

Product Life Cycle Extension in the Circular Economy: A systematic review of strategics, methodologies and industrial applications

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Product Life Cycle Extension in the Circular Economy: A systematic review of strategics, methodologies and industrial applications.

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Abstract

Product life cycle extension (PLCE) has emerged as an important strategy for manufacturing companies transitioning toward circular economy models, as it simultaneously addresses resource scarcity, environmental degradation, and economic sustainability. Three critical research gaps constrain both scientific advancement and industrial implementation: absence of evaluation models for circular economy strategies, lack of systemic integration across domains and deficit of holistic quantitative methods. This paper aims to provide guidance on critical literature gaps found, identify best PLCE practices according to product type and industrial sector, and assess environmental impact implications that contribute to sustainable development. The methodology was based in a systematic review followed PRISMA guidelines, by synthesizing articles extracted from the Web of Science database. The search strategy involved a temporal scope 2019-2026. The investigation identified six principal domains on transversely applied PLCE strategies, and seven methodologies related to PLCE. The analysed papers revealed that successful PLCE strategies integrate methodologies from at least seven major domains. These strategies, supported by seven complementary methodological frameworks, demonstrate that successful PLCE implementation requires their integration, opposed to their isolated optimization. This integrated approach directly addresses the three critical research gaps identified in the introduction. It was concluded that Design for Circularity, which is responsible for 60-80% of environmental impact, is only implemented by 14% of organizations, while Maintenance Optimization, with 15-25% environmental efficacy, is implemented by 47.3%. This discrepancy shows that organizational decision-making prioritizes immediate economic viability over maximum environmental potential, which constitutes both the biggest challenge and opportunity to improve PLCE effectiveness.

Keywords: Product Life Cycle Extension (PLCE); Circular Economy; Design for Circularity; Life Cycle Assessment (LCA); Remanufacturing; Sustainable Manufacturing

1 Introduction

The transition from linear and take-make-waste economic models to circular economy approaches is a main imperative faced by manufacturing and industrial systems. At the heart of this transformation lies a fundamental strategic shift: rather than treating products as disposable commodities designed for single-use cycles, the deliberate extension of useful product life appears as a suitable approach to simultaneously address resource scarcity, environmental degradation, and economic sustainability. This transition is increasingly mandated by regulation. The European Union has established durability, reparability, and upgradability as fundamental design principles through the Circular Economy Action Plan, the Eco-design Directive (2009/125/EC), Right to Repair initiatives, and Digital Product Passport frameworks, as per e.g. [1], [2], [3], [4], positioning the Product Life Cycle Extension (PLCE) as a regulatory requirement and market opportunity.

PLCE represents a multidimensional strategy that is significantly different from conventional waste management and recycling approaches [2], [5]. Rather than treating end-of-life products as waste streams to be processed, PLCE extends the period during which products deliver functional value to users, thereby maximizing utility extracted from material and embodied energy investments. This distinction is critical: while recycling recovers material value by energy-intensive reprocessing, PLCE maintains materials in high-value technical cycles, thus preserving the embodied energy and functional capacity [2], [5]. The scope of PLCE extends to the entire product lifecycle, by encompassing five distinct intervention phases: (1) design, which establishes technical foundations for durability, modularity, and reparability [2]; (2) manufacturing, which optimizes production processes and supply chain structures; use phase (3), which maintains efficiency and enabling repairs [6], [7]; end-of-use (4), which implements recovery strategies including remanufacturing and refurbishment [8], [9], [10]; and business model architecture (5), which restructures revenue streams and customer relationships to promote lifecycle optimization [11], [12], [13]. Critically, design-phase decisions determine 60-80% of subsequent environmental impact [2], [8], by creating technical prerequisites that management strategies cannot tackle with. This hierarchical relationship means that effective PLCE requires systematic integration between all five phases rather than isolated optimization within individual phases.

Despite substantial academic progress in PLCE research, three critical research gaps persist, which constrain both scientific advancement and practical application of circular economy strategies. First, comprehensive evaluation frameworks for circular economy strategies are non-existent [14], [15]. While individual PLCE methodologies (design for durability, predictive maintenance, remanufacturing, and digitalization) demonstrate measurable environmental and economic benefits when implemented in isolation, as per e.g. [9], [10], [16], [17], [18],

systematic frameworks that make it possible for practitioners to evaluate which strategy combinations provide optimal outcomes in diverse industrial contexts is limited. The literature explicitly confirms this void: *"Unfortunately, we could not identify any studies focusing on models or tools for evaluating the CE"* [14], while simultaneously stating that *"a major challenge remains the evaluation of these strategies as to which are the most relevant, effective, and efficient ones"* [15]. Second, PLCE spans multiple disciplines, such as engineering, environmental science, business innovation, and digital technology, as per e.g. [3], [16], [19], [20], but research is predominantly siloed within individual domains with no established systemic integration. Design improvements, maintenance optimization, remanufacturing processes, and digital enablement are typically analysed as independent interventions instead of complementary components of integrated systems, as per e.g. [5], [11], [21], [22], [23], [24]. The literature confirms this fragmentation: *"Most studies address either mitigation technologies or CE practices in isolation"* [21], while mentioning that *"a comprehensive morphological framework capturing the full scope of order processing in circular production is notably absent"* [24]. This disciplinary fragmentation prevents important synergies and interdependencies: design decisions determine 60-80% of environmental impact [2], but design improvements are only implemented by 14% of organizations [13], while maintenance strategies adoption represent 47.3% [13], and demonstrate substantially lower environmental efficacy [6], [7]. Third, existing quantitative approaches fail to capture the complete scope of PLCE effectiveness in the environmental, economic, and social dimensions through universal standardized methodologies [5], [15], [23]. Current research explicitly identifies that *"existing quantitative methods fail to guarantee the complete Triple Bottom Line evaluation"* [5] and *"limited research exists on quantifying the synergistic benefits"* [21]. Critical gaps include inadequate representation of resource consumption during the use phase (with evidence confirming that *"no indicator accounts for resource use in the use phase"*) [22]; insufficient capture of lifecycle extension strategies within indicator frameworks [22], inability to assess multiple sequential use cycles, and failure to evaluate the absolute material mass variations during product life cycle. The systematic review of circularity indicators reveals *"a significant divergence of indicators' scope"* [22], with most capturing only partial product system aspects.

Addressing these gaps requires systematic integration of six complementary strategic domains that operate at different lifecycle phases and through distinct causal mechanisms: (1) Design for Circularity establishes technical foundations through durability optimization, modularity, and design for disassembly, determining 60-80% of subsequent environmental impact [2], with nanomaterial integration achieving 130-3100% lifecycle extensions [25]; (2) Advanced Technical Recovery and Remanufacturing extends material lifecycles through systematic restoration, additive manufacturing repair, and component recovery, achieving 40-60% cost reduction versus new

manufacturing [9], [10], [18]; (3) Maintenance Optimization prevents failures and optimizes efficiency through preventive, condition based, and predictive maintenance strategies, which reduce total cost of ownership by 15-25% [6], [16], [26] and unplanned downtime by 40-50% [16], [27]; (4) Use-Phase Efficiency maximizes functional value extraction through repair, refurbishment, and operational optimization, with use phase dominating lifecycle environmental impact for energy-intensive products (48-95%) [6], [7], [28]; (5) Digitalization enables real-time monitoring, predictive analytics, and integrated information management through internet of things (IoT), artificial intelligence, digital twins, and blockchain technologies, as per e.g. [1], [3], [16], [20], [26]; (6) and Circular Business Models restructure revenue streams and customer relationships through product-service systems, access schemes, and remanufactured product markets, thus aligning economic incentives with lifecycle optimization, as per e.g. [11], [12], [13], [29]. These six domains distinct strategic choices validated through bibliometric analysis, temporal and functional differentiation, organizational implementation patterns, and quantitative business model taxonomy [13].

The traditional linear business model follows the classic product lifecycle stages of Introduction, Growth, Maturity, and Decline, generating repeated sales peaks as consumers replace worn-out products at regular intervals. Figure 1 illustrates this commercial transformation: the Introduction stage marks initial market entry with low sales; Growth accelerates as market adoption increases; Maturity represents peak market penetration with stable sales; and Decline occurs as product reaches end-of-life and consumers replace it with new alternatives, triggering a new cycle. This pattern repeats cyclically as consumers purchase replacement products, which creates multiple sales peaks across time. In contrast, PLCE strategies mainly convert these replacement cycles into fewer and more distant events by extending the Maturity phase and delaying the Decline stage. Instead of moving rapidly from Maturity to Decline and triggering replacement purchases, PLCE strategies, through design durability, maintenance optimization, technical recovery, and digital enablement, substantially extend the Maturity phase, thus deferring the Decline stage and subsequently the replacement cycle. This shift in sales trajectory represents a

fundamental business model challenge that manufacturers must address through service-based revenue models and customer retention strategies.

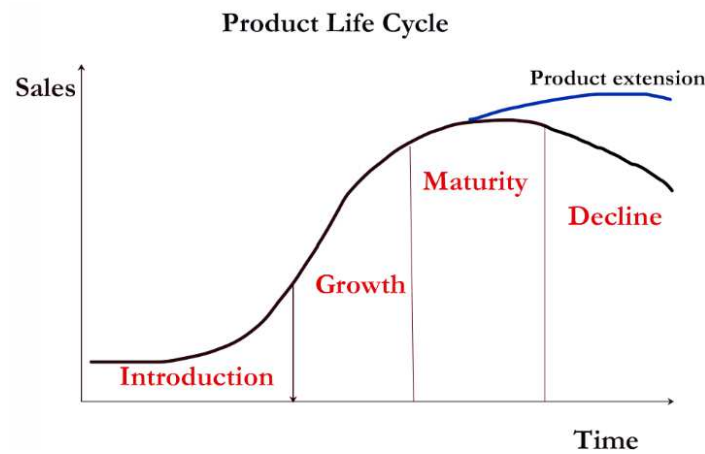


Figure 1 - Product Lifecycle Stages: Traditional linear model (repeated Introduction-Growth-Maturity-Decline cycles) versus Product Life Cycle Extension model (extended Maturity phase delaying Decline and replacement cycles) – Font: economicshelp.org

Successful PLCE implementation necessitates a fundamental restructuring of business model architecture. This involves more than just adjusting revenue streams; it requires a transformation in how value is created through durable design, delivered via continuous services, and captured through recurring to product lifecycle extension methodologies. Extended life strategies transform short replacement cycles fewer and more distant events by altering sales trajectories and necessitating different revenue structures [11], [12], [13]. Organizations successfully navigating this transition implement Product-Service Systems (PSS) that align manufacturer and consumer incentives toward lifecycle optimization, capturing value through maintenance services, component upgrades, and performance-based pricing instead of repeated product sales [5], [11], [29]. Research on 150 organizations engaged in PLCE reveals a critical strategic asymmetry: product "nurture strategies" (maintenance, repair, remanufacturing, redistribution, and access schemes, which extend existing product life) are substantially more prevalent than product "nature strategies" (design improvements, which establish durability from inception). Adoption rates reflect this distribution: maintenance at 47.3%, access schemes at 42.0%, and repair at 37.3%, compared to only 14% for design improvements [13]. This distribution is influenced by rational economic incentives. Actually, nurture strategies generate recurring revenue streams and customer lock-in with minimal organizational disruption [13], while design investments require substantial upfront research & development (R&D) capital with longer payback periods and the need to build organizational capabilities following various functions [2]. However, this

economic structure creates incentives that may be suboptimal from a systems perspective: design establishes prerequisites for all other strategies to function effectively [2], but receives disproportionately low investment relative to its environmental impact potential [13].

According to Sarig et al. [13], seven distinct circular business model types emerge from quantitative analysis of these 150 organizations, each combining different strategies and revenue structures, which demonstrates that circular business models are not uniform but rather represent a portfolio of complementary and competing strategies that enable organizations to capture value along multiple product use cycles. These are the principal orchestration areas mentioned by the author: (1) Mathematical and Statistical Modelling enables reliable degradation prediction and lifecycle cost analysis, as per e.g. [6], [26], [28], [30], [31], [32], [33]; (2) Computational Intelligence and Optimization enhances real-time operational decisions and complex multi-objective trade-offs, as per e.g. [10], [31], [32], [34], [35]; (3) Engineering, Reliability, and Diagnostics validates technical feasibility and predicts component performance, as per e.g. [31], [35], [36], [37]; (4) Environmental and Economic Assessment quantifies lifecycle impacts and cost-benefit trade-offs through LCA, Life Cycle Costing (LCC), and sustainability metrics, as per e.g. [7], [23], [38], [39]; (5) Material and Surface Science enables durability enhancement through tribological optimization, nanomaterial integration, and self-healing materials, as per e.g. [14], [21], [25], [40]; (6) Digital Technologies and Data Management integrates fragmented information through IoT, machine learning, digital twins, and blockchain, as per e.g. [1], [34], [41], [42]; and (7) Business Model and Market Analysis structures commercial viability and stakeholder alignment, as per e.g. [11], [20], [43], [44].

The state of the art demonstrates that no single methodology is effective. Thus, PLCE strategies typically employ carefully sequenced combinations of complementary approaches, each one addressing specific decision contexts [5], [16].

This systematic review synthesizes evidence from 62 peer-reviewed articles (2019-2026) to address these three critical research gaps and provide practitioners with actionable guidance for PLCE implementation. This paper pursues the following objectives: to identify and categorize PLCE strategies in relation to product type and industrial sector, and to assess the environmental impact implications contributing to sustainable development.

2 Methodology

This study is based on a systematic literature review aimed at identifying and analysing the most significant tools developed to support PLCE within the industrial sector. As noted by Page et al. [45], adopting a systematic approach ensures transparency, objectivity, and reproducibility in the documentary selection. A systematic literature review with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol [5], [24], [46] ensures rigorous evidence synthesis for multiple studies.

This work includes data collection using the *Web of Science* (WoS) database, selected for its comprehensive coverage of high-impact journals in engineering and industrial management. The search strategy utilized the specific keyword "product life cycle extension," with the temporal scope limited to publications between 2019 and 2026. This timeframe was established to capture the current state-of-the-art and the most recent innovations aligned with global circular economy goals [47]. The initial search yielded a total of 713 articles. To ensure a rigorous and transparent reporting of the literature search results, the selection process followed the PRISMA guidelines [48]. The selection criteria specifically targeted studies focused on the industrial sector, filtering out purely theoretical frameworks that lacked evidence of real-world applicability or concrete tool development. The conceptual view of PLCE research reveals multiple interconnected themes and methodological approaches on related topics as: circular economy, remanufacturing, design for circularity, life cycle assessment, and digital technologies; all clustered and interconnected within the research scope. This conceptual view demonstrates that PLCE research is multidisciplinary, since it integrates perspectives from engineering, environmental science, business innovation, and digital technology domains.

The flow diagram presented in Figure 2 illustrates the sequential stages of the methodology, by detailing the transition from the initial identification of 713 records in the WoS database to the final set of articles included in this review. This systematic screening was essential to isolate studies with direct industrial applicability and high correlation with real-world PLCE strategies.

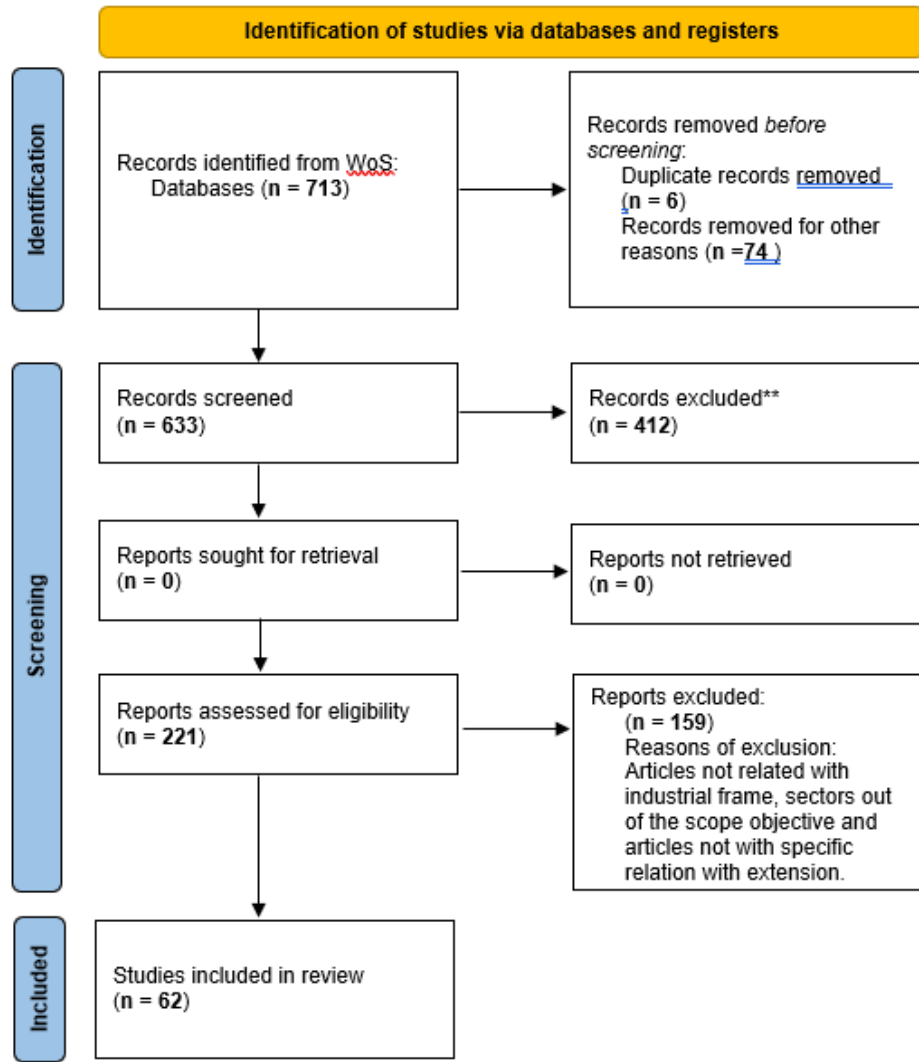


Figure 2 - PRISMA systematic review - diagram flow

3 Results and discussion

3.1 Main Strategies Identified

PLCE is not a singular action, but a multidimensional challenge that requires coordinated interventions along the value chain. This systematic review of 62 peer-reviewed articles (2019-2026) identifies and categorizes PLCE strategies into six complementary strategic domains: Design for Circularity; Advanced Technical Recovery and Remanufacturing; Maintenance Optimization; Use-Phase Efficiency; Digitalization; and Circular Business Models. The six-fold division results from systematic paper review using multiple validation approaches. Instead of imposing a predetermined framework, the categorization was identified by: (1) thematic clustering visible in bibliometric analysis, where design, recovery, maintenance, and digital technologies appeared as distinct

conceptual nodes; (2) temporal and functional differentiation (these domains operate at different lifecycle stages and through distinct causal mechanisms); (3) validation against organizational implementation practices (analysis of 150 organizations revealed that companies adopt these domains independently and at significantly different rates confirming they represent genuine strategic choices rather than sequential stages); and (4) alignment with quantitative business model taxonomy (identification of seven distinct circular business model types, each combining different strategies from these four domains, provided independent empirical validation) [13]. These PLCE strategic domains represent parallel intervention areas that are temporally distinct (pre-manufacturing, post-failure, during-operation, transversal), causally differentiated (engineering, material transformation, operational management, information systems), independently implementable (each demonstrates measurable isolated impact), complementary (gain synergy when combined), and empirically validated (organizations adopt at significantly different rates, suggesting distinct strategic choices). This structure enables systematic analysis while accommodating the diversity of real-world PLCE implementations in different sectors and organizational contexts.

3.1.1 Design for Circularity

Design decisions made during product development determine 60-80% of the subsequent environmental impact [2]. This critical threshold means that investments in recovery technologies, maintenance strategies, or business model innovation cannot overcome fundamental design limitations. Instead of treating environmental considerations as afterthoughts, systematic Eco-design frameworks must integrate complementary strategies, as durability, modularity, and repairability, from initial concept through end-of-life planning.

Within this design-centric framework, four complementary sub-categories operate sequentially and synergistically to maximize product longevity and environmental performance, namely:

- (1) **Design for Durability**, who establishes the foundations; The material property selection and the structural geometry optimization extend service life by 2-3 times baseline performance [17], [38]. For instance, integrating nanomaterials achieves remarkable extensions. Nano Safe batteries, for example, achieve 12 times more charge cycles than conventional lithium-ion cells (9,000 vs. 750 cycles), while nanoparticle-enhanced coatings extend protective lifespan by 16 times [25]. Other example is the optimized lubrication systems that reduce friction coefficients from 0.400 to 0.018, significantly

extending mechanical component lifespan in applications such as automotive turbochargers [17]. A material durability indicator that integrates chemical and mechanical durability characteristics with environmental impacts provides comprehensive comparison of selection alternatives and supports design decisions favouring lifecycle extension [49].

- (2) **Modularity and Disassemblability** enable selective component replacement without full product substitution. Modular furniture designs reduce material per functional unit by up to 95% compared to monolithic alternatives [38]. Products incorporating Design for Disassembly features achieve 38-84% recovery rates, compared to <50% for poorly designed components [17]. Advanced non-destructive disassembly technologies reduce extraction forces by up to 80%, thus preserving component properties and enabling reuse [37].
- (3) **Design for Re-manufacturability** optimizes geometry and material compatibility to facilitate efficient recovery. Direct Energy Deposition (DED) technologies repair aerospace components to 90% of base material tensile strength with zero waste generation [18].
- (4) **Design for Upgradability** addresses technological obsolescence through backward compatibility and modular software architecture. Mid-life upgrades extend industrial turbines from 25 to 50+ years through progressive hardware and software enhancements, generating recurring revenue streams for original equipment manufacturers (OEM) [50].

3.1.2 Advanced Technical Recovery and Remanufacturing

Advanced recovery technologies operationalize the circular vision using systematic restoration processes. Remanufacturing, defined as complete industrial restoration to OEM specifications through systematic disassembly, component replacement, and reassembly, achieves 40-60% cost reduction versus new manufacturing [8], [9], [10] while extending material retention from 18 years with linear recycling to 43-47 years [9].

Additive manufacturing technologies, such as DED, enable in-situ repair of aerospace, automotive, and offshore applications [18], [42], to offer material utilization rates reaching 50-80% compared to 5-15% for conventional machining [41].

Aerospace utilizes DED for high-value components that were previously considered irreparable [18], [51]. Repair success rates of 85-95% for aerospace applications [18] demonstrate the technical reliability of this process. Friction stir additive remanufacturing (W-FSARM), a solid-state repair technique, achieves 90% of base material tensile strength (409 ± 10 MPa) with 100% material utilization and zero waste [18]. These advanced techniques establish the foundations for sectoral applications.

Sectoral adoption trends reveal varying implementation success rates across industries. Automotive remanufacturing achieves 38% recovery rates with 65.94-99.61% component utilization when employing dynamic infill strategies that replace unavailable remanufactured components with new ones [10]. Battery recycling via hydrometallurgy achieves >94% recovery rates of critical materials [15]. Industrial machinery implements coordinated recovery networks that enable mid-life upgrades, as per e.g. [20], [27], [52], [53].

Powder recycling in additive manufacturing reduces waste by 50-80% compared to conventional manufacturing, since mixtures of virgin and recycled powder preserve final object properties while limiting process costs [41]. However, the economic viability depends on product value, commodity prices, labour costs, and technology maturity [9], [54]. High-value components justify remanufacturing investments, while low-value items favour recycling. Remanufacturing can be 2 times more lucrative than new manufacturing when economies of scale are achieved [9]. This evidence demonstrates that advanced recovery technologies are operationally proven rather than theoretical. The limitation to adoption lies not in technical feasibility but in the economic viability and market demand for remanufactured products.

3.1.3 Maintenance Optimization

Strategic maintenance converts a potential risk into an extension opportunity through systematic intervention. Preventive Maintenance reduces unplanned failures by 30-40% compared to reactive approaches [6], establishing the foundation for lifecycle extension. Predictive Maintenance operates through a fundamentally different causal mechanism than preventive approaches: rather than executing interventions at predetermined intervals, predictive systems trigger maintenance only when condition indicators signal imminent failure. This selectivity generates dual benefits: (1) Economic efficiency with interventions concentrate resources only on components requiring attention, thus reducing unnecessary maintenance cycles and associated labour costs by 1.6% over 3-year operational periods; (2) Operational continuity: by preventing unplanned failures, predictive systems reduce

unplanned downtime by 40-50%, maintaining productivity and avoiding cascading failures in interconnected machinery systems [16], [27]. The mechanism underlying this effectiveness is information asymmetry reduction: traditional preventive maintenance operates under uncertainty (maintenance scheduled regardless of actual component condition), while predictive maintenance utilizes real-time sensor data to align interventions with actual degradation trajectories. This alignment is particularly valuable in heterogeneous industrial environments where component degradation rates vary substantially based on operational conditions, material properties, and usage intensity. IoT monitoring infrastructure enables this alignment by providing continuous condition data (temperature, vibration, pressure, energy consumption) that would be prohibitively expensive to collect through manual inspection [15], [25], [26].

Condition-Based Maintenance (CBM) balances between scheduled and reactive approaches by triggering interventions based on measured condition parameters [6], [27], [52]. Reliability-Centred Maintenance (RCM) systematically identifies failure modes and prioritizes interventions based on risk and consequence [26], complementing CBM with structured decision frameworks. The control of these maintenance parameters avoids energy efficiency degradation that occurs naturally over operational life due to erosion, wear, and material degradation [6]. The maintenance strategy significantly impacts efficiency loss trajectories: preventive maintenance maintains efficiency at approximately 0.2 loss, corrective maintenance at approximately 0.3, and predictive maintenance at approximately 0.1. This efficiency differential carries substantial economic consequences. An efficiency loss of 0.3 costs \$1,668-\$2,404 additional electricity over 3 years and emits 25,100 kg CO₂ [6].

PSS fundamentally restructures maintenance incentives through novel ownership models. Equipment-as-a-Service (EaaS) models, where OEMs retain ownership and customers pay based on usage, achieve 15-25% reduction in customer total cost of ownership while generating 20-30% higher OEM margins [29]. This incentive alignment ensures that OEMs maximize product lifespan and efficiency rather than accelerating replacement cycles. The critical insight emerging from this evidence is that maintenance represents not merely cost-minimization but value-creation. By preventing failures, optimizing efficiency, and enabling repairs, maintenance strategies defer product replacement while extending material utility across operational lifecycles.

3.1.4 Use-Phase Efficiency

The use phase dominates lifecycle environmental impact for energy-intensive products, accounting for 48-95% of total impact [6], [7], [28]. This dominance creates significant leverage for optimization strategies. Repair and Refurbishment applications extend the use-phase benefits through targeted interventions. In-situ repair via W-FSARM achieves 90% of base material properties with zero waste for aerospace components [18]. Off-site refurbishment results in 30-40% reduction in global warming potential compared to new manufacturing when extended to 8-year service life [38]. Simple maintenance interventions also contribute meaningfully: descaling with vinegar, the most effective repair intervention for electric kettles, reduces environmental impact by 20% [28]. Prognostics and Health Management (PHM) approaches enable prediction of remaining useful life through statistical analysis of key performance parameters, aiming to support both service life extension and scheduled maintenance decisions [26]. When integrated with condition-based maintenance strategies, PHM frameworks enable optimization of component orientation within circular loops based on technical-functional indicators, particularly state of health assessments [55]. This integration demonstrates the value of combining predictive analytics with maintenance planning. A generic algorithm for industries with degrading equipment provides decision support regarding appropriate lifetime extension strategies, optimal implementation timeframes, and relevant machine components, demonstrating potential to reduce Key Performance Indicator (KPI) penalties by 30-40 percent [32].

The concept of through-life services translates life-extension service into an actionable pathway, by proposing services per life stage based on the chain of Observation-Analysis-Acting for industrial through-life services [27]. A conceptual framework applied to PLCE strategies enables understanding whether the application of a strategy is beneficial from environmental and economic perspectives [52]. Achieving a deep and comprehensive understanding of the factors that influence consumer replacement behaviour is crucial for the successful development of strategies aimed at extending product lifetimes. Research demonstrates that, when expected product lifetime increases by 1, 2, and 3 years, actual product lifetime rises by 0.9, 1.8, and 2.72 years, respectively, thus indicating substantial potential for product lifetime extension through business strategies targeting consumer expectations [356].

3.1.5 Digitalization

Digital technologies do not act transversally along all circular practices. Instead, their effectiveness significantly varies depending on specific applications and implementation contexts [16]. This selective effectiveness requires strategic sequencing of technology adoption rather than treating all technologies as equally valuable investments. IoT enables continuous collection of operational data including temperature, vibration, pressure, and energy consumption [16], [26], [27], which triggers maintenance alerts and generates optimization recommendations. IoT reduces unplanned downtime by 40-50% [16], [27] and simultaneously supports dynamic pricing in PSS models based on actual usage patterns [29], [53].

Artificial Intelligence and Machine Learning complement IoT capabilities by predicting remaining useful life from sensor data, which makes it possible to forecast failure modes using historical records and optimize maintenance scheduling [26]. AI-based remaining useful life prediction for electric vehicle batteries achieved 95% accuracy in predicting degradation trajectories [15], which demonstrated the practical reliability of these approaches. Digital Twins and Simulation create virtual replicas of physical assets with synchronized operational data, enabling simulation of maintenance interventions before physical execution [29], [20]. Digital twin simulations for industrial turbines reduced commissioning time by 30-40% and identified upgrade pathways that extended the operational life by 10-15 years [50].

Additive Manufacturing for Repair enables layer-by-layer material deposition for in-situ repair, while eliminating waste generation compared to subtractive machining [18], [42]. Material utilization reaches 50-80% for DED versus 5-15% for conventional machining [41], with repair success rates of 85-95% for aerospace applications [18]. Blockchain technology and Digital Product Passports are being utilized to maintain immutable records of a product's history, including details of manufacturing, maintenance, and repairs. These records track component provenance and material composition, ensuring transparency and traceability. Pilot implementations in the automotive (Volkswagen), electronics (Fairphone), and aerospace sectors demonstrate the emerging adoption of these technologies. [3], [16].

Digital Thread integrates data flow connecting design, manufacturing, use, and end-of-life phases, enabling an overview of lifecycle activities and promoting interdepartmental synergy [1]. Technology-Practice Associations reveal selective effectiveness patterns. Simulation and Additive Manufacturing support product redesign: Simulation enables LCA of production processes and supply chain impact calculation, while Additive Manufacturing identifies technical cycles that enable lifecycle extension [16], [56]. Artificial Intelligence and IoT redesign customer interfaces: Artificial Intelligence enables understanding of user behaviour and efficient PSS development, while IoT provides continuous customer interface for data collection and real-time product use data

[16]. This selective effectiveness implies that organizations should sequence or group technology adoption decisions rather than treating them as independent investments [16].

3.1.6 Circular Business Models

A study of 150 organizations reveals that the adoption rates of the principal extension strategic domains vary significantly across different implementation approaches and scopes. Maintenance and consultancy dominate at 47.3%, followed by access schemes at 42.0% and repair at 37.3%, while design improvements appear in only 14% of organizations, primarily Type C quality designers [13].

Seven distinct circular business model (CBM) types (A to G) emerge from the quantitative analysis of this study on the organizations involved, using k-medoids clustering with a Silhouette coefficient of 0.651 [13]. Type A, relational product-as-a-service, comprises 38 large manufacturers emphasizing maintenance at 100% and repair at 81.6%. Type B, Brick and digital product nurturer, combines 17 organizations integrating physical and digital channels across PLCE activities. Type C, Quality product designer, focuses on 18 organizations pursuing design-for-durability with premium positioning. Type D, Second-hand vendor, operates 13 organizations with redistribution-only models. Type E, Marketer-managed access systems, manages 32 organizations controlling company-based asset access. Type F, Peer-to-peer access brokers, connects 19 organizations through peer platforms. Type G, Consumer redistribution marketplaces, facilitates 13 organizations enabling consumer to consumer (C2C) transactions between consumers.

The dominance of nurture strategies (maintenance 47.3%, access 42.0%, repair 37.3%) over nature strategies (design 14.0%) reveals a fundamental strategic asymmetry driven by economic motivations [13]. Organizations prioritize extending existing product life over designing products for longevity because nurture strategies generate recurring revenue and customer lock-in with minimal organizational disruption, while design investments require substantial upfront capital with longer payback periods and multi-functional capability development. However, this focus may be suboptimal from a systems perspective, as design establishes prerequisites for all other strategies to function effectively [2]. The distribution between seven types demonstrates that circular business models are not monolithic [13]. Different combinations of activities, partnerships, channels, and revenue streams enable organizations to capture value across multiple product use cycles. Consumers are primarily involved in access and redistribution through C2C and C2B segments, while design, maintenance, and recovery remain dominated by

organizations [13]. Digital platforms prove critical for Types D, E, F, and G representing 51% of the sample, facilitating matching between supply and demand while enabling new peer-to-peer models [13], [16].

These seven circular business model types coexist within the same sectors, suggesting that multiple business model archetypes can thrive simultaneously. This diversity indicates that PLCE is not a single transformation but rather a portfolio of complementary and competing strategies [13].

After describing all the PLCE strategies analysed during this systematic review study, figure 3 was developed to support the selection of the most appropriate strategy to apply, depending on the type of product and the type of application to be considered.

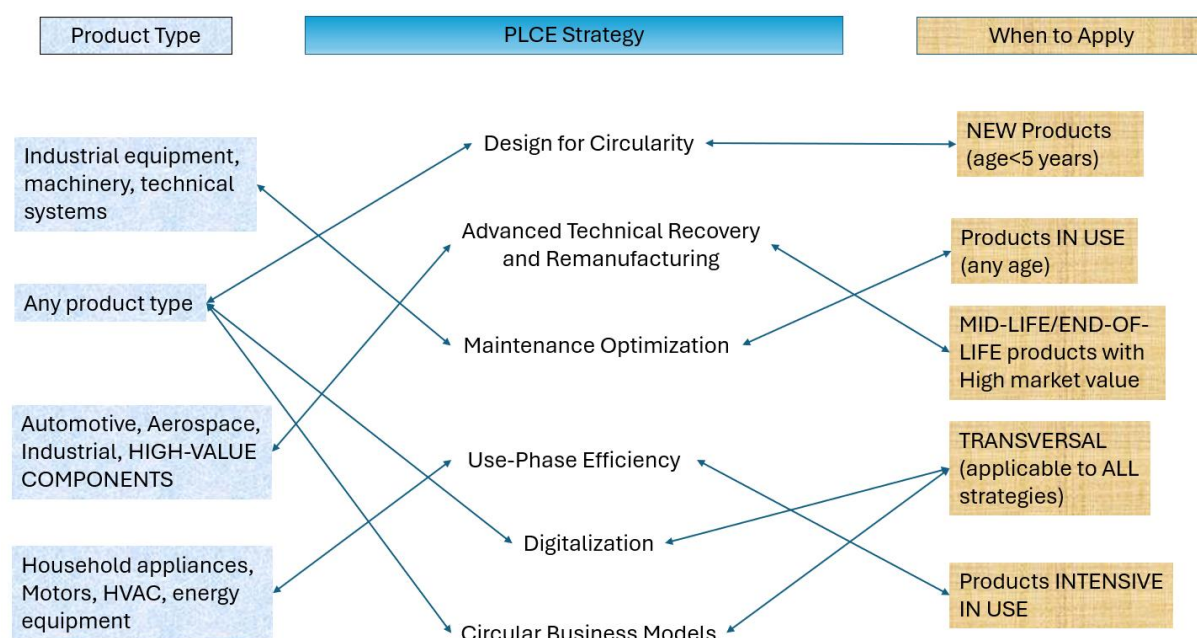


Figure 3 - Supporting Map to PLCE strategies chosen

3.2 PLCE Methodologies

The transition from linear and take-make-dispose economic models toward genuinely circular systems represents one of the most important challenges and opportunities in contemporary industrial practice. PLCE represents a convergence of technical innovation, business model transformation, and environmental imperatives. Rather than viewing products as disposable commodities, PLCE involves the strategic integration of design, manufacturing,

operational, and end-of-life strategies to maximize the utility derived from material and embodied energy investments. The methodological approach to promote PLCE has dramatically evolved over the past two decades. What began as relatively isolated technical interventions, repair techniques, maintenance protocols, and material science improvements, has matured into an integrated ecosystem of approaches spanning mathematical modelling, artificial intelligence, digital infrastructure, business innovation, and stakeholder governance. This evolution reflects a fundamental recognition that extending product life is not merely an engineering problem but instead a systemic challenge that requires coordination between multiple knowledge domains and organizational boundaries.

The analysis of 62 distinct articles and research documents on PLCE reveals a sophisticated and multidisciplinary methodological frame. This classification synthesizes the diverse analytical, computational, and empirical approaches employed in the field, which demonstrates that PLCE is fundamentally an evidence-based discipline that requires rigorous quantitative validation, advanced computational modelling, and comprehensive environmental and economic assessment frameworks.

The methodologies documented here, and illustrated in figure 4, span seven major categories, from traditional engineering disciplines through advanced computational intelligence, from established environmental assessment frameworks through emerging digital technologies, and from quantitative analytical methods through qualitative stakeholder engagement approaches. Critically, the evidence suggests that no single methodology suffices. Instead, effective PLCE strategies typically employ carefully sequenced combinations of complementary approaches, each addressing specific decision points or knowledge gaps in the lifecycle extension journey.

The PLCE overall resume presented on figure 4 structured to provide both breadth, covering the full spectrum of available methodologies and depth, with each methodology situated within its practical application context, its underlying assumptions, its empirical validation, and its integration with complementary approaches. The objective of this PLCE map board is to equip practitioners, researchers, and policymakers with a comprehensive overview of the methodological terrain, enabling informed selection and combination of approaches appropriate to their specific industrial, organizational, and environmental contexts.

PLCE Methodologies

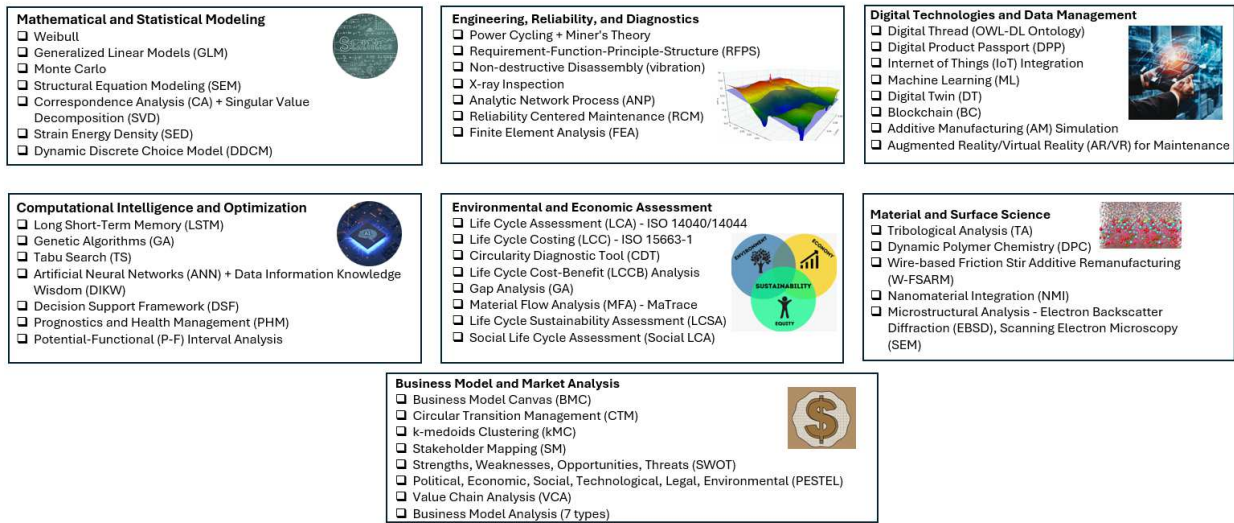


Figure 4 - PLCE Methodologies Overview Board

3.2.1 Mathematical and Statistical Modelling

The quantitative analysis of extended product lifecycles rests on sophisticated mathematical methodologies that transform operational data into reliable predictions. Weibull distribution analysis forms the foundation to calculate failure probabilities over time, enabling estimating optimal maintenance intervention points. Studies on Insulated Gate Bipolar Transistor (IGBT) components demonstrated that, even under reduced thermal oscillations ($\Delta T_j = 40K$), damage accumulates progressively, contradicting assumptions of unlimited operational life, as per e.g. [6], [26], [30], [33]. This approach was similarly applied to predict failures in vacuum pumps operating continuously in nanotechnology environments. The results revealed that the choice of degradation model significantly affects predicted costs, with differences of up to 36% between models for identical operational scenarios.

Generalized Linear Models enabled robust multivariate analysis of 2,640 repair scenarios for electric kettles, which ensured statistical significance in environmental impact reductions [6], [28]. This methodology isolated the independent effects of variables such as usage intensity and material composition while controlling multiple confounding factors. Monte Carlo simulation complemented these analyses by modelling prolonged operational cycles spanning 200 to 292 years and validating preventive maintenance policies in uncertain scenarios [26], [32]. This approach produced probability distributions of outcomes that reflected real-world variability. Structural Equation Modelling identified and weighted the drivers of eco-innovation adoption in 8,544 Polish industrial

companies, revealing that regulations impact adoption at 0.071, reputation at 0.162, and financial incentives at 0.179, with significant variation by company size [57]. A study employing Correspondence Analysis combined with Singular Value Decomposition revealed a correlation between digital technology adoption and circular economy practices among 41 Italian manufacturers [16]. The analysis revealed that simulation and additive manufacturing played a significant role in PLCE through redesign.

The Strain Energy Density method [31], enabled precise fatigue life predictions in mechanical components using the relationship $\Delta W = C$ multiplied by N raised to power D_f (C equals 67.55, D_f equals 0.34875), demonstrating strong agreement with experimental data on cylindrical gears under variable loads of 68-95 kN. The Dynamic Discrete Choice Model quantified the relationship between air conditioner replacement decisions and expected product lifetime [58]. This analysis revealed that each additional year of expected life resulted in approximately 0.9 years of actual lifecycle extension, which represented a near-unity ratio, to validate that consumer longevity expectations effectively translate into extended product use.

3.2.2 Computational Intelligence and Optimization

Long Short-Term Memory neural networks process sequential sensor data in real time, enabling automatic corrections during additive manufacturing restoration of crankshafts [35]. The system achieved mean squared error of 0.0047 mm² and dimensional precision of plus or minus 0.15 mm (within aerospace specifications), with processing time of 3.2 s per layer. This approach increased restoration success rates from 73% with manual compensation to 94%, significantly reducing material waste and failed restoration attempts.

Genetic algorithms identified operational parameters maximizing tool and component lifespan through efficient exploration of solution space [31]. In gear optimization, the algorithm discovered 47 non-dominated solutions, revealing that improving one objective often comes at the expense of another. This enables decision-makers to select from a Pareto front based on their priorities. Tabu search resolved the multidimensional knapsack problem in automotive engine remanufacturing, achieving utilization rates of 65.94%-99.61% for 31 component types and reducing premature disposal of usable components by 23% [10].

Artificial Neural Networks integrated with the DIKW (Data-Information-Knowledge-Wisdom) pyramid transform raw sensor data into autonomous end-of-life treatment decisions for electronic devices [10], [35]. This hierarchical approach captured specialist knowledge and implemented it in machine learning systems, facilitating knowledge transfer between domains through federated learning. The Decision Support Framework DSF Core algorithm integrated stochastic simulation with decision support, enabling identification of optimal maintenance policies that reduce KPI penalties by 30-40% compared to reactive repair strategies [32].

Prognostics and Health Management implemented the transition from "fail and fix" to "predict and prevent" through continuous condition monitoring [26], [27], [55]. Integrated from design phase through operational sustainment, PHM systems continuously monitor temperature, vibration, pressure, and electrical properties. The methodology Potential failure-to-Functional failure (P-F interval) analysis monitors the interval between potential failure and functional failure, enabling proactive maintenance scheduling based on observed degradation trajectories. Validation in aerospace components demonstrated 87% prediction accuracy within plus or minus 15% of predicted timeframe, with false alarm rates of 3.2%, acceptable for safety-critical applications [26].

3.2.3 Engineering, Reliability, and Diagnostics

Power Cycling Tests combined with Miner's cumulative damage theory validate second-life semiconductor reliability through rigorous experimental protocols [33]. Studies demonstrated that low thermal oscillations ($\Delta T_j = 40$ K) do not result in unlimited operational life, with damage accumulating progressively over time. The RFPS (Requirement-Function-Principle-Structure) model provides systematic engineering guidance for product upgrades through functional, principle, and structural innovation [36]. Application to Computer Numerical Control (CNC) cutting tables reduced friction from 0.400 to 0.018 through lubrication system improvements, demonstrating the effectiveness of targeted interventions over comprehensive redesigns.

Non-destructive disassembly via vibration waves employed acoustic energy (42 Hz, 2.5 J) to separate components without structural damage, reducing required extraction force by up to 80% while simultaneously improving surface properties through increased micro-hardness and reduced roughness [37]. X-ray inspection detected internal defects in microchips, enabling identification of manufacturing defects before deployment [35]. The Analytic Network Process provided multi-criteria decision-making frameworks incorporating feedback loops and

dependencies between criteria, moving beyond traditional linear weighting approaches [17]. These diagnostic techniques establish the foundation for informed engineering decisions.

Reliability-Centred Maintenance systematically identified failure modes and prioritizes interventions based on risk and consequence, aligning with Prognostics and Health Management for integrated lifecycle management [26], [27]. Finite Element Analysis supported design optimization through structural and thermal analysis, predicting stress concentrations and thermal gradients that affect component life [31], [35]. Combined with optimization techniques, Finite Element Analysis enabled identification of design parameters maximizing durability while meeting performance requirements. This integrated approach demonstrated that engineering reliability depends on coordinating multiple analytical methods rather than relying on isolated techniques.

3.2.4 Environmental and Economic Assessment

LCA per ISO 14040/14044 quantifies environmental impacts across entire product lifecycles using SimaPro or ReCiPe for midpoint and endpoint indicators [2], [7], [8], [30], [38]. Analysis of furniture demonstrated that lifecycle extension through durability is more determinant than material choice: products with 100 years lifespans exhibit 94% lower impact per year of service compared to single-year products. This finding demonstrates a critical insight about lifecycle extension. Analysis of 2,640 electric kettle repair scenarios showed that the use phase dominates (48-64% of total environmental burden), while material and end-of-life management represent only 5 to 10%, suggesting that usage intensity reduction yields greater environmental benefit per functional unit than material substitution.

Life Cycle Costing per ISO 15663-1 structures economic analysis across Capital Expenditure, Installation Cost, Operational Expenditure, Capital Maintenance Expenditure, and Risk Expenditure [30], [52], [54]. Analysis of a 45-year-old offshore separator revealed that Risk Expenditure constitutes 60% of total lifecycle cost in safety-enhancement strategies, dominating over CapEx and OpEx. This finding highlights that traditional LCC analyses focusing solely on capital and operational costs underestimate true costs by 60% for ageing assets.

The Circularity Diagnostic Tool provided four-step quantitative assessment based on eight cross-cutting attributes: disassemblability/reassemblability, durability, modularity, simplicity, standardization, commonality, relative cost

of spare parts, and secondary functions [39], [59]. Application to a skateboard with 11 pieces and 47 components generated concrete redesign intervention lists. A comprehensive review of 36 circularity indicators disclosed that the majority provide a narrow representation of product system aspects, with critical gaps including resource use during the use phase and lifecycle extension strategies [22].

Life-Cycle Cost-Benefit Analysis integrates risk expenditure with traditional LCC components, using the metric Benefit-Cost Ratio (BCR) equals Life-Cycle Benefit - estimated (LCBe) divided by Life-Cycle Cost - estimated (LCCe) to determine economic viability [43], [54]. A gap analysis compared linear (manufacture to use to disposal) and circular (manufacture to use to remanufacturing to use) pathways, quantifying environmental and economic benefits of circular approaches [52]. Material Flow Analysis with extended modelling tracked material flows through multiple remanufacturing cycles, demonstrating 2-5% reduction in material dissipation and 25-29 year extension in material retention compared to linear approaches [9].

Lifecycle Sustainability Assessment integrates Triple Bottom Line dimensions (economic, environmental, social) through combined LCA, LCC, and Social LCA. Social Life Cycle Assessment quantifies employment impacts, working conditions, community effects, and consumer satisfaction. These dimensions are frequently neglected in traditional environmental assessments, yet represent critical components of comprehensive sustainability evaluation. [5], [15], [23].

3.2.5 Material and Surface Science

Tribological analysis studies friction, wear, and lubrication to extend mechanical contact life through optimized lubricant selection and surface treatments [17]. Solid-State Repair via W-FSARM restored aluminium alloys without melting, preserving microstructural integrity while achieving 90% of base material tensile strength (409 plus or minus 10 MPa) with 100% material utilization and zero waste. The process generated equiaxial refined grains that enhance mechanical properties [18].

Dynamic polymer network chemistry exploited reversible bonds including hydrogen bonds, ester, and amine enabling self-healing capabilities [60] [40] [14]. Demonstration of 100 or more curing cycles at 130 degrees Celsius with approximately 82% efficiency at cycle 100 using EMAA (ethylene-methacrylic acid copolymer) on

textile reinforcement reveals viability for extended product lifecycles. Nanomaterial integration analysis evaluated durability enhancement through nanoparticles and nanofibers, achieving 130-3,100% lifecycle extensions (NanoSafe batteries: 12 times more cycles; silver nanoparticle-treated jackets: 31 times extension) [25] [21]. The energy premium of nanomaterial production is compensated through production avoidance of multiple conventional products.

Microstructural analysis via EBSD (Electron Backscatter Diffraction), SEM (Scanning Electron Microscopy), and optical microscopy characterized grain structure, phase distribution, and defects affecting material properties, thereby validating repair quality and predicting long-term durability [18], [40]. This comprehensive characterization demonstrated that material science provides the analytical foundation supporting all advanced repair and recovery technologies.

3.2.6 Digital Technologies and Data Management

The Digital Thread, based on Web Ontology Language Description Logics (OWL-DL) ontology, integrates data flow connecting design, manufacturing, use, and end-of-life phases [1]. This framework enables holistic visualization and cross-functional collaboration for lifecycle management through ten circularly oriented protocols (Z-Modernization through Omega-Remanufacturing and Testing) organized hierarchically. Prototype implementation demonstrated successful integration of data from five different manufacturing systems, handling 10,000 or more product instances without performance degradation, and reducing strategy identification time from two to three days to twenty minutes.

The Digital Product Passport systems maintain immutable records of product composition and lifecycle history [3], [4]. The implementation of these systems in washing machine remanufacturing captured detailed information across four categories, assessed through 10 evaluation indicators (brand, bearing condition, information completeness, and others). This enabled informed decisions on whether to repair or replace washing machines at collection points. Decision Support Systems increased value recovery by 23% through better routing of products to appropriate end-of-life pathways.

IoT sensor integration enables continuous collection of operational data including temperature, vibration, pressure, and energy consumption. Implementation in three industrial partners revealed that predictive maintenance reduced unplanned downtime by 83%, reduced maintenance costs by 27%, and extended component life by 56%, as e.g. [20], [27], [29], [53] .

Machine Learning algorithms predicted the remaining useful life from sensor data and historical patterns [26], [34]. Hybrid physics-data approaches combining known degradation mechanisms with learned patterns from historical observations achieved 87% prediction accuracy within plus or minus 15% of predicted failure time. Digital Twin simulation created virtual replicas synchronized with physical assets, enabling intervention simulation before execution. Implementation reduced commissioning time by 30-40% for industrial turbines and maintenance time by 34% for friction welding machines [20], [29], [50].

Blockchain maintained tamper-proof records of manufacturing, maintenance, repairs, and certifications, facilitating supply chain transparency and remanufactured product authentication [3], [16]. Additive Manufacturing process simulation optimized parameters including laser power, scanning speed, and material feed rate before physical production, reducing errors and material waste in repair operations [18], [41], [42]. Technology-Practice Associations revealed selective effectiveness patterns. Simulation and Additive Manufacturing supported product redesign: Simulation enabled LCA of production processes and supply chain impact calculation, while Additive Manufacturing identified technical cycles enabling lifecycle extension [16]. Artificial Intelligence and IoT redesigned customer interfaces: Artificial Intelligence enabled understanding of user behaviour and efficient PSS development, while IoT provided continuous customer interface for data collection and real-time product use data [16]. This selective effectiveness implies that organizations should sequence or group technology adoption decisions rather than treating them as independent investments.

3.2.7 Business Model and Market Analysis

The Business Model Canvas framework structures circular business model design for nine elements including value proposition, segments, channels, relationships, activities, resources, partnerships, costs, and revenue streams.

The Fairphone concept (multiple utilization policy) demonstrated how to integrate multiple product use cycles, with revenue streams that include new equipment sales, component replacement, refurbished device sales, and material recovery credits [11], [44].

Circular Transition Management guides phased transition from linear to circular models, particularly for EaaS implementations. Implementation along three phases (foundation, service expansion, circular integration) reduced disruption risk and allowed learning adaptation [29], [53]. Phase 1 established digital monitoring; Phase 2 implemented predictive maintenance; and Phase 3 established remanufacturing. Results demonstrated that incremental approaches are preferable to radical transformation, avoiding disruption while building capabilities.

Stakeholder mapping identified five principal actors with divergent interests: OEMs, customers, service providers, recyclers, and regulators [43], [61]. In the maritime industry [61], despite achieving 95-98% recycling by weight, three structural barriers impeded transition to genuine circular strategies (reuse, remanufacturing). First, lock-in to established recycling infrastructure renders alternative pathways economically unattractive [61]. Second, fragmented international governance and classification society scepticism toward remanufactured components create regulatory obstacles. Third, misaligned incentives to stakeholders perpetuate suboptimal choices. Specifically, shipowners prioritize cost minimization and operational uptime, OEMs face market conservatism despite pilot remanufacturing programs, and classification societies systematically prefer component replacement over remanufactured alternatives. The Strengths-Weaknesses-Opportunities-Threats (SWOT) and Political-Economic-Social-Technological-Environmental-Legal (PESTEL) analyses provided strategic positioning frameworks [15], while value chain analysis traced material and value flows, identifying leverage points for circular intervention [20], [53]. In other works, successful PLCE required not merely technical feasibility but deliberate multi-stakeholder coordination to align competing objectives across the value chain [43], [61].

3.3 PLCE strategies adoption across the industrial sectors

PLCE strategies exhibit substantial variation in effectiveness between industrial sectors. Instead of treating extension strategies as isolated technical interventions applied uniformly across sectors, effective PLCE integrates multiple complementary approaches into coordinated frameworks adapted to sectoral characteristics. Table 1

demonstrates the correlation between the principal industrial sectors and PLCE strategies bases on reviewed articles.

Table 1 - Industrial sectors vs PLCE strategies application – systematic literature review

INDUSTRIAL SECTOR	Design for Circularity	Advanced Technical Recovery & Remanufacturing	Maintenance Optimization	Use-Phase Efficiency	Digitalization	Circular Business Models
Automotive	X	X	X	X	X	X
Aerospace	X	X	X	X	X	—
Energy (Wind)	X	X	X	X	—	—
Furniture	X	X	X	X	—	—
Consumer Electronics	X	X	X	X	—	X
Maritime	X	X	X	X	X	X
Textile & Apparel	X	—	—	—	—	X
Industrial Equipment	X	X	X	X	X	X
Power Electronics	X	—	—	—	—	—
Energy Storage (Batteries)	X	X	X	X	—	X

In aerospace and aeronautic manufacturing, metal additive manufacturing processes offer potential for resource efficiency improvements, particularly for energy-intensive materials such as titanium [23]. For wind energy systems, modernization and lifecycle extension through component replacement prove environmentally superior to complete facility repowering [62]. The electrical and electronic equipment sector presents particular urgency, as rapid technological evolution creates tension between extending product lifetimes and accommodating functional obsolescence [3]. Furniture products demonstrate significant potential for environmental impact reduction through lifecycle extension prioritization [38]. Automotive applications present complex challenges, as the sector must balance product lifetime extension with technological advancement and energy efficiency improvements [15].

3.4 Industrial Cases

The industrial cases mapped considering diverse sectors reveal distinct implementation patterns. In the automotive industry, lubrication system optimization in turbochargers achieved 95.5% friction reduction, while dynamic infill remanufacturing attained component utilization rates between 65.94%-99.61% [10], [17]. The aerospace sector demonstrated that friction stir additive remanufacturing restored 90% of original mechanical properties with zero material waste [18]. Industrial machinery revealed that predictive maintenance reduces operational costs by 20 to

25% compared to preventive maintenance, while circular transition models extended equipment life by 25 to 50% [20], [27], [29], [53]. Wind energy illustrated the potential of midlife upgrades, extending operational life from 25 to 50 years more efficiently than complete replacement [62]. Consumer electronics showed that simple repair services such as descaling reduced environmental impact by 20%, with maximum life extension achieving 35% reductions [28]. Electric mobility presented emerging opportunities through second-life batteries in stationary applications, where most of residual capacity could be utilized with lower environmental impact than primary extraction [15].

These diverse industrial cases validate that successful PLCE requires coordination of complementary strategies adapted to specific product types, industrial sectors, and organizational contexts. The evidence demonstrates that PLCE is not merely an environmental imperative but an economically viable pathway to competitive advantage through cost reduction (15-60% depending on strategy combination), supply chain resilience, and brand differentiation.

3.5 PLCE strategies and environmental impact

The transition to extended circular product lifecycles represents a systems integration challenge. Success requires technical innovation and coordinated application of diverse methodologies, each contributing unique insights to complex and multi-dimensional decisions. The Organisations who domains this alignment, combining technical rigour with adaptive flexibility, will emerge as leaders in the circular economy transition, capturing economic value whilst simultaneously reducing environmental and social impacts. Organizations concentrate resources on strategies that generate immediate revenue but deliver moderate environmental benefits, while simultaneously underinvesting in design improvements that determine the biggest contribute on environmental impact matters. This misalignment shown on table 2 represents both the biggest challenge and opportunity to scale PLCE effectiveness. This analysis was taken considering the 62 articles from the literature review.

Table 2 – PLCE strategic adoption and corresponding environmental impact

Strategic Domain	Adoption (%)	Environmental Impact Potential (%)	Primary Implementation Pattern
Design for Circularity	14%	60-80%	Design improvements, durability, modularity (Type C quality designers)
Advanced Technical Recovery & Remanufacturing	37.3% (Repair) & 21.3% (Remanufacturing)	40-60%	Remanufacturing, repair technologies, component recovery
Maintenance Optimization	47%	15-25%	Preventive, condition-based, predictive maintenance strategies
Use-Phase Efficiency	~10-15%	20-35%	Repair, refurbishment, operational optimization, PHM
Digitalization	~5-10%	15-40%	IoT, AI, digital twins, blockchain, digital product passports
Circular Business Models	42%	10-30%	Access schemes, maintenance services, repair (Types A-G)

Design for Circularity, which determines 60-80% of environmental impact, is implemented by only 14% of organizations, while Maintenance Optimization with 15-25% environmental potential is implemented by 47.3% [13]. This critical paradox reveals that organizational decision-making prioritizes strategies generating immediate recurring revenue over approaches delivering superior environmental outcomes. Maintenance contracts, repair services, and access schemes are operationally straightforward and create predictable income streams, while design investments require substantial upfront R&D capital, longer payback periods, and multi-functional organizational capability development [13]. Consequently, organizations systematically underinvest in design despite its dominant environmental impact potential. Advanced Technical Recovery and Remanufacturing achieve 40-60% environmental impact potential, but is implemented at only 37.3% (repair) and 21.3% (remanufacturing), suggesting that technical feasibility alone does not drive adoption [13]. Use-Phase Efficiency (10-15% adoption, 20-35% potential) and Digitalization (5-10% adoption, 15-40% potential) demonstrate moderate implementation despite significant environmental efficacy, which indicates that adoption barriers transcend technical capability [13]. This distribution validates that current decision-making reflects rational economic incentives but may be suboptimal from a systems perspective: design establishes prerequisites for all other strategies to function effectively yet receives disproportionately low investment relative to its environmental impact potential [13]. Increasing design adoption from 14% to 30% would represent a double expansion in implementation. Considering that the design's documented 60-80% impact potential, the proportional environmental gains would represent a significant environmental impact reduction, though realizing this potential requires addressing systemic barriers

including standardization deficits, fragmented policy frameworks, inadequate longitudinal data, stakeholder misalignment, and organizational capability gaps.

4 Conclusions

The systematic review of 62 peer-reviewed articles (2019-2026) along six strategic domains and seven methodological frameworks reveals a fundamental insight: PLCE has evolved from isolated technical interventions into a mature and interdependent ecosystem. This paper synthesizes the critical findings, addresses the three research gaps identified in the introduction, and establishes actionable methods for practitioners conducting to the circular economy transition.

One of the critical gaps identified in the literature review was the lack of strategic and comprehensive evaluation frameworks to support decisions based on product context. This paper directly addresses this gap through Figure 3 (Supporting Map), which provides an operational framework to select PLCE strategies adapted to different product types and lifecycle phases. This support mapping correlates product characteristics with the six identified PLCE strategies, enabling practitioners to identify appropriate combinations.

Another critical gap found was the absence of systemic integration between domains. This gap is addressed through the evidence that each PLCE strategy (Table 1) requires the coordination of multiple complementary methodologies (Figure 4), demonstrating that no single approach suffices for effective PLCE. The analysis reveals that different industrial sectors require fundamentally different combinations of both strategies and supporting methodologies. The automotive sector applies all six strategies supported by all seven methodologies, while sectors such as wind energy and furniture apply specific subsets of strategies supported by targeted methodology combinations tailored to their technical and economic constraints. Validation through Table 1 confirms that sectors with the application of multiple strategies, such as Automotive and Aerospace, require the comprehension of most or all seven methodologies, while sectors with limited strategies require specific methodology subsets. This finding confirms that systemic integration is not "all methodologies for everything" but rather appropriate combinations of methodologies sequenced to support specific strategies adapted to sectoral context and lifecycle phases.

The gap concerning the absence of generic quantitative methodologies to assess PLCE effectiveness in environmental, economic, and social dimensions is directly addressed through LCA per ISO 14040/14044, Life Cycle Costing per ISO 15663-1, and Social Life Cycle Assessment, each providing quantified metrics throughout

the three Triple Bottom Line dimensions. This paper confirms that sectors applying multiple strategies simultaneously achieve maximum environmental impact potential while sectors with limited strategies achieve moderate impact, which indicates that integrated strategy combinations generate synergistic effects not captured by isolated strategies. Table 2 exposes the fundamental gap: Design for Circularity determines 60-80% of environmental impact, but it is only implemented by 14% of organizations, while Maintenance Optimization with 15-25% impact potential is implemented by 47.3%, revealing that current decision-making prioritizes immediate economic viability over maximum environmental potential. This paradox validates the necessity of integrated universal quantitative frameworks that simultaneously evaluate environmental, economic, and social dimensions.

The 62 articles analysed reveal that successful PLCE strategies integrate methodologies from at least seven major domains: Mathematical and Statistical Modelling; Computational Intelligence and Optimization; Engineering, Reliability and Diagnostics; Environmental and economic assessment; Material and Surface Science; Digital Technologies and Data Management; Business Models and Market Analysis. Several critical findings were identified on this PLCE methodological framework, namely:

- i. No Single Methodology Suffices: Effective PLCE requires combination of complementary approaches that address different knowledge gaps and decision points.
- ii. Temporal Dimension Critical: Traditional static analyses (LCA, LCC) must be complemented with dynamic approaches (System Dynamics, Monte Carlo simulation) to capture lifecycle complexity.
- iii. Stakeholder Engagement Essential & User Accountability Essential: Technical optimisation alone is insufficient; business model innovation, stakeholder alignment, and explicit user responsibility frameworks are prerequisites for effective PLCE implementation.
- iv. Digital Infrastructure Enabling: IoT, machine learning, and digital twins are increasingly central to PLCE, enabling predictive maintenance, real-time optimisation, and knowledge capture.
- v. Context Specificity & Implementation Maturity Essential: Appropriate methodology selection depends on decision context, time horizon, uncertainty level, stakeholder characteristics, product development stage, political-regulatory environment, and organizational circular maturity. Practitioners must tailor methodology combinations to their specific situations, accounting for developmental constraints, policy barriers, and capability gaps.
- vi. Continuous Learning: PLCE methodologies should incorporate adaptive management, treating initial implementations as learning opportunities that inform subsequent iterations.

The methodological framework for PLCE has evolved significantly over the past two decades. What began as isolated technical interventions, repair techniques, maintenance protocols, material science improvements, has matured into a comprehensive ecosystem of complementary approaches. This ecosystem spans mathematical modelling, artificial intelligence, digital infrastructure, business innovation, and stakeholder governance. The evidence from the scientific articles demonstrates a critical insight: successful PLCE implementation depends on conducting methodologies from seemingly disparate fields, each addressing specific knowledge gaps and decision points in the lifecycle extension journey. The transition to circular lifecycle-extended product systems is fundamentally a systems integration challenge. Success requires technical innovation and coordinated application of diverse methodologies, each contributing unique insights to complex multi-dimensional decisions. The frameworks and examples provided in this synthesis offer practitioners a comprehensive map of available tools and guidance for their strategic deployment.

5 Future work

Future success requires continued innovation in materials, processes, and business models, coupled with supportive policy frameworks and stakeholder alignment across value chains, with particular emphasis on closing the gap between academic research and industrial practice.

Regarding the critical paradox observed in the adoption of strategies and their environmental impact, understanding the industrial cause for why the strategy with the greatest environmental impact is the least adopted in general is essential for the sustainability. Systemic interactions and network effects remain underexplored. Most PLCE research examines individual strategies or products in isolation, but the systemic interactions between multiple circular strategies, supply chain configurations, and market dynamics, remain mostly unanalysed.

This study leads to the conclusion that there is a pressing need for companies to develop a well-structured and comprehensive strategy. This strategy should take into account the diverse domains and factors addressed in this article. By doing so, companies can effectively implement the PLCE that is most suitable and aligned with their specific needs and operational requirements.

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Author contributions

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