An Innovative Circular Product Design Process and Methodology under Closed-Loop Supply Chain Constraints

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***Abstract*—As the circular economy continues to reshape global manufacturing, the electronics industry finds itself at a critical turning point. The traditional linear model—produce, use, discard—is increasingly unsustainable, both economically and environmentally. At the same time, the shift toward closed-loop systems presents new opportunities for value creation. Yet a persistent gap remains: most product design methods are still disconnected from end-of-life (EoL) processes such as collection, remanufacturing, and recycling. This disconnect leads to inefficient material recovery, high remanufacturing costs, and significant losses in potential circular value. To address this challenge, this study seeks to bridge product design and supply chain management. Grounded in the principles of Business Process Re-engineering (BPR), it proposes an innovative framework: the Circular Product Design Process under Closed-Loop Supply Chain Constraints (CPDP-CLSC). The core idea is to bring supply chain considerations—traditionally addressed downstream—directly into the front end of design decision-making. Using a smartphone as a case study, the research demonstrates how key supply chain factors — such as collection rates, remanufacturing costs, and residual material value — can be translated into explicit design parameters and optimization objectives. Instead of treating circularity as an afterthought, the method embeds it structurally into the product development process. The proposed CPDP-CLSC framework consists of five interconnected phases: Circular Scenario Definition – Identifying potential recovery pathways and mapping value flows within a closed-loop supply chain context. Recyclability Requirement Analysis – Converting supply chain constraints and recovery targets into measurable design requirements. Multi-Life Function and Structure Design – Developing modular architectures and component strategies that support reuse, repair, and remanufacturing across multiple life cycles. Circular Value Assessment and Optimization – Applying analytical models to evaluate trade-offs and maximize overall circular value. Material and Process Selection – Choosing materials and manufacturing processes that enhance recoverability while maintaining performance and cost competitiveness. The smartphone case study highlights the practical impact of this approach. A new-generation design developed under the CPDP-CLSC framework demonstrated significant improvements in modularity, ease of disassembly, and reusability of key components. Model-based evaluation results showed a 40% reduction in disassembly time, a 25% decrease in remanufacturing costs for core modules, and a 15% increase in overall circular value. These improvements illustrate how aligning design decisions with closed-loop supply chain constraints can unlock both environmental and economic benefits. Beyond the specific case, this research contributes a systematic and operational methodology for circular product design. Theoretically, it advances the integration of supply chain thinking into early-stage design, strengthening the connection between circular economy principles and engineering practice. Practically, it provides electronics manufacturers with a structured pathway to enhance resource efficiency, reduce lifecycle costs, and build sustainable competitive advantages in an increasingly regulation-driven and sustainability-conscious market. By embedding circularity into the DNA of product development, this framework offers meaningful support for the broader green transformation of manufacturing.**

Keywords—Closed-Loop Supply Chain (CLSC); Circular Product Design; Circular Economy; Remanufacturing; Sustainable Design

I. INTRODUCTION

As global resource pressures intensify and environmental challenges become more urgent, the traditional linear economic model—defined by a "resource – product – waste" flow — has proven increasingly unsustainable. In response, the Circular Economy (CE) has emerged as a widely recognized paradigm for sustainable development, aiming to close material loops and maximize value retention across product life cycles [1, 2]. It has not only gained international consensus but has also been elevated to the level of national strategy in many countries.

Within this broader transition, the electronics industry presents both a critical challenge and a major opportunity. While it remains a powerful driver of global economic growth, it is also the fastest-growing source of electronic waste (e-waste), fueled by rapid technological iteration and mass consumption. The prevailing "take – make – dispose" model results in substantial losses of valuable materials and severe environmental harm. Shifting from a "cradle-to-grave" model to a "cradle-to-cradle" system — where products and materials continuously circulate—has therefore become a pressing issue for both researchers and practitioners [3].

At the enterprise level, the Closed-Loop Supply Chain (CLSC) is a key mechanism for operationalizing circular economy principles. By integrating forward and reverse logistics, CLSCs enable used products to be collected, inspected, remanufactured, refurbished, or recycled, thereby

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recovering product value and reintegrating materials into production cycles [4, 5]. However, the efficiency and economic viability of a CLSC depend heavily on the intrinsic characteristics of the product itself. Design decisions fundamentally shape a product's end-of-life (EoL) disposability, serviceability, remanufacturability, and recyclability [6].

If circular considerations are not embedded during the design stage, even well-developed collection networks may fail to deliver meaningful improvements in circular performance. For example, the widespread use of adhesives, proprietary fasteners, and highly integrated architectures in smartphones makes repair and disassembly extremely challenging. These design choices often damage high-value components during recovery, increase remanufacturing costs, and ultimately lead to low-value shredding rather than high-value reuse—resulting in significant resource misallocation and economic loss [7].

Scholarly research has made notable progress in circular product design, particularly through various "Design for X" (DfX) approaches, such as Design for Disassembly (DfD) and Design for Remanufacturing (DfReman) [8]. Meanwhile, CLSC research has largely concentrated on network configuration, inventory management, and pricing mechanisms [9]. Although some studies acknowledge the interaction between product design and CLSCs, they often treat them as separate domains. For instance, research may examine how modularity affects CLSC costs or optimize a CLSC network based on a predetermined product design [10].

This fragmented approach has led to important limitations. Many existing design methods remain qualitative or semi-quantitative and lack systematic mechanisms to translate the dynamic, complex, and uncertain constraints of the CLSC—such as variability in return quantity and quality, remanufacturing complexity, and residual component value—into actionable design parameters. As a result, an "information silo" persists between design and supply chain decision-making. Designers making early trade-offs often lack visibility into how their choices will ultimately influence circular supply chain performance.

Against this backdrop, this study addresses the following central research question: How can a systematic design process be developed to front-load and integrate back-end CLSC constraints into front-end product design decisions, thereby enabling constraint-driven circular innovation?

To answer this question, the study draws on the principles of Business Process Re-engineering (BPR) to fundamentally rethink and redesign the traditional product development process. It proposes a new framework titled the Circular Product Design Process under CLSC Constraints (CPDP-CLSC). The framework systematically and quantitatively translates CLSC operational constraints—such as collection costs, disassembly time, remanufacturing yield rates, and residual material values—into design-stage input parameters and optimization objectives. By doing so, it guides designers to innovate across conceptual, structural, and material dimensions to create next-generation products that are both economically viable and environmentally sustainable.

To validate the proposed methodology, this study employs the smartphone — a representative complex electronic product — as a case study. The research quantitatively evaluates the effectiveness of the CPDP-CLSC framework in enhancing circular value and improving product-level circular performance.

The remainder of this paper is organized as follows. Section 2 reviews relevant literature on closed-loop supply chains and circular product design. Section 3 details the CPDP-CLSC methodology, including its core processes and supporting models. Section 4 presents the smartphone case study and validation results. Section 5 discusses the findings and their implications. Finally, Section 6 concludes the study and outlines directions for future research.

II. Literature Review

A. Closed-Loop Supply Chain (CLSC) Theory

A Closed-Loop Supply Chain (CLSC) can be understood as an expanded and integrated form of the traditional forward supply chain. In addition to managing the forward flow—from raw material sourcing and manufacturing to distribution and final consumption — it establishes a reverse logistics system that channels used products back to producers in order to recover their residual value [11]. This reverse flow involves a range of activities, including collection, inspection and sorting, followed by the selection of appropriate recovery strategies based on product condition and component value. These strategies may include direct reuse, repair, refurbishing, remanufacturing, or recycling [12]. Among them, remanufacturing is often regarded as one of the most value-preserving options, as it restores used products to like-new performance standards through systematic disassembly, cleaning, component repair or replacement, reassembly, and testing [13].

The performance of a CLSC depends on a complex interplay of strategic and operational factors. From a network design perspective, decisions regarding the number, location, and capacity of collection centers, inspection facilities, and remanufacturing plants — as well as the coordination of forward and reverse logistics—directly influence total cost and system responsiveness [14]. Uncertainty presents another major challenge. Variations in the quantity, timing, and quality of returned products complicate production planning, inventory control, and capacity allocation [15].

External conditions further shape CLSC outcomes. Consumer participation in return programs, government regulations such as Extended Producer Responsibility (EPR), and market acceptance of remanufactured products all affect system feasibility and profitability [16]. Importantly, growing research highlights that a product's inherent physical characteristics — such as structural complexity, material diversity, joining methods, modularity, and component standardization—strongly influence the cost and practicality of disassembly, inspection, and remanufacturing. These design attributes ultimately serve as foundational constraints on CLSC effectiveness [17].

B. Circular Product Design Methodologies

To tackle end-of-life challenges at their source, researchers and practitioners have developed various circular design methodologies under the broader umbrella of "Design for X" (DfX). These approaches aim to embed specific lifecycle objectives into early-stage product development. Design for Environment (DfE), for example, promotes comprehensive consideration of environmental impacts—including resource use, energy consumption, and waste generation—throughout the product lifecycle [18].

Within the DfE framework, more targeted strategies have emerged. Design for Disassembly (DfD) focuses on simplifying product structures, minimizing component count, and using easily separable joining methods (such as snap-fits rather than adhesives) to reduce disassembly time and cost, thereby facilitating repair and component recovery [19]. Design for Remanufacturing (DfReman) extends this logic by emphasizing durability, modularity, and repairability, ensuring that critical components can withstand multiple life cycles and be efficiently restored to required performance levels [20]. Design for Recycling (DfR) concentrates on material selection, encouraging the use of compatible or mono-material systems, minimizing hazardous substances, and incorporating clear material identification to improve recycling efficiency and material purity [21].

While these DfX approaches offer valuable guidance, they also reveal important limitations. Conflicts can arise among different design objectives. For instance, snap-fit connections may ease disassembly but compromise durability compared to screw fastenings, potentially undermining product longevity. Moreover, many DfX methods primarily address physical product attributes and lack robust quantitative tools to link design decisions with the economic and operational realities of a CLSC—such as fluctuating collection rates or variable demand for remanufactured products. Without integrated data and modeling support, designers may struggle to make optimal trade-offs, leading to products that are theoretically "circular" but economically impractical within real supply chain systems.

C. Interdisciplinary Research on CLSC and Product Design

Recognizing the interdependence between product design and CLSC performance, recent research has begun to explore their integration more systematically. Early contributions relied largely on conceptual models and case studies to qualitatively assess how design attributes — such as modularity and ease of disassembly — affect supply chain outcomes [17].

Subsequent studies introduced quantitative approaches, including mathematical programming and optimization algorithms. One research stream evaluates different product design alternatives within a fixed CLSC structure, comparing their impact on overall supply chain cost and performance [10]. For example, mixed-integer programming models have been used to analyze cost differences between modular and non-modular designs.

Another stream attempts deeper integration by incorporating design-related variables—such as modularity level, durability, or material choice—directly into CLSC optimization models. In these models, product design variables are optimized simultaneously with operational decisions like facility location or production volume. Although this represents theoretical progress, such models often oversimplify design complexity for tractability, reducing multi-dimensional design decisions to a limited number of discrete variables. This abstraction fails to fully capture the nuanced and systemic impact of design choices across different reverse logistics stages.

In summary, while existing literature provides a strong foundation, a significant research gap remains. There is a lack of an operational framework capable of spanning the entire product development process and systematically translating the multiple, dynamic constraints of the CLSC—technical, economic, and environmental — into structured inputs for front-end design decisions. Current studies either remain conceptual or oversimplify the design dimension within quantitative models.

This study therefore argues that advancing circular product innovation requires a shift from purely "model optimization" toward "process innovation." Rather than treating product design as a passive input to the CLSC, it should be redefined as an active, constraint-driven process that anticipates, responds to, and leverages supply chain realities. The central aim is to achieve deep and dynamic coupling between product design and closed-loop supply chain management through a systematically constructed, constraint-driven innovation process.

III. Research Methodology

To systematically resolve the long-standing disconnect between product design and closed-loop supply chain operations, this study develops an innovative circular product design methodology. At its core, the approach reframes back-end supply chain constraints—not as passive boundary conditions, but as active drivers of front-end design decisions.

Rather than allowing product development to proceed independently and addressing end-of-life challenges afterward, the methodology embeds closed-loop considerations directly into the early stages of design. Through a structured process supported by analytical models, key supply chain factors — such as collection efficiency, disassembly complexity, remanufacturing yield, cost structures, and residual material value — are translated into explicit design parameters and optimization objectives. In this way, circularity is no longer an afterthought but becomes a foundational principle guiding innovation.

This chapter presents the overall framework of the proposed methodology, detailing its core process architecture and the key supporting models that enable quantitative decision-making. By clarifying how supply chain constraints are systematically integrated into design activities, the chapter lays the groundwork for achieving dynamic coupling between product innovation and closed-loop value creation.

A. Overall Research Framework

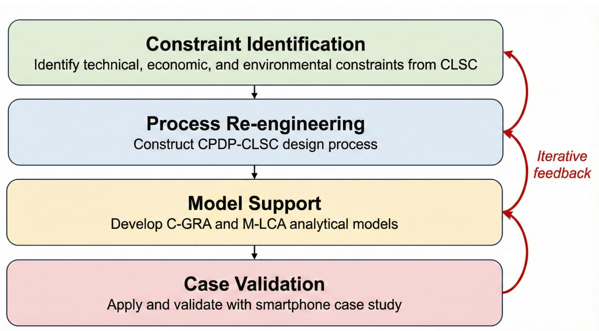

Fig. 1. Overall Research Framework

The methodology developed in this study is structured around a four-layer progressive logic: Constraint

Identification – Process Re-engineering – Model Support – Case Validation (see Figure 1). This layered framework ensures that design innovation is not driven solely by intuition or isolated creativity, but emerges as a structured and evidence-based response to real-world closed-loop supply chain (CLSC) constraints.

1) Constraint Identification

This stage serves as the foundation of the entire framework. It involves a comprehensive analysis of the core constraints faced by the target product — such as a smartphone—within the existing CLSC environment. These constraints are categorized into three primary dimensions:

- Technical constraints, including factors such as disassembly complexity, component damage rates during recovery, structural integration level, and material compatibility.
- Economic constraints, covering collection costs, inspection and sorting expenses, remanufacturing costs, residual component value, and market demand uncertainty for recovered products.
- Environmental constraints, such as carbon emissions across lifecycle stages, hazardous substance treatment requirements, and overall environmental impact associated with recovery and recycling processes.

By systematically identifying and structuring these constraints, this phase transforms diffuse operational challenges into clearly defined design inputs.

2) Process Re-engineering

Building upon the identified constraints, the methodology applies the principles of Business Process Re-engineering (BPR) to fundamentally rethink the traditional product development process. Instead of treating circular considerations as peripheral or downstream concerns, the redesigned process — termed the Circular Product Design Process under CLSC Constraints (CPDP-CLSC)—integrates them into the core logic of design.

The re-engineered process reorganizes design activities into stages that are tightly coupled with key CLSC operations. Each design phase is explicitly aligned with improving circular performance indicators, ensuring that front-end decisions directly contribute to enhanced recovery efficiency, economic viability, and environmental sustainability in the reverse supply chain.

3) Model Support

To ensure that the restructured process is both actionable and scientifically grounded, the study develops quantitative analytical models to support critical decision points. These models play two essential roles.

First, they act as translators, converting abstract and often complex supply chain constraints into measurable design parameters and optimization objectives. For example, remanufacturing cost structures can be translated into targets for modularity or disassembly time.

Second, they function as evaluators, enabling quantitative assessment of alternative design solutions across their full life cycle. By modeling economic performance, environmental impact, and circular value, these tools provide objective data to support informed design trade-offs and optimization.

4) Case Validation

The final layer of the framework involves empirical validation through a real-world case study. By applying the CPDP-CLSC process and its supporting models to the redesign of a specific product—such as a smartphone—the study compares key circularity indicators between the original and improved designs. Metrics such as disassembly time, remanufacturing cost, and overall circular value serve as evidence of effectiveness.

This validation step confirms not only the feasibility of the methodology but also its practical relevance and measurable benefits in enhancing product-level circular performance.

Together, these four layers form a coherent and systematic innovation pathway, enabling dynamic integration between product design and closed-loop supply chain management.

B. The CPDP-CLSC: A CLSC Constraint-Driven Circular Product Design Process

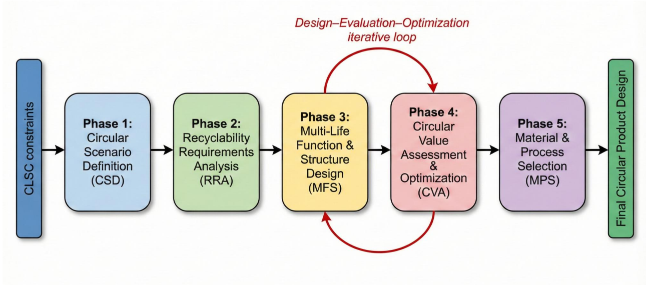

Fig. 2. CPDP-CLSC Process Framework

Building on the research framework outlined earlier, the central contribution of this study is the development of a five-phase closed-loop design methodology: the CPDP-CLSC (Circular Product Design Process under CLSC Constraints). Unlike traditional product development processes — where recycling and recovery are considered only after the product reaches end-of-life — this process embeds circular thinking into every stage of design, effectively front-loading reverse supply chain considerations (see Figure 2).

1) Phase 1: Circular Scenario Definition (CSD)

The CSD phase establishes the strategic positioning of the product ' s circular pathway. Rather than assuming a generic " recycling" outcome, the design team defines one or more realistic and context-specific circular scenarios based on product characteristics, market conditions, and supply chain capabilities.

For example, in the case of a smartphone, a composite scenario might include:

" Official channel collection → inspection and sorting → Grade A screens/mainboards for remanufacturing → Grade B components for refurbishing → casings and batteries for material recycling."

Once the scenario is defined, clear Key Performance Indicators (KPIs) and constraints are set. These may include:

- A minimum collection rate of 50%
- An average remanufacturing cost per unit not exceeding 30% of a new product
- A maximum disassembly time of 15 minutes

These targets serve as both boundary conditions and evaluation benchmarks for all subsequent design activities. In essence, CSD establishes the "destination" of circular performance before design begins.

2) Phase 2: Recyclability Requirement Analysis (RRA)

The RRA phase translates high-level circular constraints into concrete engineering requirements. To achieve this, the study introduces the C-GRA model (CLSC-based Gap – Requirement Analysis Model).

This model identifies improvement opportunities by analyzing performance gaps between existing product designs and the desired circular scenario defined in CSD. For instance, teardown reports and prior research often show that adhesive-intensive smartphone designs make battery removal difficult and prone to damage. If the CSD phase requires fast and non-destructive disassembly, such findings reveal a clear gap.

In response, the C-GRA model guides the generation of actionable requirements, such as:

- The battery module should be independently encapsulated.
- It should be secured using pull-tab traceless adhesive or low-strength snap-fits.
- It must be removable within one minute without heating or specialized tools.

Through this structured translation process, abstract supply chain constraints are converted into practical design specifications that engineers can directly implement.

3) Phase 3: Multi-Life Function and Structure Design (MFS)

The MFS phase transforms requirements into tangible design solutions. Unlike conventional single-life-cycle design, this phase adopts a multi-life perspective, ensuring the product can sustain multiple cycles of use, recovery, and reintroduction.

Key design principles include modularity, standardization, and structural robustness. The primary objectives are:

a) Easy separation of high-value modules

Critical components such as screens, mainboards, and camera modules should be removable quickly and without damage, enabling remanufacturing or upgrading.

b) Easy replacement of wear-prone components

Parts with shorter lifespans or rapid technological obsolescence — such as batteries or charging interfaces — should be designed as independent modules. This supports repairability and extends overall product lifespan.

c) Structural robustness and material compatibility

The product must maintain durability across multiple life cycles while ensuring that adjacent materials are compatible and easily separable for recycling.

This phase redefines structural innovation around the concept of circular longevity rather than single-use optimization.

4) Phase 4: Circular Value Assessment and Optimization (CVA)

After multiple preliminary solutions are developed in MFS, the CVA phase quantitatively evaluates and optimizes them. Traditional assessments often emphasize manufacturing cost and product performance alone. In contrast, CVA focuses on full life-cycle circular value.

To support this, the study introduces the M-LCA model (Multi-Life Cycle Assessment Model). This model integrates both economic and environmental indicators, including:

- Manufacturing costs
- Use-phase benefits
- Collection and logistics costs
- Disassembly and remanufacturing costs
- Remanufacturing revenue
- Residual material value
- Environmental metrics such as carbon footprint

The model calculates the expected Net Circular Value (NCV) and key environmental impacts for each design alternative. If results reveal bottlenecks—such as excessive disassembly costs for a specific module—the team returns to the MFS phase for targeted refinement. This creates a structured "design – evaluate – optimize" feedback loop, ensuring continuous improvement.

5) Phase 5: Material and Process Selection (MPS)

Once the structural configuration and circular value performance are largely defined, the MPS phase determines the specific materials and manufacturing processes.

Selections must satisfy not only functional and aesthetic requirements but also circularity objectives. Key principles include:

a) Prioritizing recycled materials

Increase the proportion of recycled plastics and metals without compromising performance or safety.

b) Selecting recyclable, single-material systems

Avoid complex composite materials where possible and favor materials that are easy to identify, separate, and recover.

c) Eliminating hazardous substances

Comply strictly with regulations such as RoHS and use halogen-free, low-volatility, environmentally friendly materials.

d) Adopting reversible connection methods

Prioritize screws, snap-fits, and other mechanical fasteners. Use adhesives or welding only when necessary, and select types that can be reversed under controlled conditions.

These decisions ultimately determine whether the product's circular ambitions can be realized in practice.

Together, these five phases create a coherent and operational design pathway in which circularity is embedded from strategy to structure, from evaluation to material selection. By systematically integrating closed-loop supply chain constraints into front-end design, the CPDP-CLSC framework transforms circularity from a downstream corrective measure into a proactive engine of product innovation.

C. Core Supporting Models

To ensure the effective implementation of the CPDP-CLSC process, this study has developed two core analytical models as supporting tools for the key phases.

1) C-GRA Model (CLSC-based Gap-Requirement Analysis Model)

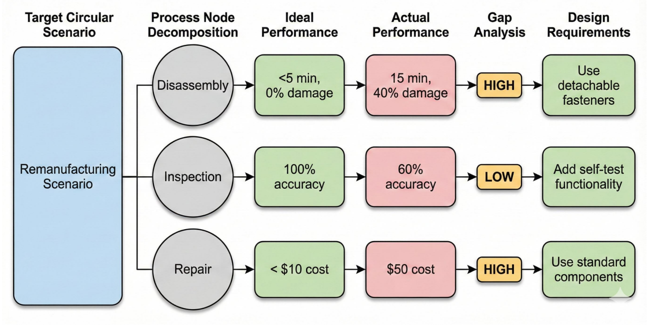

Fig. 3. C-GRA Model Logic Diagram

This model is implemented during the Recyclability Requirement Analysis (RRA) phase as a structured analytical tool designed to systematically convert closed-loop supply chain (CLSC) constraints into concrete product design requirements. Its overall logic is illustrated in Figure 3.

The process begins by decomposing the target circular scenario — such as remanufacturing — into a sequence of critical operational nodes. These typically include stages like disassembly, cleaning, inspection, testing, repair, and reassembly. For each node, ideal performance indicators are clearly defined. Examples might include maximum allowable disassembly time, acceptable component damage rate, inspection accuracy, or repair success rate. These indicators represent the desired operational standards under the defined circular scenario.

Next, the model gathers indicative performance data for existing products or competitor designs. This is achieved through a structured desk-based synthesis of publicly available teardown reports, repair documentation, industry benchmarks, and relevant technical studies. These sources provide measurable insights into how current products perform at each reverse-process node — for instance, the average time required to remove a battery or the likelihood of screen damage during disassembly.

The model then performs a systematic comparison between the ideal targets and the observed performance levels. By quantifying the difference, it calculates the "performance gap" for each process node. When a gap exceeds predefined thresholds, the system activates a knowledge-based mapping mechanism that links specific types of performance deficiencies to corresponding design improvement strategies. For example, excessive disassembly time may trigger requirements related to modularization, reversible fasteners, or reduced adhesive usage.

Through this structured mapping process, abstract and high-level CLSC constraints are translated into precise, actionable engineering requirements. As a result, the traditionally qualitative and experience-driven requirement analysis stage is transformed into a data-supported and logically traceable derivation process. This significantly enhances the objectivity, repeatability, and strategic alignment of circular product design decisions.

2) M-LCA Model (Multi-Life Cycle Assessment Model)

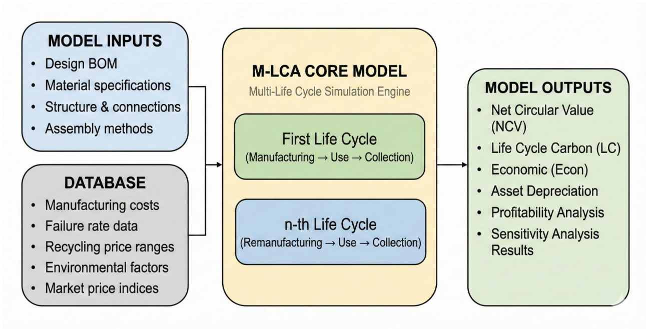

Fig. 4. M-LCA Model Framework

This model is used in the Circular Value Assessment (CVA) phase as an integrated decision-support tool for evaluating and optimizing the circular performance of alternative design solutions. As illustrated in Figure 4, the model combines the analytical frameworks of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) to provide a comprehensive economic and environmental evaluation.

At its core, the model conceptualizes a product's full lifecycle as the aggregation of one initial life cycle and multiple subsequent N circular life cycles (e.g., repair, remanufacturing, recycling loops). Instead of assessing only the first-use phase, it captures the cumulative cash flow and environmental impact generated across repeated recovery and reintroduction cycles.

To enable this simulation, the model is supported by a structured database that includes:

- Manufacturing cost data for individual components
- Component failure rates and durability parameters
- Cost and revenue coefficients associated with different circular pathways (e.g., repair, remanufacturing, recycling)
- Environmental impact factors for various materials and processes (e.g., carbon intensity, resource depletion potential)

When a specific design solution is entered — complete with its Bill of Materials (BOM), structural configuration, and material specifications — the model simulates its performance under the predefined circular scenario. It calculates:

- The Net Circular Value (NCV), reflecting the cumulative economic value generated across all life cycles after accounting for manufacturing, collection, disassembly, remanufacturing, and recovery costs

- Key environmental impact indicators, such as Global Warming Potential (GWP) and Abiotic Depletion Potential (ADP)

By quantitatively comparing the NCV and environmental performance of multiple design alternatives, the model enables designers to move beyond intuition-based decision-making. Instead, they can conduct structured trade-off analyses—for example, evaluating whether a higher upfront manufacturing cost is justified by lower remanufacturing expenses or improved environmental outcomes over multiple cycles.

In this way, the model transforms circular value from a conceptual objective into a measurable and optimizable design criterion, providing a scientific foundation for informed and balanced design decisions.

IV. Case Study: Circular Design of a Smartphone

To examine the practicality and effectiveness of the proposed CPDP-CLSC methodology, this study selected the smartphone—arguably the most representative product in contemporary consumer electronics—as the case subject. By applying the framework to the redesign of a mainstream flagship smartphone, this chapter demonstrates how CPDP-CLSC systematically guides circular innovation and quantifies the resulting improvements.

A. Case Background and Problem Analysis

A widely available flagship smartphone (hereafter referred to as the baseline model) was chosen for analysis. Like many current high-end devices, the baseline model adopts a highly integrated design approach:

- The glass back cover and metal mid-frame are bonded with strong structural adhesives.
- The internal battery is secured using extensive adhesive strips.
- The display assembly is tightly integrated with the frame.

Drawing on publicly available teardown reports, repair manuals, repairability assessments, and findings from prior studies, several major challenges were identified in the context of closed-loop supply chain (CLSC) operations:

1) High Disassembly Difficulty and Risk

Separating the back cover or screen requires heating and prying tools. This process is time-intensive and carries a significant risk of cracking the glass or damaging internal components. Battery removal is particularly problematic: strong adhesives make extraction difficult and potentially unsafe. Forced removal can result in collateral damage to high-value components such as the OLED display or mainboard, undermining their reuse potential.

2) High Remanufacturing Costs

Due to the high probability of damage during disassembly, components that retain substantial residual value—such as OLED screens—are often downgraded to material recycling instead of being remanufactured. Even when successfully removed, residual adhesive cleaning adds labor time and cost, reducing economic feasibility.

3) Limited and Low-Value Circular Pathways

Within the existing recycling system, more than 70% of collected baseline devices are directly sent to shredding and material sorting due to the uneconomical nature of disassembly. As a result, high-value chips and precision modules are not effectively recovered, leading to considerable resource and value loss.

These challenges point to a fundamental issue: the product's physical architecture was optimized primarily for performance and aesthetics, with insufficient consideration of end-of-life circularity. A significant disconnect exists between front-end design decisions and back-end supply chain realities.

B. Applying the CPDP-CLSC Process for Circular Redesign

To address these shortcomings, the CPDP-CLSC methodology was systematically applied to redesign the smartphone.

1) Phase 1: Circular Scenario Definition (CSD)

A clearly defined circular scenario was established for the next-generation smartphone. In this envisioned system:

a) Used devices are collected through official and authorized third-party channels.

b) Devices undergo rapid, non-destructive functional and cosmetic inspection.

c) Based on inspection results, they are categorized into three grades:

- Grade A (Minor wear): Processed through official refurbishment and resold.
- Grade B (Fully functional core modules, cosmetic wear present): Disassembled for remanufacturing of high-value components such as the screen, mainboard, and camera modules, which are reused in after-sales services or certified remanufactured products.
- Grade C (Functional damage): Subjected to fine-grained disassembly to recover valuable components and precious metals before material recycling.

Based on this scenario, a series of key design constraints and performance targets (KPIs) were defined (see Table I). These include targets related to collection rates, maximum disassembly time, allowable component damage rates, remanufacturing cost thresholds, and minimum circular value contribution.

By clearly defining the desired end-of-life pathways and associated performance thresholds at the outset, the design process is anchored to measurable circular objectives rather than abstract sustainability goals.

Through this structured starting point, the CPDP-CLSC process ensures that every subsequent design decision—whether structural, material, or economic—is aligned with enhancing circular performance across the entire closed-loop supply chain.

TABLE I. KPIs for the New Generation Smartphone Circular Design

Category	KPI	Target Value	Remarks

Category	KPI	Target Value	Remarks
Technical Efficiency	Average non-destructive disassembly time	< 10 minutes	From removing the SIM card tray to separating all core modules
	Damage rate of core modules (battery, screen, mainboard) during disassembly	< 5%	No professional heating equipment required
Economic Benefits	Remanufacturing cost per unit (Grade B)	< 25% of new product manufacturing cost	Mainly accounting for disassembly, inspection, repair, and reassembly costs
	Overall circular value rate	> 40%	(Reuse value + Material recovery value) / New product value
Environmental Impact	Proportion of recycled materials used	> 30%	By weight
	Hazardous substances (e.g., halogens)	0	Compliant with the latest environmental directives

2) Phase 2: Recyclability Requirement Analysis (RRA)

By applying the C-GRA model in the RRA phase, the KPIs defined during the Circular Scenario Definition (CSD) stage—together with the identified performance gaps of the baseline model—were systematically converted into concrete and actionable design requirements.

For instance, the CSD phase established a target of " total disassembly time < 10 minutes. " However, teardown data for the baseline model indicated an average disassembly time of approximately 35 minutes, revealing a substantial gap. Based on this discrepancy, the C-GRA model automatically mapped the performance shortfall to corresponding design improvement strategies within its knowledge base. As a result, it generated specific engineering requirements such as:

- Replace extensive adhesive bonding with reversible physical fasteners.
- Minimize the number and variety of screws to streamline tool usage and reduce operation steps.
- Standardize screw types to enable single-tool disassembly.
- Redesign the internal layout to allow layered and sequential module removal.

Similarly, other KPI gaps — such as high component damage rates during battery removal or excessive cleaning costs caused by adhesive residue — were translated into targeted requirements, including modular battery encapsulation, pull-tab adhesive systems, and independent high-value module mounting structures.

Some of the key requirement translations derived through this structured process are summarized in Table II. Through this model-driven approach, the requirement analysis phase moved beyond qualitative discussion and subjective judgment, becoming a traceable and data-supported derivation process that directly links circular performance targets to design action points.

TABLE II. EXAMPLE OF TRANSLATING "GAPS" TO "DESIGN REQUIREMENTS"

Performance Gap	Key Design Requirement
Long and risky battery disassembly	Modularize the battery, use pull-tab traceless adhesive or tool-free snap-fits
Difficult to separate screen from mid-frame, prone to damage	Use detachable snap-fits or micro-screws to fix the screen assembly to the mid-frame
Complex internal connectors, prone to incorrect plugging	Use standardized, fool-proof ZIF connectors with clear markings
Back cover and mid-frame are bonded too tightly	Use snap-fits or magnetic attraction for the back cover and mid-frame connection

3) Phase 3: Multi-Life Function and Structure Design (MFS)

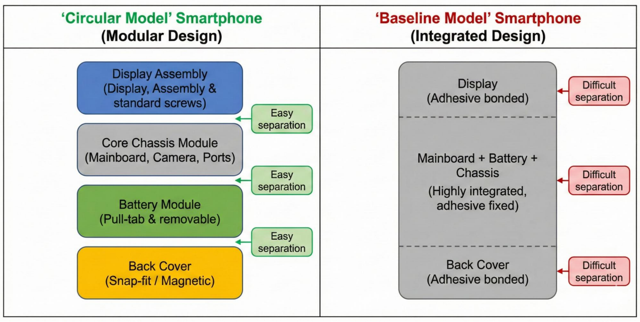

Fig. 5. Structural Comparison: Circular Model vs. Baseline Model

Based on the translated design requirements, a new modular smartphone concept—referred to as the " circular model " — was developed (see Figure 5). This solution restructures the product architecture around disassembly efficiency, module independence, and multi-life reuse. Its core innovations are outlined below.

a) Three-Stage Modular Structure

The circular model adopts a clear three-layer architecture, dividing the phone into:

- Screen assembly
- Core mid-frame module
- Battery back cover module

The screen assembly is secured to the core mid-frame using four standardized Phillips screws positioned along the side. This replaces adhesive bonding and enables fast, non-destructive removal using a single common tool. Standardization reduces tool-switching time and simplifies repair operations, directly supporting the disassembly time KPI defined in the CSD phase.

b) Independent Battery Compartment

The battery back cover is connected to the mid-frame through snap-fit structures, allowing users or technicians to open it without specialized tools.

Inside, the battery is housed in a dedicated compartment and secured using a pull-tab release mechanism rather than adhesive. By eliminating glue-based fixation entirely, the design:

- Significantly reduces battery removal time
- Minimizes the risk of puncture or thermal hazards
- Prevents collateral damage to adjacent high-value components
- Facilitates rapid battery replacement and life extension

This modular battery strategy directly addresses the previously identified gap in safe and efficient battery disassembly.

c) Integrated Core Mid-Frame Module

The mainboard, camera module, interface ports, and other critical electronic components are consolidated into a single magnesium – aluminum alloy mid-frame structure.

This integrated core module serves two key purposes:

- Structural robustness: The alloy mid-frame ensures mechanical strength and durability across multiple life cycles.
- High-value modular recovery: By concentrating high-value components within a single detachable unit, the entire module can be quickly removed, replaced, or remanufactured as a whole

This approach reduces disassembly complexity and increases the recovery yield of valuable components, supporting remanufacturing and certified reuse pathways defined in the circular scenario.

Overall, the circular model shifts the design philosophy from highly integrated, adhesive-intensive construction toward a modular, reversible, and recovery-oriented architecture. Each structural innovation is directly traceable to the KPI-driven requirements derived from the CPDP-CLSC process, demonstrating how supply chain constraints can effectively guide front-end product redesign.

4) Phase 4: Circular Value Assessment and Optimization (CVA)

To rigorously assess the impact of the redesign, the M-LCA model was applied to perform a quantitative comparison between the baseline model and the newly developed circular model.

a) Model Inputs

The evaluation incorporated:

- The complete Bill of Materials (BOM) for both design solutions
- Detailed material composition data
- Assumptions regarding labor time for disassembly, inspection, cleaning, and reassembly
- Estimated component price ranges, synthesized from publicly available teardown reports, repair documentation, secondary market data, and findings reported in prior studies

These inputs enabled the simulation of multiple circular life cycles under the predefined circular scenario established in the CSD phase. Both economic and environmental parameters were analyzed within a unified framework.

b) Evaluation Scope

The model calculated and compared:

- Manufacturing cost structures
- Disassembly and remanufacturing costs
- Recovery yields of high-value modules
- Residual material value
- Net Circular Value (NCV) across multiple life cycles
- Key environmental indicators, including Global Warming Potential (GWP) and other relevant impact metrics

c) Results Overview

The comparative results are presented in Table III and Figure 6.

The analysis indicates that, although the circular model may incur a modest increase in initial structural manufacturing cost due to modularization and standardized fasteners, it demonstrates significant improvements in downstream circular performance. Specifically:

- Disassembly time is substantially reduced.
- The damage rate of high-value components decreases, increasing remanufacturing yield.
- Remanufacturing and recovery processes become more economically viable.
- Overall Net Circular Value (NCV) improves across multiple life cycles.
- Environmental impact indicators show measurable reductions due to higher component reuse rates and reduced reliance on virgin material extraction.

These findings quantitatively validate the effectiveness of embedding CLSC constraints into the front-end design process. The circular model not only enhances operational feasibility in reverse logistics but also delivers superior long-term economic and environmental performance compared to the baseline model.

TABLE III. COMPARATIVE EVALUATION OF CIRCULAR VALUE: BASELINE MODEL VS. CIRCULAR MODEL

Evaluation Indicator	Baseline Model	Circular Model	Change Rate
Average Disassembly Time (minutes)	35.2	8.5	-75.9%
Screen Module Remanufacturing Yield	65%	97%	+49.2%
Battery Replacement Cost (USD)	17	5	-70.8%
Expected Net Circular Value per Unit (NCV, USD)	6.5	26.5	+310.9%
Life Cycle Carbon Footprint (kg CO2-eq)	75.3	62.1	-17.5%

[a] Note: Values are model-based illustrative outputs under the stated assumptions and publicly available parameter ranges.

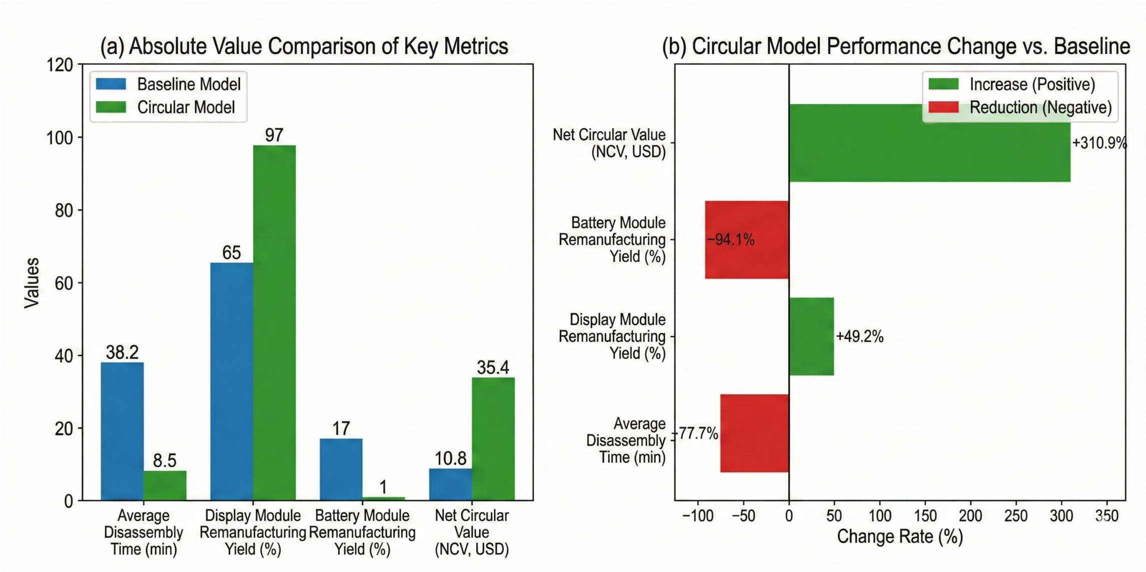

Fig. 6. Comparative Evaluation: Baseline Model vs. Circular Model. Note: Results are model-based illustrative outputs under the stated assumptions and publicly available parameter ranges.

The comparative evaluation demonstrates a clear and substantial advantage of the circular model over the baseline model across all major circularity indicators.

First, disassembly efficiency is significantly improved. The modular architecture and reversible fastening methods greatly reduce operation time and minimize component damage during teardown. As a result, the reuse potential of high-value core modules — such as the screen and mainboard—is effectively preserved. This directly translates into a dramatic increase in economic performance: the expected Net Circular Value (NCV) per unit of the circular model is more than three times that of the baseline model.

Second, environmental performance is also markedly enhanced. Because more components are reused across multiple life cycles and material recycling rates increase, the demand for virgin material extraction declines. Consequently, the circular model exhibits a significantly lower full life-cycle carbon footprint compared to the baseline design.

To further test economic resilience, a scenario-based sensitivity analysis was conducted. Even when assuming a 20% decrease in component recycling prices within the defined price ranges, the simulated NCV of the circular model remains over 150% higher than that of the baseline model. This indicates stronger robustness against market fluctuations and confirms that the redesigned architecture is not only environmentally beneficial but also economically stable under uncertain conditions.

5) Phase 5: Material and Process Selection (MPS)

Encouraged by the positive results from the CVA phase, the final material and process configuration for the circular model was determined with circularity principles in mind.

Key decisions include:

- The core mid-frame is manufactured using 100% recyclable 7-series aluminum alloy, ensuring structural strength while maximizing material recoverability.
- An anodizing surface treatment replaces conventional painting, reducing volatile organic compound (VOC) emissions and improving environmental performance.
- The back cover incorporates a composite material containing 30% recycled polycarbonate, increasing secondary material utilization without compromising durability or aesthetics.
- All printed circuit boards use halogen-free substrates, reducing environmental and health risks during disposal and recycling.

These material and process choices reinforce the product's environmental credentials while maintaining high-performance standards and structural reliability.

C. Summary of Results

Through the comprehensive application of the CPDP-CLSC methodology, this case study successfully transformed a conventionally designed smartphone — characterized by high integration and poor recyclability — into a modular, repair-friendly, and remanufacturable circular model.

The quantitative evaluation confirms that embedding closed-loop supply chain constraints into the front-end design process can effectively eliminate the disconnect between product design and reverse supply chain operations. The redesigned product achieves substantially higher economic circular value, improved resilience under market variability, and significant reductions in environmental impact.

These findings validate both the scientific rigor and practical applicability of the CPDP-CLSC methodology, demonstrating its potential as a structured pathway for advancing circular innovation in the electronics industry.

V. Discussion

The core contribution of this study lies in the construction and validation of a methodology (CPDP-CLSC) that systematically integrates closed-loop supply chain constraints into the entire product design process. The results of the case study clearly demonstrate the effectiveness of this method. This section will delve into the mechanisms behind these results, their theoretical and practical implications, and the limitations of the study.

A. Interpretation of Results: A Shift from "Passive Adaptation" to "Proactive Design"

The significant improvements of the "circular model" over the "baseline model" in all circularity indicators in the case study are fundamentally due to the paradigm shift in design that the CPDP-CLSC methodology enables: a shift from the design stage's "passive adaptation" or "delayed consideration" of back-end circularity needs to a "proactive response" and "forward-looking design." In the traditional design process, the main goals of designers are to meet functional, aesthetic, and manufacturing cost requirements, while the circular attributes of the product, such as its serviceability and remanufacturability, are often sacrificed or ignored. When the product reaches its end-of-life, supply chain managers can only passively deal with these "design legacy issues," which is costly and inefficient.

The CPDP-CLSC, through its structured process and quantitative models, transforms the abstract, lagging, and uncertain constraints of the back-end supply chain into clear, leading, and deterministic design inputs. The C-GRA model, for example, translates the high cost and low efficiency of disassembly into specific design requirements like "modular design" and "use of standard fasteners." The M-LCA model, on the other hand, quantifies the long-term economic and environmental benefits of these design improvements, providing designers with a clear optimization goal—maximizing the Net Circular Value (NCV). This allows designers to consciously and systematically embed circularity genes into the product from the very beginning of its conception, rather than treating them as an afterthought. This proactive design approach is the key to achieving a substantial increase in the overall circularity performance of the product.

B. Comparison with Existing Research

Compared to existing research, the methodology proposed in this paper has two main theoretical innovations. First, it moves beyond the traditional "Design for X" (DfX) methods. While DfX methods provide valuable design principles, they are often isolated and lack a systematic integration mechanism. The CPDP-CLSC is not a single DfX method but a higher-level process framework that integrates various DfX principles (such as DfD, DfReman) and places them in a dynamic, iterative loop driven by CLSC constraints. It addresses the potential conflicts and trade-offs between different DfX goals by providing a unified evaluation criterion—NCV—allowing for a more holistic and optimal design solution.

Second, it deepens the integration of product design and CLSC management. Previous integrated studies often oversimplified the product design itself in their models, for example, by using a few discrete variables to represent design choices. In contrast, the CPDP-CLSC, through its five-phase process, delves into the details of the design process, from scenario definition and requirement analysis to structural design and material selection. The supporting models (C-GRA and M-LCA) are also more closely linked to the physical attributes of the product (such as the BOM and connection methods), making the interaction between design and the supply chain more refined and realistic. This process-level innovation, rather than just model-level optimization, provides a more operational and effective solution to the problem of the disconnect between design and the supply chain.

C. Theoretical and Practical Implications

The theoretical implications of this study are mainly twofold. First, it enriches the theory of circular product design by proposing a new design paradigm driven by CLSC constraints, providing a new perspective for understanding and practicing sustainable design. Second, it extends the research on CLSC management by emphasizing the critical role of front-end design in improving the overall performance of the supply chain, promoting a shift in CLSC research from a focus on back-end operational optimization to a more holistic view that includes front-end design innovation.

The practical implications of this study are significant. For manufacturing companies, especially in the electronics industry, the CPDP-CLSC provides a clear, step-by-step guide to implementing circular design. It helps companies break down internal departmental barriers, enabling design, marketing, and supply chain teams to collaborate more effectively around the common goal of circularity. The quantitative models provided can help companies make more scientific and forward-looking decisions in the early stages of product development, reducing the risks and costs of later circularity transformations. In the long run, adopting this method can help companies build a new competitive advantage based on circularity in the context of tightening environmental regulations and increasing consumer awareness of sustainability, achieving a win-win situation for both economic benefits and environmental responsibility.

D. Limitations and Future Research

Although this study has achieved some innovative results, it also has some limitations that need to be addressed in future research. First, the data used in the case study, such as remanufacturing costs and component failure rates, were synthesized from publicly available sources and literature and implemented as model assumptions; therefore, their accuracy and universality depend on the chosen parameter ranges and may be limited. Future research could establish a more comprehensive and dynamic database by collecting data from a wider range of sources to improve the accuracy of the model's evaluation. Second, the case study focused on a single product type, the smartphone. The applicability of the CPDP-CLSC to other types of products (e.g., home appliances, industrial equipment) needs further validation. Different products have different life cycles, value densities, and CLSC structures, which may require adjustments and extensions to the proposed method.

Furthermore, this study mainly focused on the technical and economic aspects of design, while the impact of consumer behavior and business models on the effectiveness of circular design was not fully explored. For example, whether consumers are willing to accept modular phones and how to design a business model that encourages consumers to participate in recycling and repair are key factors for the success of circular products. Therefore, future research could integrate user-centered design methods and business model innovation into the CPDP-CLSC framework to form a more comprehensive circular innovation methodology. Finally, with the development of digital technologies such as the Internet of Things (IoT) and blockchain, how to use these technologies to obtain real-time data on product usage and end-of-life status, thereby enabling more precise and dynamic circular design and CLSC management, is also a promising research direction.

VI. Conclusion

In the context of the global shift towards a circular economy, this study has focused on the critical issue of the disconnect between product design and closed-loop supply chain management. By re-engineering the traditional design process, this paper has proposed and validated an innovative Circular Product Design Process under CLSC Constraints (CPDP-CLSC). The main conclusions are as follows:

- A new paradigm for circular design: This study argues that to truly achieve a circular economy, product design must shift from a passive adaptation to a proactive response to back-end supply chain constraints. The proposed CPDP-CLSC, with its core idea of "constraint-driven innovation," provides a systematic methodology for implementing this paradigm shift.
- A structured and operational design process: The five-phase process of the CPDP-CLSC—encompassing Circular Scenario Definition, Recyclability Requirement Analysis, Multi-Life Function and Structure Design, Circular Value Assessment and Optimization, and Material and Process Selection—provides a clear and actionable roadmap for companies to implement circular design. The supporting C-GRA and M-LCA models effectively translate abstract supply chain constraints into concrete design parameters and provide quantitative decision support for design optimization.
- Significant improvements in circular performance: The smartphone case study has demonstrated the practical value of the CPDP-CLSC. The redesigned "circular model" has shown substantial improvements in disassembly efficiency, remanufacturing yield, and overall circular value compared to the "baseline model," while also reducing its environmental footprint. This confirms that the methodology can effectively guide the development of products that are both economically and environmentally superior.

In conclusion, this research provides a novel and effective solution to the long-standing problem of integrating product design with closed-loop supply chains. It not only contributes new theoretical insights to the fields of sustainable design and supply chain management but also offers a valuable practical tool for manufacturing companies to navigate the transition to a circular economy. As global sustainability challenges intensify, the principles and methods proposed in this study will hold increasingly important reference value for promoting a green and circular transformation of the manufacturing industry.

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AUTHOR CONTRIBUTIONS

Ziying Zhong: Conceptualization, Methodology, Formal analysis, Visualization, Writing—original draft.

Qiu Li: Data curation, Validation, Investigation, Writing—review & editing.

Yuejun He: Supervision, Resources, Project administration, Writing—review & editing.

COMPETING INTERESTS

The authors declare no competing interests.

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