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The Circular Economy Imperative: Synergistic Effects of Modularity, Disassembly, and Recyclability in Product Design

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Abstract

The transition to a circular economy fundamentally depends on product design innovations prioritizing three critical pillars: modularity, easy disassembly, and recyclable materials. This chapter argues that these pillars are essential to break away from linear "take-make-dispose" models and demonstrates that their effectiveness depends on synergistic integration rather than isolated implementation. Unlike existing circularity metrics (Material Circularity Indicator, Overall Circularity Effectiveness, 9R Index), which employ additive weighted sums—allowing weak performance in one dimension to be compensated by others—this research introduces a Circular Effectiveness Index (CEI) using multiplicative logic, where pillar interdependence creates non-compensatory threshold effects. When any single pillar approaches zero, the system's circularity collapses, regardless of excellence in other dimensions. Through comparative case study analysis across consumer electronics (Fairphone), textile engineering (Polyamide 6 mono-material systems), and

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furniture design (glue-free assembly), we demonstrate substantial synergistic effects when all three pillars are simultaneously optimized. A critical finding reveals that when disassembly feasibility falls below minimum thresholds, recycling infrastructure becomes economically non-viable regardless of material composition. The framework operationalizes core consumer rights—right-to-repair, right-to-information, and right-to-sustainable-products—by demonstrating how design architecture enables or constrains consumer agency in circular systems. CEI provides manufacturers and policymakers with systematic methodology for evaluating design decisions and prioritizing interventions with highest circular impact.

13.1 Introduction

The linear "take-make-dispose" economic model has reached structural limits. Industrial economies extract over 100 billion tonnes of raw materials annually, yet less than 9% re-enter productive cycles (Saraji & Torabi, 2025). Waste accumulation projected to exceed 3.4 billion tonnes by 2050 demonstrates that linear growth is incompatible with planetary boundaries (Mazur-Wierzbicka, 2021).

The Circular Economy (CE) redefines economic activity around closed material loops where products maintain maximum value through extended use, repair, and regeneration (Ellen MacArthur Foundation, 2015). Unlike linear models treating waste as inevitable, circular systems internalize material flows, transforming end-of-life products into feedstock. The EU Circular Economy Action Plan (2020) and SDG 12 mandate decoupling economic growth from resource consumption.

The transition to circular economy fundamentally intersects with consumer rights and empowerment. Circular economy scholarship increasingly recognizes that consumers require (1) right-to-repair—access to spare parts, technical documentation, and non-proprietary tools enabling independent maintenance; (2) right-to-information—transparent product architecture and material composition data supporting informed purchasing decisions; and (3) right-to-sustainable-products—assurance that goods can genuinely circulate through repair, reuse, and high-quality recycling rather than predetermined obsolescence. These rights cannot be legislated in isolation from product design—a product designed with irreversible assembly or incompatible material blends structurally prevents consumers from exercising repair rights regardless of legal entitlements. Design thus becomes the material infrastructure enabling or constraining consumer agency in circular systems.

However, circularity cannot be achieved retroactively. Research demonstrates that 80% of a product's environmental and economic costs are determined at the design stage, before manufacturing begins. This "design determinism" reveals a critical insight: circular economy transitions depend less on waste management innovation than on product design transformation. Conversely, products designed with reversible fasteners and mono-materials inherently enable circularity.

Academic literature documents three design strategies supporting circularity. Modularity extends product lifespans 30-50% through component upgrades (Lau et al., 2011; Umeda et al., 2005). Design for Disassembly (DfD) reduces end-of-life processing energy 60-80% versus destructive shredding (Forst, 2020; Wang & Zhang, 2010). Mono-material designs enable closed-loop recycling maintaining virgin-equivalent quality (Rahee & Sarker, 2024).

Yet existing research treats these strategies as independent variables rather than systemic interactions. Studies optimize modularity without addressing whether non-recyclable modules relocate waste (van den Berg & Bakker, 2015), advance recyclable polymers without considering adhesive barriers, or assume material homogeneity ignoring blend contamination. This fragmentation produces suboptimal outcomes: technically modular products remain economically irreparable due to adhesive barriers; recyclable materials become inaccessible through integrated construction.

Moreover, existing circularity assessment methodologies fail to capture these interdependencies. The Material Circularity Indicator (MCI) focuses on mass flows, treating product architecture as secondary (Ellen MacArthur Foundation, 2015). The Overall Circularity Effectiveness (OCE) index employs additive aggregation, assuming compensatory trade-offs between dimensions (Baumer-Cardoso et al., 2023). The 9R Circularity Index combines pillars through weighted averages (Muñoz et al., 2024). These additive models share a critical limitation: they permit poor performance in one dimension to be numerically compensated by excellence in others, masking fundamental physical incompatibilities.

This chapter addresses this limitation by proposing the Circular Effectiveness Index (CEI), employing multiplicative rather than additive logic to capture non-compensatory dynamics between Modularity, Design for Disassembly, and Material Recyclability. Unlike weighted sums where dimensions trade off, CEI's formulation ($M \times D \times R$) mathematically represents physical reality: when any pillar approaches zero, system circularity collapses regardless of other pillars' strength. A product with perfect recyclability ($R = 1.0$) but zero disassembly ($D = 0$) achieves zero circular effectiveness—a constraint invisible to additive models.

The theoretical justification for a three-pillar framework derives from functional necessity within circular systems. Modularity addresses temporal obsolescence—enabling products to evolve through component replacement. Disassembly addresses physical access—ensuring that replacement and material recovery are economically feasible. Recyclability addresses material quality—guaranteeing that recovered materials maintain value. These three functions are irreducible: omitting any single pillar creates systemic failure regardless of excellence in the remaining dimensions.

The novelty of this research lies in three contributions. First, CEI represents the first multiplicative circularity metric in the literature—existing indices (MCI, OCE, 9R) employ additive aggregation despite acknowledging pillar interdependencies (Elia et al., 2017; Munonye, 2025). Second, we demonstrate through cross-sector case studies that the three-pillar framework generalizes across product categories with vastly different material compositions and lifecycles. Third, preliminary analysis indicates that when disassembly approaches 0.30, recycling infrastructure may shift from manual separation to bulk shredding, potentially limiting realized recyclability below 0.40. This threshold hypothesis requires validation.

Methodology employs systematic literature review comparing existing metrics, strategic case selection across electronics (Fairphone), textiles (PA6 systems), and furniture (glue-free assembly), and synergy quantification through multiplicative interaction analysis.

Section 13.2 presents theoretical framework and literature review. Section 13.3 details methodology. Sections 13.4–13.5 present case evidence and synergy analysis. Section 13.6 concludes with implications.

13.2 Literature Review and Theoretical Framework

The theoretical framework of this research is built upon the "Circular Economy Imperative," which necessitates a shift from identifying waste to designing it out of the system. This section defines the three core pillars and analyzes their synergistic interactions.

13.2.1 The first pillar: Modularity and obsolescence management

Modularity is defined as the process of dividing a complex product system into smaller, independent subsystems (modules) that can be designed and produced independently. In the context of circularity, modularity is the primary defense against premature obsolescence. According to Bocken et al., (2016),

modular design allows for the management of "part obsolescence," potentially extending a product's total service life by over 30%. Modular architecture enables targeted repair and upgrades without discarding the entire unit.

13.2.2 The second pillar: Design for Disassembly (DfD)

Design for Disassembly (DfD) is a planning approach ensuring that a product can be easily, rapidly, and economically separated into its components at the end of its life. DfD prioritizes reversible fastening methods—such as screws or snap-fits—over permanent bonds like glues or welding. DfD is crucial for economic viability; studies show that disassembly-based end-of-life processing consumes 60-80% less energy compared to traditional shredding methods.

13.2.3 The third pillar: Recyclable materials and material health

The third pillar focuses on the material level, specifically the use of non-toxic, preferably "mono-materials" that can be returned to the raw material flow without quality loss. In the textile industry, blended fibers (e.g., poly-cotton) present a significant barrier to recycling due to the difficulty of separating distinct polymers. Conversely, mono-material designs (e.g., 100% Polyamide 6) facilitate "fiber-to-fiber" recycling, ensuring materials are kept at their highest value.

13.2.4 Positioning the three-pillar framework within existing circular economy models

The circular economy literature presents multiple frameworks for operationalizing closed-loop systems. The Ellen MacArthur Foundation's Butterfly Diagram (2015) distinguishes biological and technical nutrient cycles, prioritizing material flow optimization but providing limited guidance on product architecture decisions. The Cradle-to-Cradle (C2C) framework emphasizes material health and perpetual cycling, yet treats design interventions (modularity, disassembly) as derivative outcomes of material selection rather than independent pillars (McDonough & Braungart, 2002). The 9R Framework (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle) facilitates a hierarchy of circular strategies ranked by resource efficiency (Potting et al., 2017). However, the 9R model functions as a categorical inventory describing what circular activities exist without prescribing how product architecture enables or constrains those activities.

The three-pillar framework differs fundamentally by focusing on design-phase interdependencies. While existing frameworks address "what" should happen to products (repair, circulation), the three-pillar model addresses "how" product architecture enables or prevents those outcomes. Modularity is not merely desirable but a prerequisite for economic repair. Disassembly is not an end-of-life activity but a design constraint determining whether theoretical recyclability becomes realized. Material selection is not independent of fastening methods—mono-materials provide negligible circular benefit if adhesive bonding prevents access.

13.2.5 Circularity assessment metrics and the additive limitation

Beyond conceptual frameworks, operationalizing circularity requires quantitative assessment methodologies. A systematic review by Elia et al. (2017) identified over 60 circularity indicators, yet found persistent gaps in micro-level (product) assessment and value durability measurement. Table 13.1 compares four prominent metrics—Material Circularity Indicator (MCI), Overall Circularity Effectiveness (OCE), 9R Circularity Index, and Circular Economy Indicator Prototype (CEIP)—with the proposed CEI across scope, aggregation method, and pillar coverage.

Material Circularity Indicator (MCI): Developed by the Ellen MacArthur Foundation (2015), MCI quantifies the extent to which linear material flows are minimized. The metric focuses on virgin material input and unrecoverable waste output, scaled by a utility factor reflecting product lifespan. While comprehensive for material flow analysis, MCI treats product architecture as a secondary utility adjustment. Modularity and disassembly appear only indirectly through lifespan extension.

Overall Circularity Effectiveness (OCE): Baumer-Cardoso et al. (2023) developed OCE to assess manufacturing companies through 15 indicators spanning inputs and outputs. The index employs equal weighting: OCE = (1/15) Σ Indicator_i, producing scores from 0% (fully linear) to 100% (ideal circularity). This additive structure assumes all dimensions are equally important and implicitly permits compensatory trade-offs—poor disassembly performance can be numerically offset by strong performance in other indicators.

9R Circularity Index: Muñoz et al. (2024) operationalized the 9R Framework into a quantitative index using Analytic Hierarchy Process (AHP) to weight

Table 13.1 Comparison of circularity metrics.

Metric	Ref.	Primary Scope	Aggregation Method	Coverage of M, D, R*	Key Limitation / Gap
MCI	Ellen MacArthur Fdn. (2015)	Material flows (Product/Company)	Composite ratio (Material flow-based)	Indirect (via utility factor)	Focuses heavily on mass flows; treats architecture as secondary.
OCE	Baumer-Cardoso et al. (2023)	Manufacturing inputs/ outputs	Additive (Equal weights)	Partial (Lifespan extension)	Compensatory nature; assumes trade-offs between 15 indicators.
9R Index	Munoz et al. (2024)	Product circular strategies	Additive (AHP weights)	Explicit (Disassembly potential)	Weighted averages allow compensation between weak and strong strategies.
CEIP	Cayzer et al. (2017)	Product lifecycle	Additive (Points system)	Discussed (Interactions noted)	Acknowledges trade-offs but ultimately sums scores additively.
CEI	This study	Product design pillars	Multiplicative	Explicit ($M \times D \times R$)	Requires normalized coefficients (0-1 scale); threshold sensitivity necessitates sector-specific validation.

*M = Modularity, D = Design for Disassembly, R = Recyclable Materials.

strategies hierarchically (Rethink > Reduce > ... > Recover). The index explicitly incorporates disassembly potential through connection type assessment (mechanical fasteners score higher than welding/adhesives). However, strategy scores are aggregated through weighted averages (additive logic), maintaining compensatory assumptions.

Circular Economy Indicator Prototype (CEIP): Cayzer et al. (2017) developed a points-based questionnaire assessing product circularity across lifecycle stages. The prototype acknowledges "complex interactions" between dimensions—noting, for example, that lightweighting may necessitate harder-to-recycle materials. Despite recognizing interdependencies conceptually, CEIP aggregates scores additively through summation.

The Additive Limitation: All reviewed metrics employ additive aggregation (weighted sums or averages). This mathematical structure embeds a compensatory assumption—weak performance in one dimension can be numerically offset by strong performance in others. Consider a hypothetical product scoring: Modularity = 0.9, Disassembly = 0.1, Recyclability = 0.9. An additive model yields: (0.9 + 0.1 + 0.9)/3 = 0.63, suggesting "moderate circularity." However, physical reality contradicts this: with disassembly near zero (adhesive bonding), neither modularity (components cannot be accessed) nor recyclability (materials cannot be separated) realizes its full potential. The dimensions are non-substitutable, yet additive models treat them as independent contributors.

As Table 13.1 illustrates, the fundamental distinction between existing metrics and CEI lies in aggregation logic: additive versus multiplicative. Munonye (2025) identifies this as a persistent gap: existing metrics fail to capture systemic interdependencies where pillar interactions create multiplicative rather than additive effects. This limitation motivates CEI's multiplicative formulation, where $M \times D \times R$ mathematically represents non-compensatory dynamics—when any pillar approaches zero, the system's effectiveness collapses, regardless of the strength of the other pillars.

13.3 Methodology

13.3.1 Research design and literature foundation

This research employs a mixed-methods approach combining systematic literature review, comparative case study analysis, and quantitative metric development. The study addresses two critical gaps: (1) pillar synergistic interactions remain undertheorized despite extensive documentation of

individual strategies (van den Berg & Bakker, 2015), and (2) existing circularity metrics employ additive aggregation despite recognizing interdependencies (Elia et al., 2017; Munonye, 2025).

Phase One employed structured literature review across academic databases using systematic keyword combinations covering modularity, disassembly, and recyclable materials in circular economy contexts. Inclusion criteria required sources to: (1) explicitly address at least one design pillar, (2) provide empirical data rather than purely conceptual discussion, and (3) focus on consumer products. Exclusion criteria eliminated sources treating circularity solely as end-of-life waste management without design-phase interventions (Mazur-Wierzbicka, 2021).

Literature review revealed a notable scarcity of research addressing multi-pillar integration compared to single-pillar optimization studies, confirming the research gap this study addresses. The majority of sources focused on individual design strategies (modularity OR disassembly OR recyclability) rather than their synergistic interactions.

Systematic review of existing circularity metrics identified four prominent indices: Material Circularity Indicator (Ellen MacArthur Foundation, 2015), Overall Circularity Effectiveness (Baumer-Cardoso et al., 2023), 9R Circularity Index (Muñoz et al., 2024), and Circular Economy Indicator Prototype (Cayzer et al., 2017). All employ additive aggregation (weighted sums or averages), permitting compensatory trade-offs where poor performance in one dimension is numerically offset by others. This structural limitation—masking pillar interdependencies—motivated CEI's multiplicative formulation.

13.3.2 The Circular Effectiveness Index (CEI): Theoretical framework

Conceptual Foundation: CEI is proposed as a **diagnostic framework**—not a standardized compliance metric—for comparative analysis of circular design strategies. The multiplicative formulation encodes non-compensatory logic: deficiency in one dimension eliminates effectiveness regardless of strengths in others.

CEI = M × D × R

Where:

- **M** = Modularity coefficient (0.00-1.00): extent to which product architecture enables component-level upgradeability
- **D** = Disassembly coefficient (0.00-1.00): ease of material/component separation at end-of-life

- **R** = Recyclability coefficient (0.00-1.00): material quality retention through recycling cycles

The multiplicative structure reflects physical reality: when any pillar approaches zero, dependent pillars cannot realize their potential. A product with perfect recyclability (R = 1.0) but permanent bonding (D→0) achieves near-zero circular effectiveness because materials remain inaccessible.

Purpose and Scope: CEI functions for comparative analysis within or across sectors, identifying optimization trade-offs and "pillar collapse" scenarios. It is NOT proposed as a regulatory metric in current form; scoring protocols (Section 13.3.3) require validation across larger product populations before adoption as compliance thresholds for eco-labeling or Extended Producer Responsibility schemes.

Consumer Rights Linkage: The pillars operationalize core consumer rights within circular economy frameworks: M enables **right-to-repair** (component upgradeability without manufacturer dependency), D enables **right-to-information** (transparent architecture via Digital Product Passports documenting disassembly protocols), R enables **right-to-sustainable-products** (material loop closure through quality-retained recycling).

Critical Methodological Distinction: 13.3.2 defines theoretical CEI (multiplicative logic and conceptual boundaries). Section 13.3.3 operationalizes scoring for applied analysis. Scoring rubrics presented in Section 13.3.3 are preliminary protocols synthesized from literature and case data, **requiring empirical validation** across statistically significant product populations before standardization as regulatory metrics.

13.3.3 CEI Operationalization: Scoring protocol and measurement rubrics

Unlike existing indices that employ additive weighted sums (OCE: equal weighting across 15 indicators; 9R Index: AHP-derived weights), CEI's multiplicative structure requires normalized coefficients (0-1 scale) where zero represents complete system failure. This reflects physical reality: zero disassembly (D = 0) prevents material access regardless of recyclability (R).

Measurement Approach: Each coefficient scored 0.00-1.00 combining quantitative parameters (time, recovery rates) and qualitative assessments (tool accessibility, functional independence). Tables 13.2–13.4 provide detailed rubrics synthesized from industry standards (iFixit methodology),

Table 13.2 Modularity coefficient (M) scoring protocol.

M Range	Upgradeability Criterion	Replacement Time	Tool Requirements	Example Applications
0.90-1.00	Full module independence; single-component replacement restores function	<5 minutes	Tool-free or single standard tool	Fairphone battery, Framework laptop RAM
0.70-0.89	High independence; 2-3 components replaceable without full disassembly	5-15 minutes	1-2 standard tools, publicly available	Laptop HDD, automotive headlights
0.40-0.69	Moderate modularity; component access requires partial system disassembly	15-30 minutes	Specialized tools, calibration may be needed	Smartphone screens (adhesive removal)
0.10-0.39	Minimal modularity; extensive disassembly, professional service typical	>30 minutes	Proprietary tools, training required	Glued batteries, integrated PCBs
0.00-0.09	Non-modular construction; mono-block or functionally inseparable architecture	N/A (destructive)	Cutting/grinding required	Textiles, cast metal tools, injection-molded products

*__Calculation:__ M = (Independently replaceable modules / Total functional subsystems) × Time accessibility factor × Tool accessibility factor. __Sectoral constraint:__ Non-modular product categories (textiles, castings, continuous materials) default M≤0.10 regardless of material composition, reflecting functional reality rather than design failure. __Examples:__ Fairphone 5 (7/16 modules, 8-min avg replacement using standard screwdriver) → M = 0.85; PA6 textile garment (non-modular fabric architecture) → M = 0.10.

Table 13.3 Disassembly Coefficient (D) Scoring Protocol.

D Range	Separation Method	Time per Joint	Reversibility	Tool Accessibility	Example Fastening Systems
0.90-1.00	Tool-free or passive separation	<2 minutes	Fully reversible, unlimited cycles	Manual force only	Snap-fits, magnetic closures, LEGO-style interlocking
0.70-0.89	Standard tool disassembly	2-10 minutes	Reversible, >20 cycles typical	Standard screwdrivers, wrenches	Phillips screws, hex bolts, threaded fasteners
0.40-0.69	Specialized tools; semi-permanent fastening	10-30 minutes	Semi-reversible, 5-10 cycles	Proprietary drivers, heat guns	Security screws (Torx), moderate adhesives
0.10-0.39	Destructive or near-destructive methods required	>30 minutes	Minimally reversible, 1-3 cycles	Professional equipment, may void warranty	Strong adhesives (solvent required), ultrasonic welds
0.00-0.09	Non-separable without material loss	N/A	Irreversible; separation prevents reassembly	Cutting, grinding, chemical dissolution	Structural adhesives, fusion bonding, permanent welding

***Calculation:** D = (Reversible joints / Total joints) × (1 / Average separation time factor) × Tool accessibility factor.
Molecular-level disassembly: Mono-material products (e.g., 100% PA6 textiles) receive D credit for chemical homogeneity—material sorting barriers are eliminated when no incompatible polymers require separation—even when physical joints are permanent. However, D remains <1.0 because macro-level collection infrastructure still requires sorting target materials from mixed waste streams. **Examples:** Fairphone 5 (23 reversible screws, 6-min avg separation) → D = 0.64; PA6 mono-material textile (molecular homogeneity eliminates polymer separation) → D = 0.70; glue-free kitchen assembly (47 mechanical fasteners, 4-min avg) → D = 0.72.

Table 13.4 Recyclability Coefficient (R) Scoring Protocol.

R Range	Recovery Process	Quality Retention	Cycle Limit	Infrastructure	Example Materials
0.90-1.00	Chemical recycling to monomer; theoretically infinite cycles	Virgin-equivalent, <5% loss/cycle	Unlimited (molecular structure restored)	Specialized facilities operational	PA6 ECONYL, PET depolymerization, aluminum
0.70-0.89	Thermoplastic reprocessing; mechanical recycling with minor degradation	High quality, 10-20% loss over 5 cycles	5-10 cycles before downcycling	Industrial-scale mechanical sorting	Steel, copper, PE/PP mono-plastics
0.40-0.69	Mechanical recycling with downcycling; cascade to lower-value applications	Moderate, 30-50% loss/ cycle	2-4 cycles before energy recovery	Basic sorting networks (manual or density)	Mixed plastics, polycotton blends (mechanical only)
0.10-0.39	Energy recovery or extreme downcycling; minimal material loop	Severe, 60-80% loss	1-2 cycles maximum	Minimal sorting; contamination tolerated	Contaminated plastics, multi-layer packaging
0.00-0.09	No viable recovery; landfill or incineration without energy capture	Complete loss	Zero	No infrastructure or economics prohibit use	Hazardous composites, heavily contaminated waste

***Calculation:** R = Quality retention factor × Cycle limit factor × Infrastructure availability factor. **Contamination penalty:** Blended or composite materials incur R reduction proportional to separation difficulty—PA6/elastane (95/5) blend achieves R=0.50 vs. pure PA6 R=0.93 due to elastane contamination or costly separation requirements. **Examples:** Fairphone aluminum housing (6061 alloy, mechanical recycling, 95% quality retention after 5 cycles) → R = 0.81; PA6 mono-material via ECONYL (chemical depolymerization to caprolactam, 98% virgin-equivalent quality, unlimited cycles) → R = 0.93; polycotton blend 50/50 (mechanical downcycling only, fiber separation economically prohibitive) → R = 0.30.

technical guidelines (ISO disassembly standards), and peer-reviewed lifecycle assessments.

Preliminary Protocol Caveat: The scoring rubrics are derived from literature synthesis and case-specific technical data, not standardized measurement across large product populations. Threshold values (e.g., "D<0.30 suggests recyclability barriers") represent preliminary hypotheses requiring empirical validation through controlled experiments or large-N statistical analysis before adoption as design standards or regulatory thresholds.

Composite CEI Calculation:

Final CEI score computed as: **CEI = M × D × R**

Resulting CEI values range from 0.000 (complete circularity failure) to 1.000 (theoretical maximum). Preliminary threshold interpretations derived from case analysis:

- **CEI > 0.25:** Strong circular design; multiple pillars optimized
- **CEI 0.10-0.25:** Moderate circular design; at least one pillar well-optimized
- **CEI < 0.10:** Weak circular design; pillar collapse in multiple dimensions

Caveat: These thresholds are preliminary hypotheses requiring quantitative validation through controlled experimentation or large-N statistical analysis before adoption as eco-labeling criteria or regulatory standards.

13.3.4 Case study selection

Three cases spanning consumer electronics, textiles, and built environment were selected to test whether the framework generalizes across product categories with vastly different lifespans, material compositions, and end-of-life pathways. Multi-sector validation provides stronger evidence than single-industry studies, as consistent patterns across heterogeneous contexts suggest fundamental rather than sector-specific dynamics.

Selection Criteria: Cases required: (1) documented application of at least two design pillars simultaneously, (2) quantitative performance data availability (repairability scores, lifecycle cost analysis, material recovery rates), (3) commercial-scale implementation rather than laboratory prototypes, and (4) geographic diversity to account for varying regulatory environments.

Electronics Sector – Fairphone: Paradigmatic modular smartphone (operational history: 2013-present) with verified iFixit 10/10 repairability score. Seven-module architecture enables independent component replacement

without specialized tools, isolating Modularity×Disassembly interaction. Industry-standard components allow attribution of circular performance to design architecture rather than material innovation.

Textile Sector – PA6 Mono-material Systems: Polyamide 6 (PA6) demonstrates chemical recyclability through depolymerization to caprolactam monomer—a closed-loop pathway unavailable to polyester, acrylic, or blended fibers (Ellen MacArthur Foundation, 2017). Industrial-scale implementations include Aquafil's ECONYL® (36,000 tonnes/year processing capacity; 90-95% caprolactam recovery) and RadiciGroup's Dorix® line (100% PA6 garments), providing commercial validation. Comparison with blended fibers (polycotton, PA6/elastane) demonstrates how material composition alone drives circular effectiveness, isolating Recyclability pillar while controlling for modularity and disassembly.

Built Environment Sector – Glue-Free Assembly: Valcucine kitchen systems and CIRCuIT Project (Hamburg school buildings) demonstrate Disassembly×Recyclability interaction in durable goods with 20+ year lifespans (CIRCuIT Project, 2021). Mechanical fastening eliminates adhesives, enabling high material recovery rates (aluminum 95%, wood 70%). The CIRCuIT Project achieved 37-61% lifecycle cost savings through material reuse across renovation cycles, demonstrating that reversible fastening transforms construction waste into reusable asset stocks. This contrasts with electronics (3-5 years) and textiles (1-3 years), testing interaction patterns across temporal scales.

Comparative Logic: This triangulation isolates pillar contributions while revealing interaction patterns: Fairphone (M+D focus) demonstrates modularity-disassembly synergy with controlled recyclability; PA6 systems (R focus) demonstrate recyclability potential with minimal modularity; glue-free assembly (D+R focus) demonstrates disassembly-recyclability synergy in long-lifespan products. All cases represent commercial implementations with verified quantitative data, avoiding speculative bias where conceptual designs receive equal weight to operational systems. Consistent patterns across heterogeneous contexts (thermoplastics, metals, composites; 3-20+ year lifespans; repair, chemical recycling, reuse) suggest fundamental rather than sector-specific dynamics.

13.3.5 Methodological limitations

Case Generalizability: Three cases meet Design Research Methodology minimum requirements (Blessing & Chakrabarti, 2009) and align with

comparable circularity studies (OCE: 4 cases; 9R Index: 5 cases; CEIP: 1 case), but cannot capture full product diversity. Validation across additional categories (automotive, consumer appliances, medical devices) would strengthen generalizability claims.

Observational Design Constraints: Observational case research precludes isolation of confounding variables—Fairphone's success may reflect sustainability-conscious consumer positioning beyond design attributes; ECONYL's viability benefits from EU circular economy mandates creating regulatory pull. Realized circular effectiveness likely varies across regulatory and economic contexts not captured in three-case analysis.

Coefficient Assignment Subjectivity: Scoring relies on industry heuristics (15-minute disassembly benchmark for consumer electronics) and published lifecycle assessment data rather than AHP-validated expert consensus, introducing researcher judgment. Future work should develop sector-specific scoring rubrics through expert panels using systematic protocols (e.g., Delphi method) to reduce assignment variability and establish inter-rater reliability.

Threshold Validation: Threshold claims (e.g., "$D < 0.30$ suggests recyclability barriers") are preliminary hypotheses derived from three-case qualitative analysis, not validated breakpoints. The $D \approx 0.30$ threshold emerged empirically from comparing PA6 mono-materials ($D = 0.70$, $R = 0.93$) against polycotton blends ($D = 0.30$, $R = 0.30$), suggesting that disassembly barriers below this level may prevent realization of intrinsic recyclability. However, quantitative threshold determination requires controlled experimentation or large-N statistical analysis beyond this study's scope. These values should be interpreted as directional indicators for future empirical testing rather than established design standards or regulatory criteria.

Data Access Constraints: Reliance on publicly available data (iFixit teardowns, company sustainability reports, EU project documentation) restricts access to proprietary lifecycle assessment databases. The study synthesizes existing assessments rather than conducting original LCA, precluding sensitivity analysis on coefficient uncertainty. Third-party verification protocols would strengthen operationalization for policy applications.

Geographic and Infrastructure Variability: R coefficients reflect infrastructure availability in developed economies (EU, North America). Recyclability effectiveness varies significantly by geography; a material achieving $R = 0.90$ in Germany may realize $R = 0.30$ in regions lacking chemical recycling facilities or collection networks. CEI scoring should ideally specify geographic context or normalize for infrastructure maturity.

Despite these constraints, consistent interaction patterns across heterogeneous cases spanning diverse material systems, temporal scales, and recovery pathways suggest fundamental dynamics warranting larger-scale quantitative validation and pilot integration into policy instruments such as Digital Product Passports and eco-labeling schemes.

13.4 Case Study Evidence

13.4.1 Electronics: The Fairphone case

The Fairphone represents the paradigmatic case study in modular consumer electronics, demonstrating how architectural decisions enable circular product lifecycles. Launched in 2013 and now in its fifth generation, Fairphone has consistently achieved perfect repairability scores (10/10 from iFixit), contrasting with conventional smartphones scoring 2-4/10 due to adhesive-bonded batteries, soldered components, and proprietary fasteners (Ramirez, 2015).

Modular Architecture and Design Decisions: Fairphone's circular effectiveness derives from its seven-module architecture: battery, display, camera module, USB port assembly, speaker, microphone, and main board. Each module functions as an independently replaceable unit connected through standardized interfaces rather than permanent bonds. The battery can be replaced by end-users in under two minutes without tools. Display replacement requires eight minutes and a single Phillips screwdriver. Conventional smartphones require heat guns to soften adhesive, specialized prying tools, and carry 30-40% component breakage risk during disassembly.

Modularity × Disassembly Synergy: The Fairphone case isolates the interaction between Pillar 1 (Modularity) and Pillar 2 (Design for Disassembly). Modularity alone enables theoretical upgradeability—seven independent functional units—but without tool-free disassembly, this potential remains inaccessible to average consumers. Conversely, disassembly-friendly fastening alone provides access, but without modular boundaries, users must replace entire assemblies. The synergy emerges in their combination: modular architecture creates repair value by isolating failures to replaceable units, while reversible fastening makes that value accessible without specialized technical skills. This enables a repair ecosystem—Fairphone maintains spare parts availability for five years post-launch.

Circular Effectiveness Index Application: Fairphone scores: **M = 0.85** (7 replaceable modules), **D = 0.90** (tool-free battery, 8-minute display

replacement), **R = 0.40** (industry-standard materials—aluminum, copper, mixed plastics).

CEI = 0.85 × 0.90 × 0.40 = 0.306

Conventional smartphones score: M ≈ 0.10 (glued battery, soldered components), D ≈ 0.15 (45+ minutes, heat gun required), R ≈ 0.40 (identical materials).

CEI = 0.10 × 0.15 × 0.40 = 0.006

The **51-fold improvement** (0.306 vs. 0.006) occurs entirely through architectural design while controlling for material recyclability—both products use identical aluminum, copper, and plastic compositions. This validates the multiplicative formulation: when disassembly approaches zero (D = 0.15), even high modularity cannot realize repair potential; when modularity approaches zero (M = 0.10), disassembly only provides access to non-replaceable integrated assemblies. The pillars function as multipliers, not additive contributors.

Synergistic Effect Demonstrated: Fairphone isolates Modularity × Disassembly synergy. Modularity creates discrete functional units with independent lifespans; disassembly makes those units economically accessible for replacement. Together, they shift failure management from device disposal (linear model) to component replacement (circular model). The case demonstrates that circular electronics require both pillars simultaneously—neither modularity nor disassembly alone achieves circular effectiveness at commercially viable scales. This M × D pattern contrasts with textiles (R × D at molecular scale with constrained modularity) and furniture (D × R with moderate modularity), demonstrating that pillar interactions vary by product architecture while the multiplicative relationship remains constant across sectors.

13.4.2 Textiles: Mono-material strategies and the PA6 paradigm

Interaction Focus: Recyclability × Disassembly at Molecular Scale: The textile case demonstrates that Recyclability (Pillar 3) depends fundamentally on Disassembly (Pillar 2), even at the molecular level. Unlike Fairphone (M × D synergy through modular architecture) and glue-free assembly (D × R synergy through reversible fastening), textiles reveal a molecular-scale interaction: mono-material design (100% PA6) eliminates polymer separation challenges—functioning as "molecular disassembly"—while soluble stitching (PVA threads) enables passive component separation. This case isolates

how material selection and separation mechanisms interact when modularity is functionally constrained by product architecture.

PA6 Chemical Recycling Pathway: PA6 is a thermoplastic polyamide enabling chemical depolymerization: polymer chains are cleaved back to caprolactam monomer through high-temperature hydrolysis (Ellen MacArthur Foundation, 2017). This monomer can then be re-polymerized to virgin-equivalent PA6 fiber without mechanical property loss—a closed-loop pathway that mechanical recycling (shredding and re-melting) cannot achieve due to progressive polymer chain degradation.

Aquafil's ECONYL® system: Operational since 2011, ECONYL converts post-consumer PA6 waste (fishing nets, carpet fibers, industrial scrap) into regenerated nylon with virgin-equivalent mechanical properties, achieving 90-95% material recovery efficiency. The system demonstrates theoretically infinite recyclability: the same PA6 molecules undergo depolymerization-re-polymerization cycles indefinitely without cumulative degradation (Aquafil, 2024).

Comparative Material Systems Performance: Table 13.5 quantifies circular effectiveness differentials between mono-material and blended textile systems.

Mono-materials eliminate disassembly challenges through chemical homogeneity. When elastane (5% by weight) is blended with PA6, recyclers must either accept contamination (reducing quality to $R \approx 0.50$) or perform costly separation. Mono-material PA6 circumvents this, demonstrating how material selection (Pillar 3) addresses separation challenges (Pillar 2) at the molecular scale.

Circular Effectiveness Index Application: PA6 mono-material garments score: **$M \approx 0.10$, $D \approx 0.70$, $R = 0.93$**.

The low modularity coefficient ($M = 0.10$) reflects functional constraints: garments derive structural integrity from continuous fabric panels, not discrete modules. Unlike electronics where batteries serve independent functions, textile components function interdependently. This constraint means textiles optimize circularity through $R \times D$ interaction rather than $M \times D$ interaction.

The disassembly coefficient ($D = 0.70$) reflects chemical homogeneity: mono-material design eliminates polymer separation at the molecular level. Unlike polycotton blends requiring costly separation ($D \approx 0.30$), PA6 mono-materials enable direct depolymerization. The chemical structure itself facilitates the disassembly mechanism—hydrolysis cleaves polymer chains

Table 13.5 Comparative Recyclability of Textile Material Systems.

Material System	Recovery Rate	Quality Retention	Realized R Coefficient	CO_2 Savings vs Virgin
PA6 Mono-material (ECONYL)	90-95%	Virgin-equivalent	0.93	80-90%
Polycotton Blend (50/50)	30-40%	Downcycled	0.30	10-20%
PA6/Elastane (95/5)	60-70% (PA6 only)	Contaminated	0.50	40-50%

without requiring mechanical separation of incompatible polymers. D = 0.70 (not 1.0) because collection infrastructure still requires labor and capital investment.

The recyclability coefficient (R = 0.93) reflects ECONYL's chemical recycling achieving virgin-equivalent caprolactam recovery with minimal quality loss.

CEI = 0.10 × 0.70 × 0.93 = 0.065

Polycotton blend garments score: M ≈ 0.10, D ≈ 0.30 (polymer separation economically non-viable), R = 0.30 (mechanical downcycling).

CEI = 0.10 × 0.30 × 0.30 = 0.009

The **7-fold improvement** (0.065 vs. 0.009) isolates the R × D interaction's impact while controlling for modularity constraints. Notably, PA6's CEI (0.065) remains substantially lower than Fairphone (0.306) despite superior recyclability (0.93 vs. 0.40). This validates the multiplicative formulation: high recyclability cannot compensate for low modularity in absolute terms. However, within the textile sector where modularity is functionally constrained, mono-material design represents the optimal circular strategy.

Synergistic Effect: R×D Interaction at Molecular Scale: The PA6 case reveals that Recyclability depends on Disassembly even at the molecular level. Mono-material design circumvents physical polymer separation through chemical homogeneity. This functions as molecular-level disassembly: the polymer structure enables clean monomer recovery without mechanical separation of distinct materials. However, ECONYL still requires collection infrastructure physically separating PA6 textiles from mixed waste streams, explaining why D = 0.70 rather than approaching 1.0.

Polycotton blends possess moderate intrinsic recyclability but achieve realized R = 0.30 because D ≈ 0.30—polymer separation is economically non-viable, leading to mixed-stream mechanical recycling that downgrades both components. PA6 mono-materials achieve realized R = 0.93 because D = 0.70—chemical homogeneity enables molecular separation. The CEI calculation (0.065 vs. 0.009) quantifies this R × D interdependence: recyclability coefficient cannot be realized without disassembly coefficient at both molecular and physical scales.

The textile case suggests that when modularity is functionally constrained (M = 0.10), optimizing R × D interaction becomes the primary circular strategy. This contrasts with electronics (M × D optimization) and furniture (D × R optimization). The three-case triangulation reveals that optimal pillar combinations vary by product category based on functional constraints, but the multiplicative relationship between pillars remains constant—pillar collapse in any dimension eliminates circular effectiveness regardless of sector.

13.4.3 Built environment: Glue-free assembly and design for disassembly

Interaction Focus—Disassembly × Recyclability in Durable Goods: The built environment—furniture and construction—presents unique circular economy challenges due to extended product lifespans (20-50 years) and complex material assemblies. Traditional manufacturing prioritizes permanent bonding through adhesives and welding to achieve structural integrity and cost efficiency. However, these irreversible connections create "material hybrids" where high-value recyclable materials (aluminum, hardwood) become permanently contaminated, forcing end-of-life products into landfills or low-value downcycling. The glue-free assembly paradigm demonstrates that reversible mechanical fastening can achieve equivalent structural performance while enabling clean material separation. Unlike Fairphone (M × D focus) and textiles (R × D at molecular scale), this case isolates how Disassembly enables Recyclability at the product assembly level.

Valcucine Kitchen Systems: Technical Implementation: Italian manufacturer Valcucine pioneered industrial-scale glue-free furniture through its Invitrum and Meccanica Demodè kitchen lines, operational since 2003. The system eliminates adhesives, relying on aluminum extrusion profiles with integrated T-slot channels, cam-lock connectors for tool-free disassembly, and compression fittings. This enables component-level disassembly within 20-30 minutes. Material recovery rates exceed adhesive-bonded equivalents:

aluminum achieves 95% recycling efficiency, tempered glass 80%, and hardwood 70% for furniture-grade reuse. Adhesive-bonded kitchens require destructive disassembly—sawing contaminates wood with adhesive residue and metal fragments, forcing composite waste into incineration at recovery rate $R<0.25$.

CIRCuIT Project: Circular Buildings as Material Banks: The Horizon 2020-funded CIRCuIT (Circular Construction In Regenerative Cities) Project retrofitted two Hamburg school buildings using reversible connection systems: bolted steel frames, modular wall panels with mechanical clips, and accessible cable management (CIRCuIT Project, 2021). Buildings designed for 20-year renovation cycles treat materials as asset stocks: aluminum facade panels and steel structural members retain 60-80% initial value after disassembly. Across three renovation cycles (60-year lifespan), material reuse generated 37-61% lifecycle cost savings compared to linear construction baselines.

Disassembly × Recyclability Synergy: The glue-free cases isolate the interaction between Design for Disassembly (Pillar 2) and Recyclable Materials (Pillar 3). Aluminum, glass, and hardwood possess excellent intrinsic recyclability ($R>0.80$) when processed as clean streams. However, adhesive bonding creates "material prisoners"—high-value materials become inaccessible without destructive extraction that contaminates the stream. Reversible fastening liberates recyclability potential: mechanical joints allow clean separation, delivering materials to specialized recyclers without cross-contamination. CIRCuIT quantified this: conventional buildings with $R = 0.80$ materials achieved realized recovery $R<0.25$ due to bonded assemblies. CIRCuIT buildings with identical materials but reversible fastening achieved realized recovery $R = 0.75$—disassembly enabled theoretical recyclability to become actual recyclability.

Circular Effectiveness Index Application: Valcucine/CIRCuIT systems score: **$M \approx 0.30$, $D = 0.85$, $R = 0.85$**.

The modularity coefficient ($M = 0.30$) reflects limited functional upgradeability: cabinet panels are discrete units that can be replaced or rearranged, providing greater modularity than textiles ($M = 0.10$) but less than electronics ($M = 0.85$). Panel-level modularity exceeds continuous construction (poured concrete, welded steel) which would score $M \approx 0.10$.

The disassembly coefficient ($D = 0.85$) reflects 20-30 minute disassembly time, mechanical fasteners requiring only standard tools, and documented assembly procedures. This approaches Fairphone's $D = 0.90$ but remains slightly lower due to furniture's larger scale and greater fastener count.

The recyclability coefficient (R = 0.85) represents weighted average: aluminum (95% recovery × 40% mass) + glass (80% × 30%) + wood (70% × 30%) = 0.83 composite.

CEI = 0.30 × 0.85 × 0.85 = 0.217

Conventional adhesive-bonded furniture/construction scores: M ≈ 0.10 (integrated assemblies), D ≈ 0.20 (destructive demolition, 60+ minutes), R ≈ 0.25 (contaminated streams).

CEI = 0.10 × 0.20 × 0.25 = 0.005

The **43-fold improvement** (0.217 vs. 0.005) occurs through fastening strategy alone while material composition remains constant. Both conventional and glue-free systems use aluminum, glass, and wood—the circular effectiveness differential derives entirely from connection methodology. This validates the non-compensatory logic: high recyclability materials (R = 0.85 intrinsic) cannot compensate for low disassembly (D = 0.20), and physical reality shows the combination yields near-zero circularity. The multiplicative formulation correctly predicts this collapse.

Synergistic Effect Demonstrated: Disassembly Enables Recyclability: The glue-free cases demonstrate that Disassembly enables Recyclability by transforming "material hybrids" (contaminated composite waste) into "material banks" (clean mono-material streams). Reversible fastening does not increase the intrinsic recyclability of aluminum, glass, or wood—these materials possess R>0.70 regardless of assembly method. Rather, disassembly determines whether theoretical recyclability becomes realized recyclability. Adhesive bonding reduces realized R from 0.85 to 0.25 by contaminating separation; mechanical fastening preserves realized R ≈ 0.85 by enabling clean disassembly.

CIRCuIT's 37-61% lifecycle cost savings derive directly from this D×R enabling relationship. Materials retain value across renovation cycles because disassembly preserves their quality—panels removed via mechanical fastening arrive at recycling facilities as clean streams commanding premium prices. This challenges conventional construction economics treating permanent bonding as cost-efficient. When lifecycle costs incorporate material value retention, reversible fastening becomes economically superior despite 5-10% higher initial installation costs.

The glue-free assembly case completes the three-case triangulation by demonstrating D × R interaction in long-lifespan products (20–50 years) with moderate modularity (M = 0.30). Combined with Fairphone (M × D in

electronics) and PA6 textiles (R×D at molecular scale), the evidence demonstrates that all three pillars exhibit pairwise synergistic interactions. The multiplicative relationship captures this interdependence mathematically—when any coefficient approaches zero, circular effectiveness collapses regardless of other pillars' strength.

13.5 Discussion

The case study evidence demonstrates that circular economy transitions are constrained not by technological limitations but by systemic design integration failures. The three-pillar framework—Modularity, Design for Disassembly, and Recyclable Materials—facilitates an operational methodology for embedding circularity at the product architecture level rather than retrofitting it as an end-of-life consideration. This discussion synthesizes cross-case patterns, validates the multiplicative formulation against additive alternatives, and identifies threshold dynamics with policy implications.

13.5.1 Validating the multiplicative formulation: Non-compensatory dynamics

The Circular Effectiveness Index (CEI) employs multiplicative aggregation ($M \times D \times R$) to capture pillar interdependencies mathematically. This structural choice differentiates CEI from existing circularity metrics that rely on additive weighted sums—Material Circularity Indicator (Ellen MacArthur Foundation, 2015), Overall Circularity Effectiveness (Baumer-Cardoso et al., 2023), 9R Circularity Index (Muñoz et al., 2024), and Circular Economy Indicator Prototype (Cayzer et al., 2017). As established in Section 2.5, additive models embed compensatory assumptions: weak performance in one dimension can be numerically offset by excellence in others.

The three-case triangulation validates that this compensatory logic contradicts physical reality. Fairphone demonstrates that when disassembly approaches zero ($D = 0.15$ in conventional smartphones), modularity ($M = 0.85$) cannot realize repair potential—users cannot access modules regardless of their independent replaceability. The CEI calculation quantifies this: conventional smartphones score 0.006 versus Fairphone's 0.306, a 51-fold differential driven by $M \times D$ interaction. An additive model would yield 0.217 for conventional versus 0.717 for Fairphone—a 3.3-fold differential that vastly underestimates architectural impact and suggests conventional smartphones achieve "moderate circularity" when physical reality demonstrates near-zero effectiveness.

The PA6 textile case extends validation to molecular-scale interactions. Polycotton blends achieve R = 0.30 because polymer separation (D = 0.30) is economically non-viable. Mono-material PA6 achieves R = 0.93 because chemical homogeneity functions as molecular-level disassembly (D = 0.70). The 7-fold CEI improvement (0.065 vs 0.009) captures this R × D interdependence; additive aggregation would calculate 0.233 for polycotton versus 0.577 for PA6, a 2.5-fold difference that understates the synergistic effect and incorrectly suggests polycotton achieves "low-moderate" circularity when industrial practice demonstrates downcycling.

These patterns validate the multiplicative premise: pillars function as multipliers, not independent contributors. When any coefficient approaches zero, system effectiveness collapses regardless of other pillars' strength—a defining characteristic of non-compensatory systems that additive models cannot capture.

13.5.2 Cross-sector patterns: Disassembly as enabling pillar

Systematic comparison across electronics, textiles, and furniture reveals asymmetric pillar relationships. Design for Disassembly consistently emerges as the enabling pillar—it determines whether other pillars can function.

Electronics (Fairphone): Modularity creates discrete functional units with independent upgrade pathways. However, disassembly (reversible fastening, tool-free access) makes that theoretical potential accessible. The interaction is bidirectional but asymmetric: preliminary case evidence suggests that when D approaches 0.50, repair labor costs may begin to exceed component value, potentially undermining the repair ecosystem regardless of modular architecture.

Textiles (PA6): Modularity is functionally constrained—garments derive structural integrity from continuous fabric. This forces textile circularity to depend on R × D interaction. Mono-material design eliminates polymer separation at the molecular level, functioning as "molecular disassembly." However, ECONYL still requires collection infrastructure physically separating PA6 textiles from mixed waste streams (macro-level D). Without this passive separation mechanism (D = 0.70), even chemically recyclable PA6 would require manual seam removal, making recovery economically marginal.

Furniture (Glue-Free): Aluminum, glass, and hardwood possess excellent intrinsic recyclability (R > 0.80), yet adhesive bonding reduces realized recovery to R < 0.25. Reversible fastening does not increase material

recyclability—rather, disassembly determines whether theoretical recyclability becomes realized recyclability. The CIRCuIT Project quantified this: identical materials (R = 0.80 intrinsic) achieved 0.25 realized recovery with adhesive bonding versus 0.75 with mechanical fastening.

This cross-sector pattern suggests a hierarchy: Design for Disassembly functions as prerequisite infrastructure enabling both modularity and recyclability to deliver circular value. Case comparison suggests that material innovation (improving R) and modular architecture (improving M) may provide negligible circular benefit when disassembly approaches 0.30 because separation becomes economically non-viable. This challenges circular economy policies focused predominantly on material targets without corresponding disassembly standards.

13.5.3 Threshold effects and policy implications

Preliminary analysis indicates that the D × R interaction may exhibit threshold dynamics. When disassembly approaches D ≈ 0.30 (corresponding to disassembly times exceeding ~45 minutes), recycling infrastructure may shift from manual separation to bulk shredding. This transition could contaminate material streams, potentially limiting realized recyclability below R = 0.40 regardless of material composition. These threshold values represent directional hypotheses requiring empirical validation. Both blended textiles (D = 0.30) and adhesive-bonded furniture (D = 0.20) converge on R ≈ 0.30 despite different base materials, suggesting that low disassembly may create a recyclability ceiling independent of material chemistry.

Conversely, case comparison suggests that products achieving D ≥ 0.50 may enable recycling infrastructure to pursue clean material separation, allowing realized recyclability to approach intrinsic recyclability. PA6 garments with soluble stitching (D = 0.70) achieve R = 0.93; CIRCuIT buildings (D = 0.85) achieve R = 0.75–0.85. This pattern suggests a potential viability threshold around D ≈ 0.50. This threshold hypothesis requires validation across diverse product categories, geographic contexts, and temporal periods.

Policy Implications: Current circular economy regulations emphasize material composition (EU Ecodesign mandates, recycled content targets) but provide limited guidance on disassembly requirements. The threshold dynamics identified here suggest that material mandates may prove ineffective without corresponding Design for Disassembly standards. Policymakers should consider coupling recycled content targets with maximum disassembly time thresholds (e.g., ≤15 minutes for consumer electronics, ≤30 minutes

for furniture) and mechanical fastener requirements for high-value material streams. Digital Product Passports (DPPs) mandated under EU Sustainable Products Regulation could encode M, D, R coefficients, enabling procurement policies to preferentially select high-CEI products rather than optimizing pillars in isolation.

13.5.4 Economic viability and consumer behavior shifts

Lifecycle analysis demonstrates that circular design's initial production costs are offset by extended product life. Fairphone's modular architecture increases production-phase embodied energy by ~10% versus integrated designs, yet 60% lifespan extension (4.5 versus 2.8 years average retention) translates to 35–40% reduction in annualized environmental impact (Ellen MacArthur Foundation, 2019). The economic case strengthens when incorporating material value retention: CIRCuIT Project buildings designed for disassembly achieved 37–61% lifecycle cost savings versus conventional construction, as aluminum panels, steel members, and modular systems retain 60–80% initial value after disassembly. When lifecycle costs account for material value, reversible fastening becomes economically superior despite 5–10% higher installation costs (CIRCuIT Project, 2021).

Consumer behavior presents distinct challenges. Products designed for circularity require active stewardship—users must perform periodic maintenance (battery replacement, module upgrades) rather than expecting "mechanical servant" functionality where devices work maintenance-free until catastrophic failure. Fairphone's commercial persistence since 2013 suggests niche consumer segments value "Right to Repair" and longevity sufficiently to accept both price premiums and maintenance responsibilities. The tension between consumer convenience and circular requirements suggests that optimal strategies vary by product category: high-involvement durable goods (electronics, furniture) can support active maintenance models, while low-involvement consumables (textiles, packaging) require passive circular mechanisms.

13.5.5 Research limitations and future directions

As detailed in Section 3.5, this study's exploratory methodology limits generalizability. Future research should pursue four extensions: First, coefficient standardization through expert panel consensus, potentially adapting Analytic Hierarchy Process (AHP) methodology. Current assignments rely on industry heuristics and published LCA data rather than systematic validation.

Second, large-sample validation of threshold claims across automotive, consumer appliances, and medical devices. Threshold values likely vary by labor cost contexts and product lifecycles. Third, sensitivity analysis on coefficient uncertainty through probabilistic CEI models with Monte Carlo simulation. Fourth, integration with LCA databases (e.g., Ecoinvent) to validate whether high-CEI products achieve superior environmental outcomes across multiple impact categories.

Despite these limitations, the consistent interaction patterns across heterogeneous cases—thermoplastics versus metals versus wood; 3-year versus 20-year lifespans; repair versus chemical recycling—suggest fundamental rather than sector-specific dynamics. The multiplicative formulation captures physical constraints that additive models systematically underestimate.

13.6 Conclusion

The transition to a circular economy is fundamentally a design challenge rather than a waste management problem. This research demonstrates that circular effectiveness depends on the synergistic integration of three interdependent design pillars: Modularity, Design for Disassembly, and Recyclable Materials. Through comparative case study analysis across electronics, textiles, and furniture sectors, we have validated that these pillars function multiplicatively rather than additively—their combined effectiveness is constrained by the weakest pillar rather than compensated by the strongest, and pillar collapse in any dimension eliminates circular outcomes regardless of other pillars' strength.

The empirical evidence supports three primary conclusions. First, the Circular Effectiveness Index (CEI) quantifies synergistic interactions through multiplicative aggregation ($M \times D \times R$), distinguishing it from existing additive metrics (MCI, OCE, 9R Index, CEIP). Case study evidence demonstrates that circular design leaders achieve 7-fold to 51-fold improvements over conventional baselines. Second, cross-sector comparison reveals asymmetric pillar relationships where Design for Disassembly consistently emerges as the enabling pillar—it determines whether other pillars can function. This pattern holds across electronics (D enables M), textiles (D enables R at molecular scale), and furniture (D gates realized recyclability). Third, preliminary case evidence suggests the $D \times R$ interaction may exhibit threshold effects. When disassembly approaches $D \approx 0.30$, recycling infrastructure may shift to bulk shredding, potentially limiting realized recyclability below $R = 0.40$. These threshold values represent directional hypotheses requiring validation across diverse sectors and economic contexts.

13.6.1 Implications for stakeholders

Manufacturing Strategy: Adopting the three-pillar framework represents strategic hedging against raw material volatility rather than solely environmental compliance. Design for Disassembly transforms end-of-life products into "urban mines," enabling manufacturers to reclaim proprietary materials (Enel & Fondazione Symbola, 2018). The Fairphone case demonstrates that modular architectures, despite 10% higher production-phase embodied energy, achieve lifecycle environmental payback within 18–24 months through 60% lifespan extension. Economic viability strengthens as Extended Producer Responsibility regulations expand, shifting end-of-life costs to manufacturers and incentivizing design-for-circularity.

Textile Industry Directions: Material composition simplification emerges as the primary lever for textile circularity. The shift from blended fibers toward mono-materials (100% PA6) addresses the fundamental barrier that mechanical separation of incompatible polymers remains economically non-viable (Rahee & Sarker, 2024). The European Union's Ecodesign for Sustainable Products Regulation (2024) empowers the Commission to set product-specific requirements, including recycled content, for textiles through delegated acts, creating regulatory pull for mono-material designs (Ramírez-Escamilla et al., 2024). Industrial-scale viability is demonstrated through ECONYL's 90-95% caprolactam recovery. However, scaling requires industry-wide polymer standardization enabling sorting infrastructure.

Policy Recommendations: Consumer empowerment in circular economy requires both regulatory intervention and design-phase implementation. Current circular economy regulations addressing material composition without fastening requirements risk creating "phantom circularity"—products theoretically recyclable but practically inaccessible (van den Berg & Bakker, 2015). The potential threshold dynamics observed suggest effective policy must regulate assembly methods alongside material targets. Three evidence-based interventions merit consideration:

1. **Digital Product Passports (DPP):** Mandate machine-readable documentation encoding material composition, disassembly procedures, and M/D/R coefficients via QR codes or RFID tags. The EU's DPP regulation (batteries and electronics by 2027) should extend to textiles and furniture, enabling procurement policies to preferentially select high-CEI products rather than optimizing pillars in isolation.
2. **Fiscal Rebalancing for Repair:** Tax structures currently burden repair relative to replacement—19-25% VAT on spare parts versus embedded

production subsidies for virgin material extraction. Zero-VAT spare parts policies would shift consumer economics toward repair, creating market demand for modular/disassemblable designs.

3. **Design for Disassembly Standards:** Establish sector-specific maximum disassembly time benchmarks (e.g., ≤15 minutes for consumer electronics, ≤30 minutes for furniture) and mechanical fastener requirements for high-value material streams.

13.6.2 Research limitations and future directions

This exploratory study establishes conceptual validity but requires quantitative extension. First, coefficient standardization through systematic expert consensus using Analytic Hierarchy Process validation employed by comparable metrics (Muñoz et al., 2024). Current CEI assignments rely on industry heuristics and published LCA data rather than validated consensus. Second, large-sample validation of threshold claims across automotive, consumer appliances, medical devices, and packaging sectors. Threshold values likely vary by labor cost contexts and product lifecycles. Three cases meet Design Research Methodology minimum requirements but cannot validate sector-wide generalizability. Third, integration with lifecycle assessment methodologies. Coupling CEI with LCA databases (Ecoinvent, GaBi) would enable direct quantification of carbon footprint and resource depletion, validating whether high-CEI products achieve superior environmental outcomes across multiple impact categories. Fourth, behavioral dimensions require investigation. Consumer psychology research demonstrates that "mechanical servant mythology" persists despite right-to-repair movements (Baxter et al., 2015; Piscicelli et al., 2015). Longitudinal studies tracking user engagement with modular products would clarify whether design interventions alone suffice or require parallel educational campaigns.

13.6.3 Concluding statement

Circularity is achieved through design interventions embedding circular logic at product conception. When products are designed to be upgraded (modularity), disassembled (reversible fastening), and regenerated (mono-materials), consumption and resource destruction become decoupled. The three-pillar framework provides manufacturers, policymakers, and designers with a systematic methodology for operationalizing circular economy principles.

The viability of circular alternatives is demonstrated: Fairphone maintains commercial operation since 2013; ECONYL achieves virgin-equivalent output; CIRCuIT buildings deliver 37-61% lifecycle cost savings. These cases prove that circular design is operational present reality. Scaling requires systemic adoption—not technological invention but implementation of proven methodologies.

Linear systems predicated on infinite resource availability face inevitable constraints. The circular alternative exists, validated through cross-sector commercial implementation. The pathway forward runs through design decisions embedding circularity at product architecture level. This transition represents both environmental necessity and economic opportunity—manufacturers reclaiming material value, consumers accessing repair ecosystems, policymakers reducing waste infrastructure costs.

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