broader adoption of such models. This finding highlights that environmental gains do not automatically translate into stronger strategic alignment. This could risk undermining the circular offerings' overall attractiveness and perceived viability. By contrast, scenario S3 (VAS: 17.10) achieves the highest score, reflecting systemic reconfiguration as a PaaS model. S3 excels in value delivery and enhances the value proposition (e.g., maintaining technological relevance and novelty through periodic upgrades and comprehensive service offerings). By internalising life cycle responsibilities and realigning OEM incentives around longevity and service quality rather than unit sales, S3 demonstrates a more robust framework for creating and capturing value for all stakeholders.

TABLE 6 | Overview of achieved VAS per scenario.

	S0	S1	S2	S3
$VAS_{Value\_Creation}$	0.45	2.3	2.85	4.35
$VAS_{Value\_Delivery}$	1.25	2.80	2.80	4.65
$VAS_{Value\_Capture}$	2	3.25	2.65	4
$VAS_{Value\_Proposition}$	3.05	3.15	2.85	4.1
VAS_{Total}	**6.75**	**11.50**	**11.15**	**17.10**

4.4 | Synthesis: Eco-Cost Versus VAS

The final synthesis juxtaposes the monetised environmental externalities (total eco-cost) with the strategic CE alignment (VAS) for each scenario (Figure 3). This dual-axis evaluation provides a more holistic understanding by mapping each scenario's performance in terms of sustainability against strategic responsiveness within a sustainable CE transition.

The baseline scenario, S0, evidently represents the least desirable option, incurring the highest environmental burden (€66.17) while exhibiting the lowest VAS (6.75). Scenario S1 demonstrates a significant improvement in both parameters compared to S0, reducing eco-costs by approximately 31% while increasing VAS by 70%. This demonstrates the considerable benefits that can arise from relatively simple circular interventions such as DIY repairs and moderate lifespan extension.

Scenario S2 offers a further reduction in environmental burden (€42.26), making it the second most favourable scenario from a purely monetised externalities perspective. However, its slightly lower VAS (11.15) compared to S1 (11.50) highlights a crucial trade-off. Although S2 is environmentally more efficient per FU over its extended PLC, its strategic alignment and perceived CBM viability show a marginal decline. This finding suggests that optimising for environmental performance alone, without ensuring that the CBM remains attractive and economically sustainable for key stakeholders, may not lead to the most effective CE transition or foster widespread adoption of sustainable practices.

In contrast, scenario S3 emerges as the most promising CBM. Although its total eco-cost (€41.01) is only marginally lower than S2, it substantially outperforms all other scenarios in terms of strategic value alignment (VAS: 17.10). This synergy reflects the systemic advantages of the PaaS model (Da Fernandes

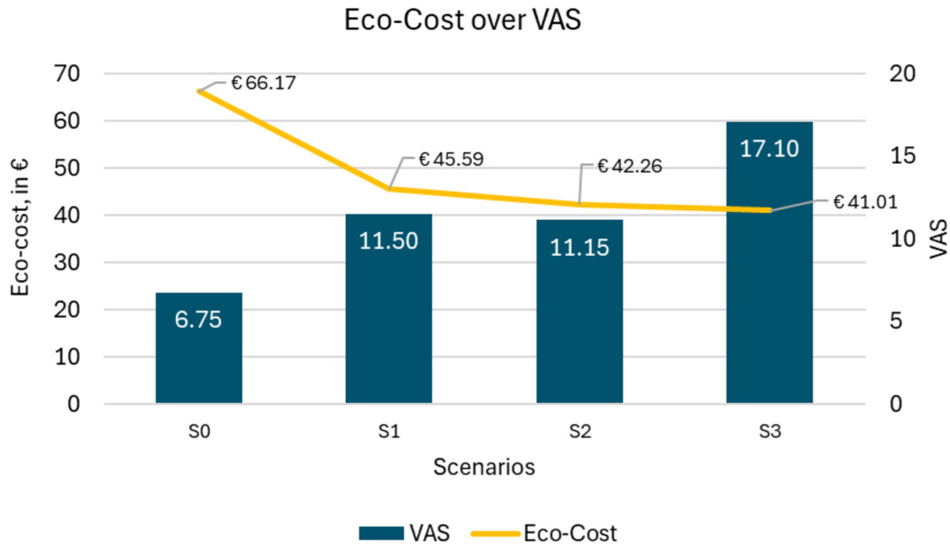

FIGURE 3 | Scenario-wise comparison of burdened eco-cost versus achieved VAS.

et al. 2020), which combines life cycle responsibility with integrated service delivery and continuous value enhancement (e.g., upgrades, maintenance and user experience improvements). S3 thus represents the most promising pathway towards achieving an outcome favourable for CE adoption, where enhanced strategic circularity is coupled with superior environmental performance.

Despite its strong performance, the practical viability of the PaaS model (S3) is constrained by several real-world challenges. Tailoring a compelling value proposition is the primary hurdle, as it must overcome deeply ingrained consumer preferences for product ownership and concerns about long-term costs (Boyer et al. 2021; Magnier and Mugge 2022). The model's approach to value creation and delivery is also operationally demanding, requiring substantial upfront investment in a sophisticated reverse logistics network for professional repair and device management (Ylä-Mella et al. 2022; Brändström et al. 2024). Finally, the shift to a recurring revenue model introduces new complexities for value capture, necessitating different adjusted risk management strategies compared to traditional sales (Rizos and Bryhn 2022; Hunger et al. 2024). These challenges underscore that real-world success hinges not only on a superior circular design and its environmental benefits but equally on overcoming operational and market complexities inherent to this reconfigured circular value architecture.

In summary, the VAS–eco-cost synthesis reveals that environmental optimisation and strategic circularity do not necessarily move in parallel. Incremental extensions of lifespan (S1, S2) improve environmental performance but may weaken business viability and consumer value if pursued in isolation. In contrast, systemic BMI (S3) enables both better environmental outcomes and stronger alignment across value dimensions. The results thus highlight that advancing CE transitions requires integrating environmental efficiency with economically and socially sustainable value architectures. At the same time, success depends on addressing the critical infrastructural, market and supply chain challenges that shape practical implementation.

5 | Discussion: Implication for CBMs

By linking the empirical results derived from the integrated assessment to the research objectives and prevailing debates in the literature, this section provides actionable insights for academia, industry and policymakers seeking to advance genuinely sustainable CE transitions.

The comparative integrated assessment confirms that all circular approaches outperform the linear baseline in terms of environmental burdens and monetised externalities. This affirms the value of slowing strategies such as reuse, repair and refurbishment (Wieser and Tröger 2018; Bocken 2021). However, the central contribution of this study lies in the nuanced and, at times, counterintuitive insights into the strategic viability of these models, providing important contributions to critical debates in the CE and CBM literature. The most important insight lies in what may be called the 'effectiveness–intensity dilemma'.

The comparative integrated assessment of four distinct smartphone CBM scenarios confirmed clear advantages of all circular approaches over the linear baseline. The results show that simply maximising longevity through product-centric attributes like repairability or physical durability does not automatically yield enhanced circularity or business model resilience. Instead, this approach can lead to a point of diminishing returns, beyond which the model's strategic alignment and overall viability begin to decline without additional systemic interventions, especially when such interventions fail to generate and sustain value for all key stakeholders (Graessler and Pottebaum 2021). Common barriers include consumers' reluctance to use technologically dated products and OEMs' uncertainty about revenue and profit in increasingly dematerialised value chains (Tunn et al. 2020; van der Velden et al. 2023).

The comparative assessment reveals that extending lifespans through slowing strategies yields clear environmental benefits (Wieser and Tröger 2018; Bocken 2021), but these benefits plateau when pursued without systemic CBMI. Scenario S2 exemplifies this—although environmentally more efficient per FU, its strategic alignment declines relative to S1. This occurs because consumers resist outdated devices and OEMs face revenue uncertainty in dematerialised value chains (Tunn et al. 2020; Graessler and Pottebaum 2021; van der Velden et al. 2023).

By contrast, BMIs that shift from product sales to service-based offerings align strongly with theoretical arguments positioning them as pivotal CE enablers (Rizos and Bryhn 2022; Conduit et al. 2023). Their ability to systemically address operational barriers, such as reverse logistics and service quality (Evans and Vermeulen 2021; Thapa et al. 2023), allows for a fundamental reconfiguration of the value framework itself. By internalising life cycle responsibility, these models realign OEM incentives with product longevity and performance, enabling new forms of value capture and evolving value propositions to consumers.

Strategically, these findings demonstrate that environmental optimisation alone is insufficient, and firms must align business model logics with consumer value and long-term viability. For OEMs, this means integrating longevity with adaptive value propositions, scalable delivery systems and equitable value capture, ensuring that circular strategies remain both environmentally effective and strategically resilient (Hobson 2021; Corvellec et al. 2022).

5.1 | Rethinking Value Creation for ce Viability

Effective value creation in a CE must be understood as a systemic effort (Lüdeke-Freund 2020), moving beyond a narrow focus on product-centric attributes like durability and repairability. Although these features are foundational, truly impactful CBMs embed circular principles directly into the product architecture and the underlying business model logic itself (Geissdoerfer et al. 2023). Such a systemic approach also necessitates optimising for EoL value recovery through design choices that enable easier disassembly and high-quality material recovery (Pamminger et al. 2021; Gómez et al. 2023). Furthermore, actively strategising for mitigating rebound effects, potentially caused by circular practices, ensures that efficiency gains translate to net positive environmental outcomes and are not compromised by accelerated consumption (Evans and Vermeulen 2021).

Finally, for value creation to be scalable, it must extend beyond the firm to the entire value network (Dembek et al. 2023). The effectiveness of design for repair or refurbishment is ultimately dependent on the participation of stakeholders in collaborative networks for professional servicing and advanced material recovery (Richter et al. 2023; Shevchenko et al. 2023). Without this ecosystem-level integration, even the most well-designed circular product risks falling short of its circular potential.

5.2 | Innovating Value Propositions to Sustain Circular Demand

Although extending the PLC promotes sufficiency, it can simultaneously erode the perceived consumer value proposition if products are perceived as outdated. Failing to meet evolving expectations for performance, features and user experience creates significant barriers, such as a loss of consumer trust and a stigma against aging devices, ultimately hindering the widespread adoption of CBMs (Magnier and Mugge 2022; van den Berge et al. 2023). Therefore, innovating value propositions is central to CBM viability, as the transition demands more than just environmentally sound products. It requires offerings that resonate with evolving consumer needs and challenge entrenched consumption patterns (Boyer et al. 2021).

Service-oriented offerings transform value propositions from static ownership to dynamic access, guaranteeing performance and evolving functionality (Poppelaars et al. 2018; Centobelli et al. 2020). However, for such service-centric models to drive CE adoption, their value proposition must extend beyond functional benefits and convenience. It must also address the deeply ingrained consumer preference for novelty and navigate the psychological aspects of 'access versus ownership'. Therefore, innovating the value proposition for a CE involves not just new service layers or product features but also transparently demonstrating compelling economic and experiential value that can successfully compete with, and ultimately reshape, the prevailing linear consumption paradigm (Centobelli et al. 2020; Geissdoerfer et al. 2023). Should CBMs supported by extensive repair ecosystems be perceived as economically burdensome or offering insufficient financial advantage over shorter-lived linear alternatives, their uptake will remain limited despite environmental or strategic CE alignment (Ylä-Mella et al. 2022; van der Velden et al. 2023).

5.3 | Systematising Value Delivery to Enable Scalability

Systematising value delivery is critical for the scalability, resilience and ultimate success of CE operations within the smartphone industry. Relying solely on user-led DIY repair efforts, while valuable, has inherent limitations for achieving widespread adoption beyond niche consumer segments (van der Velden 2021; Prabhu and Majhi 2023). Widespread CE adoption requires sophisticated infrastructure for returns, parts and quality-assured services. This involves overcoming the systemic challenge of closing material loops through an efficient reverse logistics system (Thapa et al. 2023). Such systems, by providing convenient and incentivised take-back options, not only encourage widespread consumer participation (Cordova-Pizarro et al. 2020; Ylä-Mella et al. 2022) but also facilitate multi-stakeholder collaboration and enable the return of value to the OEM, thereby catalysing a resilient service ecosystem. Business models that retain product stewardship, such as a PaaS, are inherently incentivised and better positioned to optimise reverse logistical flows, ensuring high-quality professional interventions and efficient material management.

Furthermore, PaaS also facilitates continuous and bidirectional information exchange, a principle often highlighted in literature but neglected in practice (Ahmad et al. 2023). This feedback loop delivers value outward by providing stakeholders with consistent information on repairability, spare part availability and EoL options. Simultaneously, it allows OEMs and service providers to gather data on device condition and usage, which is essential for predicting maintenance needs and also for scaling service capacity to guarantee continuous value delivery.

5.4 | Capturing Value Across Stakeholders to Ensure Viability

Ensuring multi-stakeholder value capture, especially for the implementing OEM, is fundamental to the long-term sustainability of CBMs (Centobelli et al. 2020). By shifting from selling products to selling performance, access or outcomes, businesses can generate revenue through service fees or upgrade options and by maximising the retained asset value from controlled returns and remarketing of refurbished devices or components (Konietzko et al. 2020; Hobson 2021). This aligns OEM profitability directly with product longevity, resource efficiency and customer satisfaction. Furthermore, proactive CBMs are better positioned to navigate and even leverage the evolving regulatory frameworks. For instance, efficiently managed take-back and refurbishment systems within a PSS can turn EPR obligations into value recovery opportunities, whereas high-quality, accessible service offerings can build brand loyalty in line with RtR mandates, rather than treating them merely as compliance burdens (Rizos and Bryhn 2022). However, these firm-centric value capture mechanisms are only viable if they successfully facilitate a shift in the consumer's role from a passive end-user to an active partner in value co-creation (Nerambelli et al. 2024). Although direct repair is professionalised, this partnership is realised through consumer engagement in feedback loops, participation in upgrade programs, responsible use and timely product returns. Fostering this sense of active partnership is fundamental to enabling business models that equitably share the costs and benefits resulting from a transition towards a CE (Rizos and Bryhn 2022).

5.5 | Methodological Implications: Towards Integrated CBM Evaluation

A critical methodological implication of this study is the need for adopting integrated approaches to evaluating CBMs. Single-dimensional assessments obscure trade-offs, whereas multi-layered frameworks reveal both tensions and synergies (de Giacomo and Bleischwitz 2020; Goffetti et al. 2022). As demonstrated thus far, such integrated frameworks are crucial for revealing and managing inherent trade-offs and identifying potent synergistic opportunities. This capacity for nuanced, multifaceted evaluation is what facilitates more informed, resilient and strategically sound CBM development.

By applying such an integrated framework, this study contributes to the evaluation of CBMs in two important ways. First, through the monetisation of impacts via eco-cost assessment, it reframes the debate from ‘which scenario is greener’ to ‘which scenario internalises its environmental liabilities’ (Bithas 2011; Michalke et al. 2025). Secondly, the findings indicate that the main barrier to transition is not just technological (e.g., repair infrastructure and reverse logistics) but contractual instead. Sustainable outcomes require business models in which the revenue logic rewards lifetime performance rather than volume-based turnover (Kirchherr et al. 2017; Ferasso et al. 2020).

Finally, the integrated framework also offers concrete implications for diverse stakeholder groups. Policymakers may view eco-cost factors as potential levers (e.g., carbon or critical metal depletion taxes) to further incentivise service-oriented models. Investors may interpret high VAS scores as indicators of strategic resilience under future environmental risks and cost internalisation. Practitioners may adopt the 20-item rubric as a due diligence tool for designing and evaluating CE strategies. The modular structure of the developed assessment framework allows substitution of eco-cost factors with proprietary abatement cost data or region-specific data, making recalculation straightforward and adaptable to different contexts.

A summative representation of the findings can be found below in Figures 4 and 5.

5.6 | Limitations of the Study

Although the study offers valuable insights, several limitations must be acknowledged. Firstly, the analysis is based on a single product case, intentionally selected for its ‘designed-for-circularity’ attributes. This choice was made to establish a clear benchmark of what is possible under favourable technical conditions, allowing for a nuanced analysis of the business model scenarios themselves. However, this also limits the generalisability of the findings. The specific results and the relative performance of the scenarios may differ significantly for products from companies with different design constraints, market positions, customer segments or regulatory environments.

Secondly, the applied eco-cost method focuses exclusively on environmental externalities and does not account for social impacts, particularly those arising in upstream raw material extraction. Future studies should complement eco-costing with social LCA or hybrid approaches to capture these dimensions.

Thirdly, although the VAS provides a transparent and systematic scoring rubric, it inherently includes a degree of subjectivity. To mitigate this, several strategies were employed: the indicators themselves were derived from a comprehensive literature review and validated through expert feedback; furthermore, a hierarchical weighting system was used to reflect their relative strategic importance. Yet, alternative weighting schemes reflecting varied stakeholder perspectives or alternative product typologies could potentially lead to different scenario rankings.

Finally, refraining from a detailed internal financial analysis from the OEM perspective was a conscious choice for this study's scope, which prioritised evaluating the strategic CE alignment, monetised externalities and environmental sustainability. Although a full financial viability assessment (including investment costs and profitability forecasts) is a critical step for firms considering CBM implementation, it was beyond the present research focus. Future research should integrate financial modelling to evaluate the practical viability of circular models, especially capital-intensive service models such as PaaS (as in scenario S3).

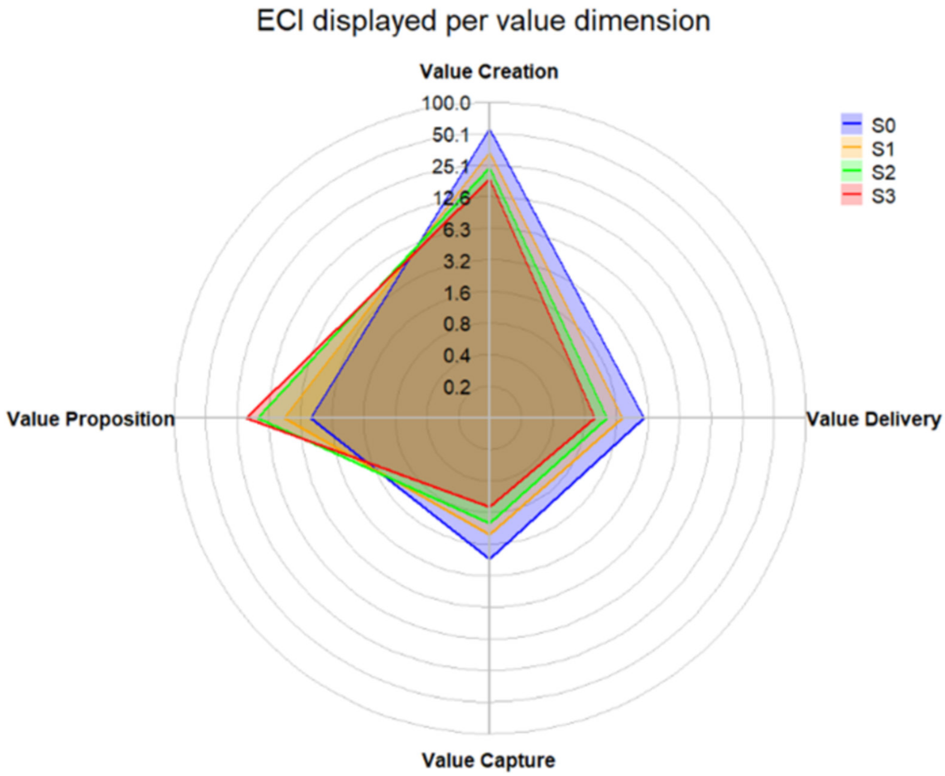

FIGURE 4 | Synthesis of eco-cost along the value dimensions.

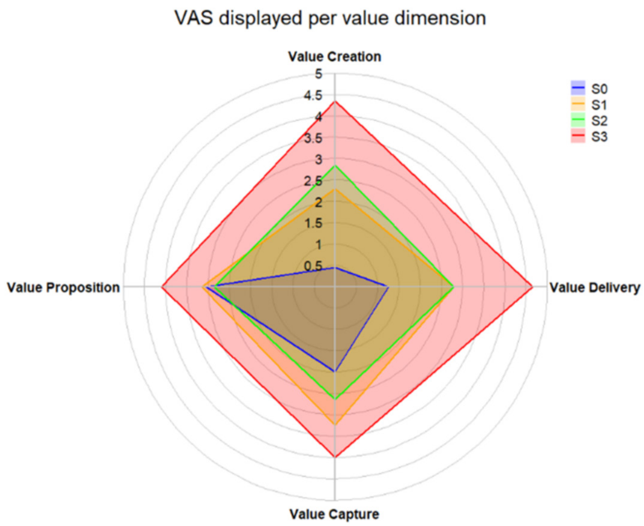

FIGURE 5 | Synthesis of VAS along the value dimensions.

6 | Conclusion

This study sought to address a critical methodological gap in the CE discourse by developing and applying an integrated framework to assess the sustainability and strategic viability of CBMs, particularly within the complex and resource-intensive smartphone sector. By combining LCA, monetised eco-cost analysis and a structured VAS, the framework moves beyond singular environmental or economic metrics to provide a holistic basis for evaluating CBMs. Applied to the Fairphone 5 case, it demonstrates how environmental impacts, the intensity of circular interventions, business model design and consumer value interact to shape both environmental performance and strategic alignment.

The results show that ownership-retaining service models, such as the PSS, outperform other CBM models by simultaneously reducing externalised environmental costs and achieving higher alignment with circular value logics. Refurbishment-based models also show meaningful improvements over business-as-usual, though their contribution to systemic circularity remains more limited. A key theoretical contribution lies in demonstrating that environmental gains and strategic viability do not always move in parallel. Incremental extensions of product life (as in S1 and S2) reduce impacts but risk diminishing strategic returns unless supported by business model innovation. By contrast, service-based models achieve stronger outcomes precisely because they reconfigure value creation, delivery, proposition and capture simultaneously.

The study's primary contribution to theory is the operationalisation of the developed framework, showing how environmental performance, external cost internalisation and strategic alignment can be assessed together in a quantifiable framework. For practice, it provides firms with a tool to evaluate trade-offs, reduce innovation risk and make more informed decisions about transitioning to circularity. Empirically, the findings enrich debates on the hierarchy of R-strategies and challenge the simplistic view of pursuing an isolated product longevity approach. This is best illustrated by the direct comparison of S1, S2 and S3. Although S3 incorporates interventions like refurbishment and upgrades, which, judging by a purely hierarchical perspective, might be considered lower R-strategies than repair and reuse in S1 and S2, it still outperforms both ecologically and strategically.

Emphasising the need to assess CBMs from a holistic value framework perspective, as the superiority of a model is determined by the systemic interplay of its value creation, delivery and capture mechanisms, not just by its adherence to a single circular principle.

The study also offers policy insights. Eco-cost analysis highlights the disproportionate environmental burden of trace materials like gold, suggesting a basis for policies that incentivise the reduction of virgin material use, for instance, through targeted resource taxes. At the same time, the results show that while policies like the RtR and EPR are valuable, they are insufficient on their own. As demonstrated in this study, user-led repair is a valid starting point for circularity but fails to actualise the full environmental and economic potential inherent in a product. Policies must therefore move beyond enabling repair toward incentivising professionalised repair services, advanced refurbishment and leasing infrastructures that allow firms to embrace life cycle responsibility.

Future research should extend the application of the framework to a wider array of products, industrial sectors and diverse organisational contexts to test generalisability. A critical avenue is the rigorous integration of comprehensive social impact assessment methodologies (e.g., social LCA and monetisation of key social externalities) to complement the environmental and strategic dimensions captured by eco-costs and VAS. Furthermore, the real-world scalability of capital-intensive, service-based CBMs, including their financial viability and wider consumer adoption, needs better understanding.

Author Contributions

Philipp Rittershaus: conceptualisation (lead), data curation (lead), formal analysis (lead), investigation (lead), methodology (equal), project administration (lead), supervision (lead), validation (lead), visualisation (lead), writing – original draft (lead), writing – review and editing (equal). **Venkat Aryan:** conceptualisation (supporting), data curation (supporting), methodology (equal), supervision (supporting), validation (supporting), writing – original draft (supporting), writing – review and editing (equal). **David Sánchez:** data curation (supporting), formal analysis (supporting), investigation (supporting), validation (supporting). **Manfred Renner:** conceptualisation (supporting), supervision (supporting). **Jens Poeppelbuss:** conceptualisation (supporting), supervision (supporting).

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Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.