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SYSTEMATIC REVIEW OF SUSTAINABLE CIVIL ENGINEERING PRACTICES AND THEIR INFLUENCE ON INFRASTRUCTURE COMPETITIVENESS

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Abstract

This systematic review examines how sustainable civil engineering practices influence infrastructure competitiveness across the full project life cycle, integrating environmental performance with decision-relevant outcomes in cost, schedule, productivity, quality, resilience, finance, and user benefits. Following a PRISMA-aligned protocol, we searched multidisciplinary databases, screened records with dual independent reviewers, and extracted standardized data on sector, life-cycle stage, intervention type, comparators, metrics, and study quality. The final synthesis encompasses 115 peer-reviewed studies covering materials and low-carbon mix strategies, circular economy and end-of-life pathways, BIM and digital twins with IoT sensing, low-impact and off-site construction, green procurement and performance-based contracting, and risk-informed operations and maintenance. Across the corpus, sustainable practices were most consistently associated with life-cycle cost advantages and schedule reliability when boundaries extended beyond first cost, when QA and performance specifications were enforced, and when digital coordination reduced rework and variance. Modularization and lean logistics yielded notable on-site duration and waste reductions, while condition-based maintenance and resilience-aware planning improved availability and recovery. Financing signals, though smaller in volume, aligned with asset-level results, indicating modest cost-of-capital benefits where transparency and verification were strong. Neutral or mixed effects clustered where sustainability was specified late, supply chains lacked maturity, or digital adoption was not paired with clear roles and data governance. Overall, the evidence supports treating sustainability as a performance discipline that, when embedded early and measured on whole-life terms, reliably co-delivers competitiveness outcomes alongside environmental goals.

Keywords

Sustainable civil engineering, Infrastructure competitiveness, PRISMA, Life-cycle assessment, Whole-life costing, Circular economy, BIM, Digital twin, Lean construction, Performance-based procurement, Condition-based maintenance, Resilience, Cost of capital.

INTRODUCTION

Sustainable civil engineering refers to the integration of environmental stewardship, social responsibility, and economic efficiency across the entire life cycle of infrastructure planning and design, procurement, construction, operations and maintenance (O&M), and end-of-life (EoL) so that assets deliver reliable services without shifting costs to future users or ecosystems. In this paper, “sustainable civil engineering practices” include design optimization and whole-life thinking (e.g., LCA/LCC), low-carbon and circular materials (e.g., SCMs, LC3, RAP/RCA), low-impact construction (e.g., warm-mix asphalt), performance-based/green procurement, data-enabled O&M (e.g., predictive maintenance), and circular deconstruction and reuse (Azhar, 2011; Duxson et al., 2007; González & Navarro, 2006). “Infrastructure competitiveness” is used here to denote an asset’s and system’s capacity to attract investment and support productivity through lower lifecycle cost and cost certainty, faster and more reliable delivery, higher productivity and innovation uptake, better quality and service performance, improved resilience/risk profiles, favorable market perception and cost of capital, and stronger user outcomes (779, 2014). Aligning these constructs makes sustainability an operational strategy rather than a peripheral objective: for example, warm-mix asphalt reduces fuel use and emissions while widening paving windows and improving compaction, linking environmental and schedule/productivity benefits (779, 2014; Rubio et al., 2012). Likewise, BIM-enabled coordination reduces rework and change orders, aligning quality and time/cost outcomes (Azhar, 2011; Evangelista & de Brito, 2007). This definitional clarity allows the review to code evidence on specific practice-to-mechanism-to-outcome pathways and to synthesize links between sustainability actions and competitiveness metrics across sectors and life-cycle stages (Scrivener et al., 2015; van Duren & Dorée, 2010).

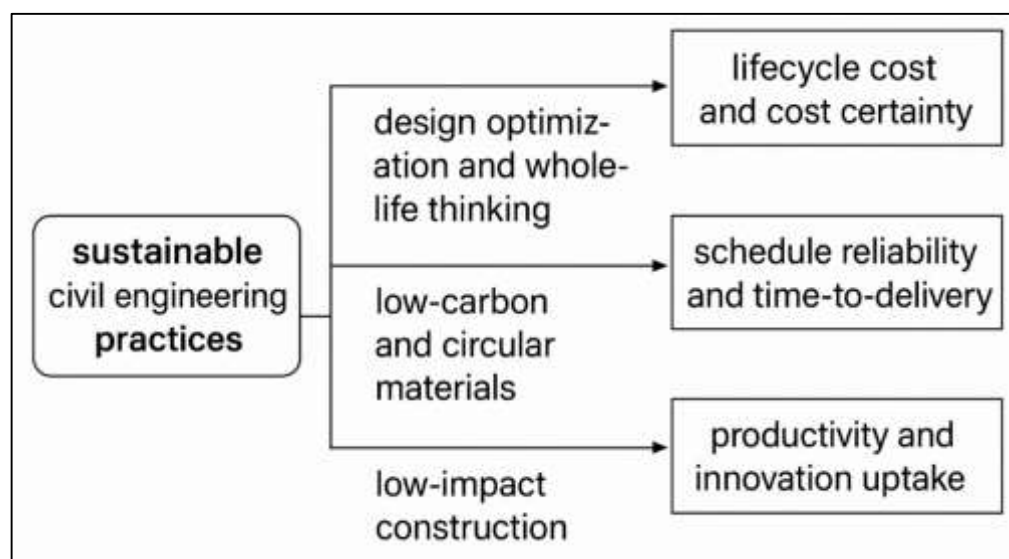
Figure 1: Framework for Sustainable Civil Engineering



The international relevance of sustainable civil engineering arises from converging pressures: a multitrillion-dollar infrastructure gap, climate commitments, local air-quality targets, and intensifying physical risks that threaten service reliability and capital productivity. Public funders and private investors are increasingly requiring demonstrable performance on carbon, resilience, and social value while also demanding timely delivery, affordability, and productivity gains (Benhelal et al., 2013; Bynum et al., 2013). In parallel, construction productivity stagnation and cost volatility have sharpened

the appeal of practices that cut waste, stabilize schedules, and improve quality (Azhar, 2011; Liu et al., 2018). Materials choices illustrate these intersecting pressures: SCM substitution and LC3 reduce embodied CO₂ while improving long-term durability in many contexts, with whole-life advantages when integrated into LCA/LCC decision frameworks (Gursel et al., 2014; Scrivener et al., 2015). In transport, warm-mix asphalt can lower energy use and emissions at the plant and site while maintaining or improving performance outcomes that appeal to both environmental regulators and delivery agencies (Love et al., 2011). Procurement reforms such as performance-based specifications and green public procurement have emerged to internalize whole-life performance, enabling innovation and value-for-money claims that are increasingly scrutinized by treasuries and development banks (Testa & et al., 2016; van Duren & Dorée, 2010). This context makes a systematic synthesis valuable: decision-makers need consistent evidence on which practices reliably co-deliver environmental gains and competitiveness outcomes across geographies and sectors (Gursel et al., 2014; Scrivener et al., 2015).

Figure 1: Sustainable Civil Engineering Practices To Infrastructure Competitiveness



Evaluating sustainability–competitiveness linkages requires a life-cycle perspective because early design and procurement choices can lock in decades of cost and performance (Wasiuddin & et al., 2007; Zaumanis & Mallick, 2015). LCA provides standardized methods to quantify environmental burdens, but translating those into competitiveness metrics cost certainty, schedule reliability, service performance, resilience requires bridging with LCC/techno-economic analysis and reliability-based models (Thomas et al., 2012). Measurement heterogeneity complicates synthesis: embodied-carbon studies use different boundaries and datasets; cost impacts are often reported as first cost (CAPEX) rather than total cost of ownership; schedule effects are sometimes qualitative; resilience is frequently scenario-dependent (Abdul, 2021; Silva et al., 2014). In pavements, emissions/energy studies compare HMA, WMA, recycling and rubberized mixtures, but methods and baselines vary (Liu et al., 2017; Pacheco-Torgal et al., 2013). In structures, RCA and geopolymers/alkali-activated concretes show promising performance and environmental profiles under specific quality control and supply contexts, yet meta-comparisons must account for strength class, exposure, and mix design (Duxson et al., 2007; FHWA, 2016; Rezaul, 2021). To support comparability, this review adopts a taxonomy of competitiveness metrics cost/finance, schedule/delivery, productivity/innovation, quality/performance, resilience/risk, market attractiveness, and user outcomes and codes studies by life-cycle stage, sector, region, study design, and effect direction. It also tracks mechanism pathways (e.g., modularization → fewer interfaces → less rework → schedule reliability; WMA → lower viscosity at a given temperature → improved compaction → durability and opening-to-traffic benefits) to interpret mixed findings (Bryde et al., 2013; IISD, 2013).

The objective of this review is to deliver a rigorous, decision-ready synthesis that clarifies how sustainable civil engineering practices influence infrastructure competitiveness across the project life cycle. Specifically, the review aims to (i) establish precise, operational definitions of sustainable practices and competitiveness outcomes and align them in a single analytical framework that is usable across transport, water, and energy civil works; (ii) map the state of evidence through a PRISMA-aligned search and screening process that captures peer-reviewed and high-quality technical studies relevant to design, materials, construction, operations and maintenance, and end-of-life; (iii) build a transparent taxonomy of practices such as low-carbon and circular materials, warm-mix asphalt, modular and lean construction, performance-based and green procurement, digitalization for design and O&M, and circular deconstruction and cross-walk that taxonomy to competitiveness metrics including lifecycle cost and cost certainty, schedule reliability and time-to-delivery, productivity and innovation uptake, quality and service performance, resilience and risk reduction, market attractiveness and cost of capital, and user outcomes; (iv) extract and structure data on contexts, study designs, comparators, and effect directions to allow both narrative synthesis and where homogeneity permits quantitative aggregation of cost, schedule, or performance effects; (v) identify and explain the mechanism pathways that connect practices to competitiveness outcomes, such as how modularization reduces interfaces and rework to stabilize delivery or how circular strategies and low-carbon mixes affect operating expenditures and availability; (vi) evaluate the strength, consistency, and transferability of findings by sector, region, life-cycle stage, and study quality, noting where results are robust and where they are contingent on standards, specifications, or supply-chain maturity; and (vii) produce tangible outputs for researchers and practitioners, including an evidence map, a mechanism model, and a structured set of reporting fields that promote comparability in future studies. Taken together, these objectives ensure the review not only summarizes what has been published but also organizes the literature into a practice-to-mechanism-to-outcome structure that supports measurement, benchmarking, and adoption decisions in real project and portfolio settings.

LITERATURE REVIEW

The literature on sustainable civil engineering practices spans multiple disciplines and life-cycle stages, yet it converges on a common question: how specific interventions ranging from materials substitution and circular resource flows to delivery models, digital tools, and operations strategies shape outcomes that matter for infrastructure competitiveness. Across transport, water, and energy civil works, studies typically cluster into five streams. First, materials and mix-design research examines low-carbon binders, recycled constituents, and performance modifiers, with attention to durability, maintenance cycles, and constructability. Second, life-cycle assessment and whole-life costing provide methodological anchors for translating environmental inventories into economic terms, though boundaries and data sources vary. Third, circular economy and end-of-life work explores design-for-deconstruction, reuse, and high-value recycling, considering logistics, quality control, and market development. Fourth, method and management inquiries focus on construction techniques (e.g., modularization, lean practices), procurement approaches (e.g., performance-based specifications, alliances, PPPs), and governance mechanisms that tie sustainability to measurable delivery performance. Fifth, digitalization research BIM, digital twins, IoT sensing, and predictive maintenance links information quality and asset intelligence to reductions in rework, variance, and unplanned outages. Taken together, these streams report outcomes along a set of competitiveness metrics lifecycle cost and cost certainty, schedule reliability and time-to-delivery, productivity and innovation uptake, quality and service performance, resilience and risk exposure, market attractiveness and cost of capital, and user outcomes yet evidence is heterogeneous in design, context, and measurement. Many studies emphasize single dimensions (e.g., embodied carbon or first cost), while fewer track multi-metric effects or quantify mechanism pathways such as interface reduction, variance control, or durability-driven OPEX changes. Differences in standards, specifications, climate, and supply-chain maturity further condition results and complicate cross-context synthesis. To navigate this heterogeneity, the review organizes the literature by life-cycle stage and practice family, codes study designs and comparators, and interprets findings through explicit practice-to-mechanism-to-outcome chains. This structure enables like-for-like comparisons where methodological alignment exists and offers transparent accommodation of mixed methods where it does not, setting up the subsequent subsections

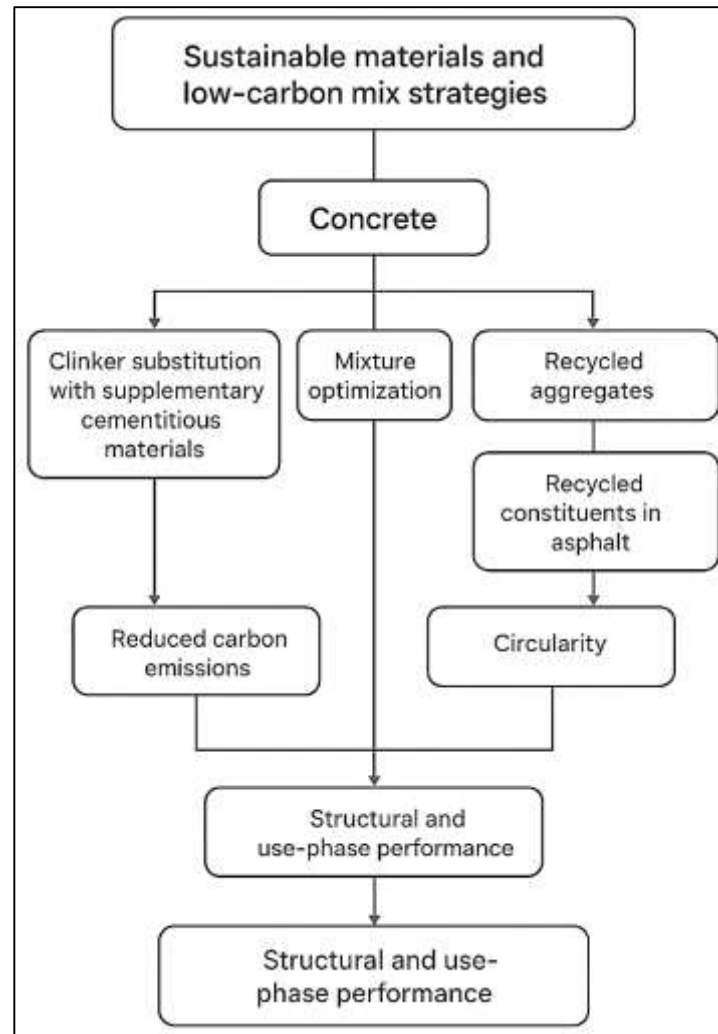
to evaluate the weight and direction of evidence for each major practice cluster.

Sustainable Materials and Low-Carbon Mix Strategies

The sustainability profile of civil infrastructure begins with the material palette and the way mixes are proportioned to deliver structural performance with lower embodied impacts. Within concrete by far the most widely used construction material the dominant levers include substituting clinker with supplementary cementitious materials, optimizing mixture “performance per unit of binder,” and incorporating recycled constituents without compromising durability. Early field-defining appraisals argued that “greening” concrete requires moving beyond volumetric metrics to functional metrics (strength/durability achieved per unit of environmental load), rethinking aggregate sourcing, and redesigning for disassembly and recycling (Meyer, 2009). Building on that logic, Damineli et al. (2010) introduced an eco-efficiency indicator that normalizes environmental burdens to mechanical performance, showing that mix optimization and clinker reduction can deliver step-change impact cuts independent of major process overhauls. On the aggregate side, life-cycle assessments (LCAs) comparing natural-aggregate concrete with recycled-aggregate concrete (RAC) demonstrate that, when supply chains are reasonably efficient and contamination is controlled, RAC can confer clear benefits in abiotic depletion and landfill diversion while meeting structural requirements (Marinković et al., 2010). Collectively, these studies converge on a material-efficiency paradigm: prioritize cement-intensive impact reductions through SCM use and binder efficiency, then capture circularity gains via high-quality recycling streams provided that durability and service life are rigorously verified (Marinković et al., 2010; Meyer, 2009; Xiao et al., 2012).

Accurately representing carbon flows over the life cycle is pivotal when comparing materials and mix designs. Conventional LCAs historically overlooked carbonation during service life and especially after end-of-life processing, which leads to systematic overestimation of concrete’s net CO₂ burden (Collins, 2010). Subsequent experimental and inventory work quantified CO₂ uptake in cementitious materials, showing that crushed and recycled concrete can re-absorb a substantial fraction of process emissions due to its increased surface area and exposure conditions (Galán et al., 2010). These insights materially alter the relative ranking of low-clinker mixes and recycling pathways in comparative LCAs, particularly where demolition and secondary use cycles are considered. Parallel LCA comparisons of “green concretes” those incorporating recycled aggregates and SCMs against conventional concrete further indicate that environmental improvements are attainable at equivalent performance, although gains vary with allocation choices, transport distances, and mix recipes (Turk et al., 2015). Taken together, this body of evidence underscores two methodological imperatives for sustainable mix design: (i) performance-adjusted functional units (e.g., MPa year) that reflect durability and service life, and (ii) consistent inclusion of carbonation across primary and secondary service lives so that carbon sinks are neither ignored nor double-counted (Collins, 2010; Mubashir, 2021).

Beyond structural concrete, pavement materials provide a complementary arena for material circularity and mix-level innovation. Reviews of recycled constituents in asphalt identify technically viable substitutions reclaimed asphalt, industrial by-products, and selected wastes that can reduce energy use and emissions if mix rheology and field performance are maintained (Collins, 2010; Huang et al., 2007). Systematic reviews of pavement LCAs caution, however, that system boundaries, maintenance assumptions, and use-phase effects (rolling resistance, albedo) often dominate cradle-to-gate differences among alternative mixes; thus, truly “sustainable” pavement materials must be evaluated over full life cycles with performance-adjusted functional units and realistic maintenance models (Inyim et al., 2016; Rony, 2021). Finally, sustainability claims around mixes increasingly consider water risks alongside carbon. A global assessment found that concrete production already accounts for a significant share of industrial water withdrawals and that future demand will concentrate in water-stressed regions, amplifying the importance of water-efficient mix designs (e.g., lower washing needs, SCMs with lower water footprints) and local sourcing (Miller et al., 2018). For civil infrastructure competitiveness, the implication is clear: low-carbon, circular mixes deliver the greatest systemic value when verified against durability, use-phase performance, and regional resource constraints within robust, boundary-complete LCAs (Damineli et al., 2010; Danish & Zafar, 2022; Miller et al., 2018).

Figure 2: Sustainable Materials and Low-Carbon Mix Strategies

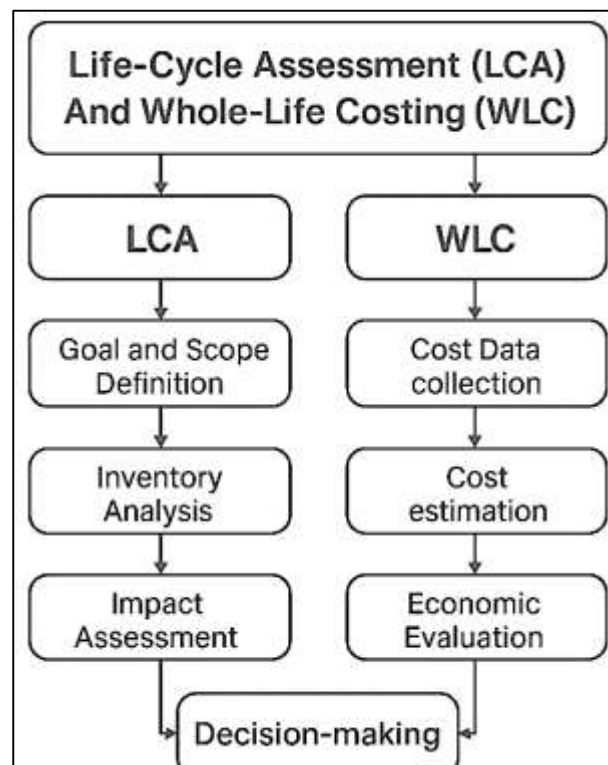
Life-Cycle Assessment (LCA) and Whole-Life Costing (WLC)

A core strand of the literature establishes LCA as the reference method for quantifying cradle-to-grave environmental burdens and framing design trade-offs at system level, while clarifying how WLC (or LCCA) translates those trade-offs into decision-relevant cost signals. Methodological reviews emphasize that contemporary LCA has progressed from energy tallies to robust impact assessment covering midpoint and endpoint indicators, with increasing attention to uncertainty, sensitivity, and data quality foundations that enable more defensible comparisons of infrastructure alternatives (Finnveden et al., 2009; Guinée et al., 2011). Impact assessment methods such as ReCiPe and TRACI operationalize this breadth by offering harmonized characterization factors for climate change, resource use, ecotoxicity, and more, calibrated to European and U.S. contexts respectively (Danish & Kamrul, 2022; Huijbregts et al., 2017). Within the built environment, syntheses document a steady shift from operational energy dominance toward embodied effects and maintenance/replacement cycles, underscoring the need to widen system boundaries and lengthen analysis horizons for civil works (Cabeza et al., 2014; Huijbregts et al., 2017). In parallel, the WLC/LCCA canon sets out principles for allocating initial, maintenance, replacement, and end-of-life costs across analysis periods, providing the economic complement to environmental inventories (Swarr et al., 2011). Together, these strands establish a dual-lens logic for infrastructure decisions: environmental inventories structured by ISO-consistent LCA, interpreted alongside discounted cash-flow representations of the same alternatives, with congruent functional units, time horizons, and scenarios to avoid apples-to-oranges comparisons (Bare, 2011; Finnveden et al., 2009; Jahid, 2022).

Applied studies translate this dual-lens into sector-specific insights. In transport assets, dynamic LCAs of pavement overlays integrate not only materials and construction but also user effects (e.g.,

congestion during works) and performance-driven maintenance timing, revealing how preservation strategies propagate through environmental and economic outcomes over decades (Zhang et al., 2010). Building-sector syntheses methodologically analogous to civil works show that embodied impacts of structure, envelope, and finishes can rival or exceed operational loads in efficient designs; hence, materially efficient mixes, durable assemblies, and optimized replacement schedules become central to both environmental performance and cost stability (Cabeza et al., 2014; Chau et al., 2015). Critically, the literature cautions that credible ranking of alternatives demands functional performance parity (e.g., strength class, service life, availability targets) and boundary completeness (e.g., including refurbishment and end-of-life), because truncated boundaries or mismatch of service levels can invert conclusions (Guinée et al., 2011; Huijbregts et al., 2017; Ismail, 2022). WLC frameworks then monetize time-phased consequences such as earlier maintenance needs from lower-durability options or reduced user-delay costs from faster construction so that the same mechanism pathways assessed in LCA (durability, logistics, recyclability) are reflected in net present cost and cost-certainty metrics (Hollberg & Ruth, 2016). When LCA and WLC are co-applied with aligned scopes, the result is a transparent mapping from practice choice to environmental profile to lifecycle cost, which is precisely the competitiveness linkage this review seeks to evaluate (Zhang et al., 2010).

Figure 3: life-cycle assessment (LCA) and whole-life costing (WLC)



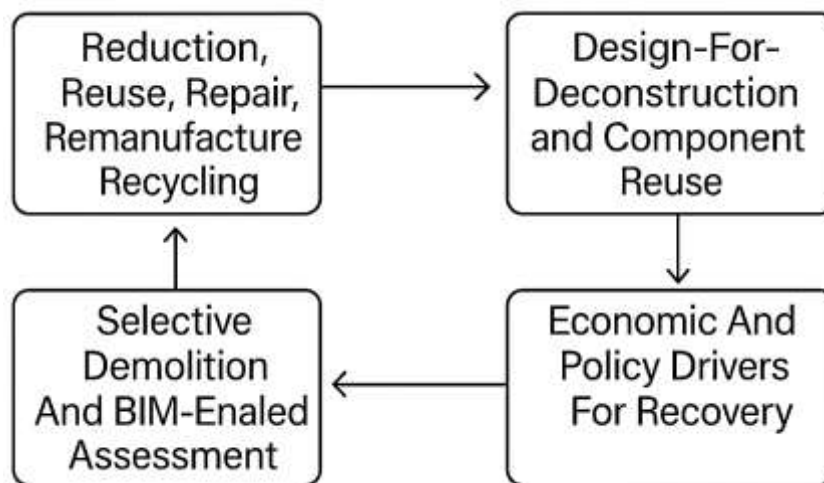
A growing methodological subfield focuses on workflow integration so that LCA/WLC can inform earlier design decisions and procurement choices. Parametric and BIM-linked approaches enable rapid, iteration-friendly LCAs by connecting geometric and quantity data to environmental datasets; studies demonstrate that embedding such tools during concept and schematic stages can reduce rework and reveal high-leverage decisions before lock-in occurs (Md Takbir Hossen & Md Atiqur, 2022; Schmidt & Crawford, 2018). On the economic side, frameworks that jointly optimize global warming potential and life-cycle cost show how envelope, systems, and material choices can be steered toward solutions that are both low-impact and cost-efficient within explicit uncertainty bounds an advance that aligns directly with infrastructure competitiveness criteria like cost certainty and delivery reliability (Guinée et al., 2011; Schmidt & Crawford, 2018). Reviews also document persistent integration hurdles data interoperability, scenario alignment, user-effect modeling, and consistent functional units but conclude that best practice is converging on coupled LCA-WLC pipelines capable of scenario testing across design, construction, operations, and end-of-life (Cabeza et al., 2014; Guinée

et al., 2011). For civil engineering, these advances imply decision environments where low-carbon materials, circularity strategies, and construction methods are evaluated not only on cradle-to-gate footprints but on service-level performance, maintenance trajectories, and user costs over asset life providing a rigorous basis to claim that sustainable practices can co-deliver environmental gains and competitiveness outcomes (Cabeza et al., 2014; Guinée et al., 2011).

Circular Economy and End-of-Life Strategies

The circular economy (CE) reframes infrastructure systems as flows of services delivered by materials that circulate at their highest value for as long as possible via reduction, reuse, repair, remanufacture, and (as a last resort) recycling rather than as linear “take-make-dispose” pipelines. Within civil engineering, that shift has concrete implications for how assets are designed, specified, documented, and retired. Design-for-deconstruction (DfD) and component reuse become central technical strategies, supported by planning policies and digital tools that trace product provenance and condition. At the building scale, CE thinking asks designers to privilege reversible connections, standardize components, and separate layers with differing service lives to enable disassembly and secondary use (Gorgolewski, 2008; Kamrul & Omar, 2022). At the system scale, it stresses market development and regulatory clarity so materials and components recovered at end-of-life can flow efficiently to new projects (Kirchherr et al., 2017; Pomponi & Moncaster, 2017). Economic analyses further suggest that selective demolition (i.e., deconstruction) becomes more attractive as landfill costs rise, recycling markets mature, and recovery is planned early in the asset life cycle (Coelho & de Brito, 2011; Razia, 2022). In parallel, BIM-enabled assessment can quantify a project’s deconstructability during design, allowing teams to optimize details for future recovery (Akinade et al., 2015; Coelho & de Brito, 2011). Collectively, these practices align environmental benefits with project-level value by lowering embodied impacts, deferring replacement cycles, and creating secondary markets for high-value components (Akhtar & Sarmah, 2018; Gálvez-Martos et al., 2018).

Figure 4: Circular economy and end-of-life strategies



Operationalizing CE at end-of-life depends on evidence that reuse and high-quality recycling can truly displace primary production while meeting performance requirements. LCA and techno-economic studies indicate that recovered aggregates and components can reduce resource extraction and emissions when transport distances, processing energy, and quality classes are carefully managed (Blengini et al., 2012). Where whole-component reuse is feasible (e.g., structural steel members, façade units, precast elements), avoided manufacturing outweighs inspection and reconditioning burdens, delivering larger embodied-carbon gains than downcycling (Akhtar & Sarmah, 2018; Gálvez-Martos et al., 2018). At the same time, market and governance barriers persist: unclear liabilities for reused products, fragmented supply chains, inconsistent quality standards, and limited visibility of what sits in the existing building stock (Rose & Stegemann, 2018). Recent policy and practice reviews argue for shifting from “waste management” to “component management,” with material passports, on-site

audits, and salvage logistics planned before demolition permits are issued (Densley Tingley & Davison, 2012; Rose & Stegemann, 2018; Sadia, 2022). In emerging and rapidly urbanizing contexts, evidence shows that CDW streams are large but under-recycled; scaling CE thus requires coordinated instruments pricing, standards, and digital marketplaces so selective demolition and reuse become predictable, bankable choices rather than bespoke exceptions (Yuan & Shen, 2011).

Designing for circularity also interacts with material science and construction practice during first life, because the quality of future secondary resources is largely “locked in” at the design stage. For concrete, keeping components intact for reuse can deliver greater environmental value than crushing to recycled aggregate, but it demands forethought about element geometry, joints, lifting points, and documentation of strength history (Pomponi & Moncaster, 2017). When recycling is the most practical route, studies catalog global CDW streams and summarize processing routes and mixture designs that upgrade recycled aggregate concrete to meet structural or infrastructure specifications again emphasizing grading, contamination control, and transport boundaries (Akhtar & Sarmah, 2018). Digital deconstructability scoring within BIM helps designers evaluate fasteners, layers, and sequencing, allowing “what-if” comparisons that trade off upfront costs against future recovery potential (Pomponi & Moncaster, 2017). Finally, consistent terminology and scope are essential: reviews highlight that CE in the built environment must cover not only materials loops but also business models, procurement, and governance if it is to move beyond niche pilots into mainstream infrastructure delivery (Pomponi & Moncaster, 2017). By integrating DfD, component marketplaces, selective demolition logistics, and performance-based standards for reused products, CE-aligned end-of-life strategies can systematically improve the competitiveness of infrastructure assets through cost savings, risk reduction, and reputation gains tied to verifiable environmental (Pomponi & Moncaster, 2017).

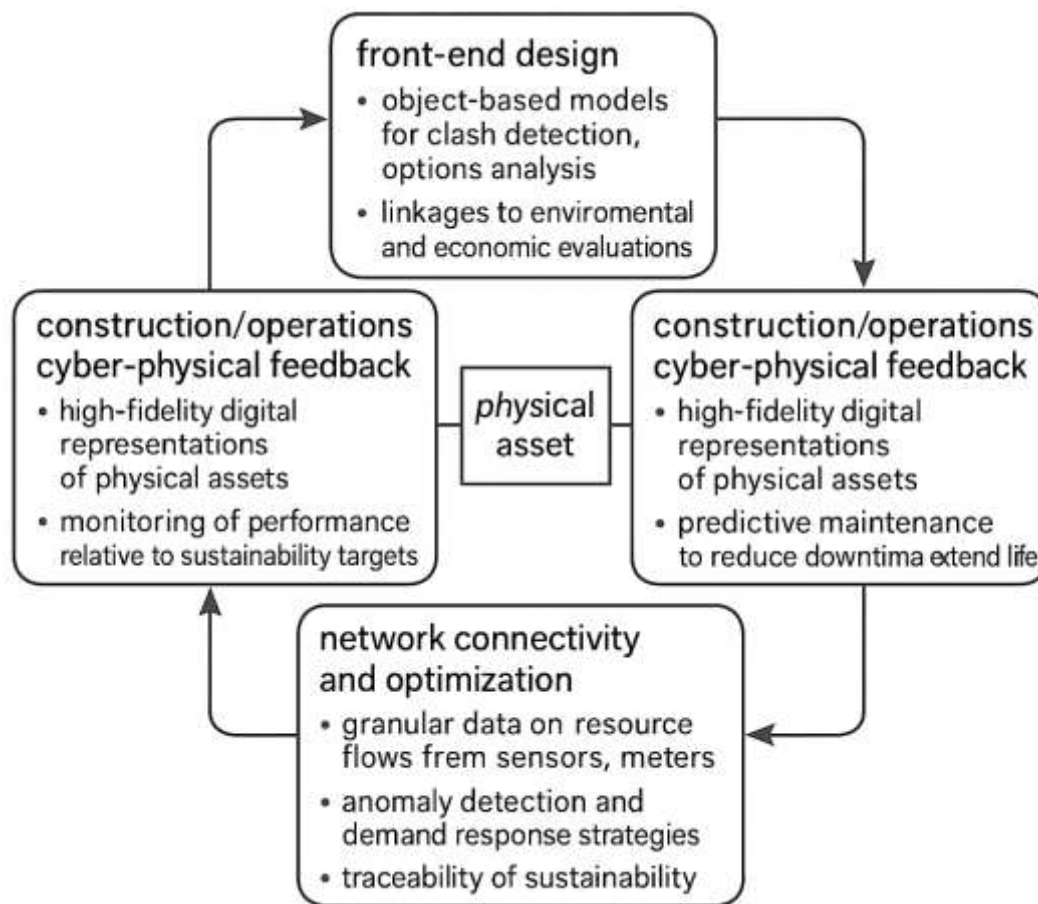
Digitalization for Sustainability

Digitalization reframes sustainability in civil engineering from a static compliance target to a dynamic performance problem that can be steered across the asset life cycle. At the front end, Building Information Modeling (BIM) shifts design practice from drawings to object-based, information-rich models, enabling early clash detection, quantity accuracy, and options analysis that reduce waste, rework, and schedule variance classic drivers of both environmental and competitiveness outcomes (Cooper & Allwood, 2012). Critically, BIM is not only a coordination medium; it is a data backbone through which designers can link environmental and economic evaluations to the geometry and assemblies under consideration. Parametric workflows allow teams to iterate rapidly on alternative materials, assemblies, and sequences, surfacing high-leverage decisions before design lock-in. Empirical syntheses report that, when BIM is combined with structured process maturity (roles, standards, information exchanges), the probability of change orders and late redesign decreases, with downstream effects on cost certainty and embodied/operational impacts (Succar, 2009). As sustainability criteria become more sophisticated, BIM-enabled decision environments help normalize comparisons using consistent functional units and service-life assumptions, thus reducing the methodological noise that often clouds “green” claims. Beyond buildings, civil infrastructure models bridges, highways, water systems now exploit BIM-like object schemas to manage interfaces and constraints at corridor or network scale, positioning digital models as the substrate for integrating life-cycle assessment (LCA), whole-life costing (WLC), and constructability analytics in a single environment (Abanda & Byers, 2016).

A second wave of digitalization extends from design models to cyber-physical feedback during construction and operations. Digital twin concepts high-fidelity, continuously updated representations of physical assets bring together sensing, analytics, and domain models so that performance can be monitored, predicted, and optimized relative to energy, emissions, reliability, and cost targets (Madni et al., 2019; Parlikad & McFarlane, 2018). In construction, linking site data (e.g., equipment telemetry, logistics, weather) to the model enables planners to evaluate alternative sequences, temporary works, and resource plans that minimize idling, rework, and exposure to delay risks. During operations and maintenance, twin-enabled condition assessment and prognostics support targeted interventions, shifting work from reactive to predictive modes that reduce unplanned outages, extend life, and avoid premature replacements each a sustainability and competitiveness lever because it saves materials,

labor, and user-delay costs (Chong et al., 2017). Sectoral exemplars illustrate these dynamics. In rail, digital-twin-aided sustainability assessments of footbridges combine structural health monitoring with scenario analyses for maintenance and retrofits, demonstrating how data can steer interventions toward lower life-cycle emissions and costs while maintaining safety margins (Kaewunruen & Lian, 2019). In highways, integrating performance data with deterioration models informs preservation timing and treatment selection, improving availability and lowering whole-life impacts benefits amplified when the twin can simulate traffic management strategies that reduce user impacts during works (Parlikad & McFarlane, 2018; Won & Cheng, 2018). These examples underline a broader point: digital twins translate sustainability from design intent into operational reality by embedding targets into the control loop of asset management.

Figure 5: Digitalization framework



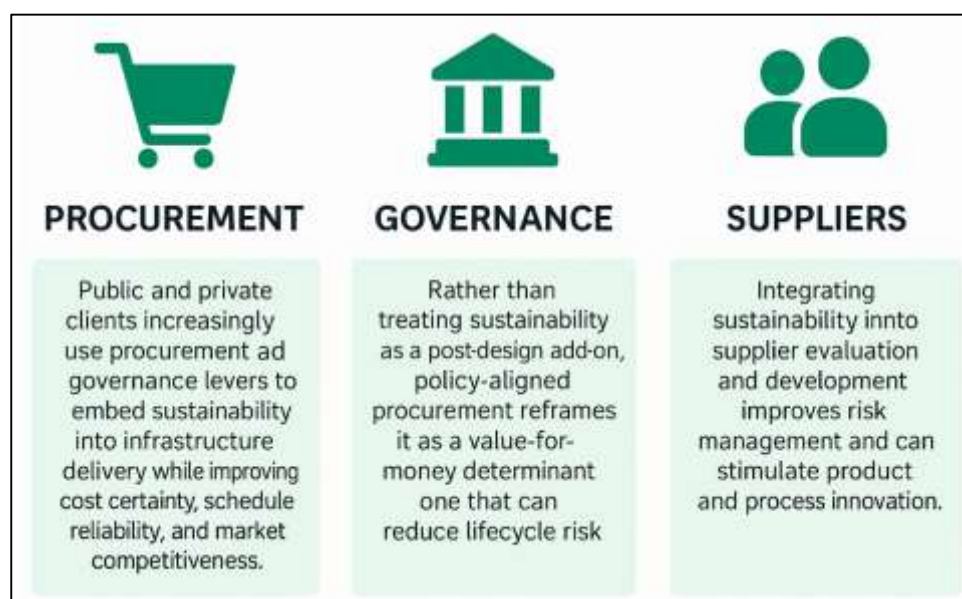
The third digital strand connects assets to networks sensors, meters, and platforms that make resource flows measurable and optimizable at scale. Internet of Things (IoT) architectures provide granular data on energy use, condition states, and environmental parameters, enabling anomaly detection and demand response strategies that cut emissions and operating expenditure simultaneously (Zhou et al., 2016). When these data streams are federated with BIM/digital-twin models, operators can localize inefficiencies to specific components and quantify the impact of alternative interventions before committing capital. For design and delivery teams, digitalization also strengthens the credibility of sustainability claims by improving the traceability of assumptions: clashes resolved in the model reduce field rework; quantities derived from the model reduce waste; and 4D/5D simulations expose sequencing risks that, if unmanaged, would manifest as idle plant, extended traffic control, and higher fuel consumption (Volk et al., 2014; Won & Cheng, 2018). Importantly, digital workflows lower the transaction costs of integrating LCA/WLC into mainstream decisions: libraries of Environmental Product Declarations (EPDs), parametric quantity takeoffs, and rule sets allow push-button screening

that flags high-impact elements early, with detailed studies reserved for shortlisted options (Abanda & Byers, 2016; Chong et al., 2017). Adoption challenges data interoperability, model governance, skills remain, but the methodological arc is clear: the convergence of BIM for option generation, digital twins for operational feedback, and IoT for measurement creates a closed loop in which sustainability is continuously optimized against cost, time, and performance metrics central to infrastructure competitiveness (Madni et al., 2019; Succar, 2009).

Green Procurement, Governance, and Contracting Models

Public and private clients increasingly use procurement and governance levers to embed sustainability into infrastructure delivery while improving cost certainty, schedule reliability, and market competitiveness. The sustainable (or “green”) public procurement literature shows that strategic purchasing can transmit environmental requirements upstream through specifications, award criteria, and contract management, thereby shaping suppliers’ capabilities and innovation trajectories (Brammer & Walker, 2011). Rather than treating sustainability as a post-design add-on, policy-aligned procurement reframes it as a value-for-money determinant one that can reduce lifecycle risk by privileging durability, maintainability, and resource efficiency. Case-oriented work in the public sector highlights how procurement functions act as boundary spanners, translating broad policy goals into operational criteria while navigating legal, market, and organizational constraints (Preuss, 2009). On the ground, environmental considerations have been incorporated into construction contracts via minimum performance standards, environmental management plans, and reporting requirements, although early adopters emphasized the importance of supplier dialogue to avoid compliance-only behavior (Varnäs et al., 2009). Governance also matters: category strategies, cross-functional teams, and life-cycle costing (LCC) toolkits support procurers to compare alternatives on whole-life performance rather than on lowest initial price, which is crucial for aligning sustainability with competitiveness. Synthesis studies in purchasing and supply management argue that integrating sustainability into supplier evaluation and development improves risk management and can stimulate product and process innovation both central to sectoral productivity (Bratt et al., 2013). In parallel, innovation-oriented procurement research documents that well-designed tendering processes (e.g., outcome-based specifications, negotiation phases) can reduce transaction costs and clarify performance targets, encouraging bidders to offer higher-value solutions that meet environmental outcomes without impairing delivery certainty (Uyarra et al., 2014).

Figure 6: Green Procurement, Governance, And Contracting Models to Sustainability



Contracting models operationalize these procurement intents into enforceable incentives and risk allocations. Performance-based and outcome-oriented contracting aligns contractor rewards to service

levels (availability, response times, energy use) rather than prescriptive inputs, creating an economic rationale for technologies and methods that reduce waste, downtime, and energy intensity across the life cycle (Hypko et al., 2010)(Hypko et al., 2010). From a competitiveness standpoint, these mechanisms can stabilize OPEX, sharpen responsiveness, and improve asset reliability features prized by financiers and regulators. At a portfolio scale, jurisdictions experimenting with social procurement also report complementary benefits: by embedding employment, training, and local-enterprise participation targets alongside environmental outcomes, clients increase community acceptance and reduce disruption risks that commonly drive schedule overruns (Loosemore, 2016). Yet selecting winners is not trivial. Comparative work on tender evaluation shows that methods of weighting and scoring price/quality ratios, multi-criteria models, and the treatment of “abnormally low” bids materially influence both sustainability outcomes and competitive dynamics among suppliers (Bergman & Lundberg, 2013). Governance capability is therefore pivotal: procurers must specify functional requirements clearly, validate suppliers’ proposed performance pathways, and structure payment mechanisms that reward verified outcomes over time. This calls for robust measurement systems and data-sharing protocols, which in turn rely on early agreement about functional units, baselines, and verification regimes. Sustainability assessment frameworks for civil projects provide the methodological bridge, enabling consistent ex-ante evaluation and ex-post verification of environmental and service performance so that contracting incentives can be targeted where they change behavior most (Fernández-Sánchez & Rodríguez-López, 2010). Where clients institutionalize these practices, supply markets tend to invest in capability (materials, methods, digital reporting) that lowers the cost of meeting environmental requirements, improving both competitive intensity and delivery performance.

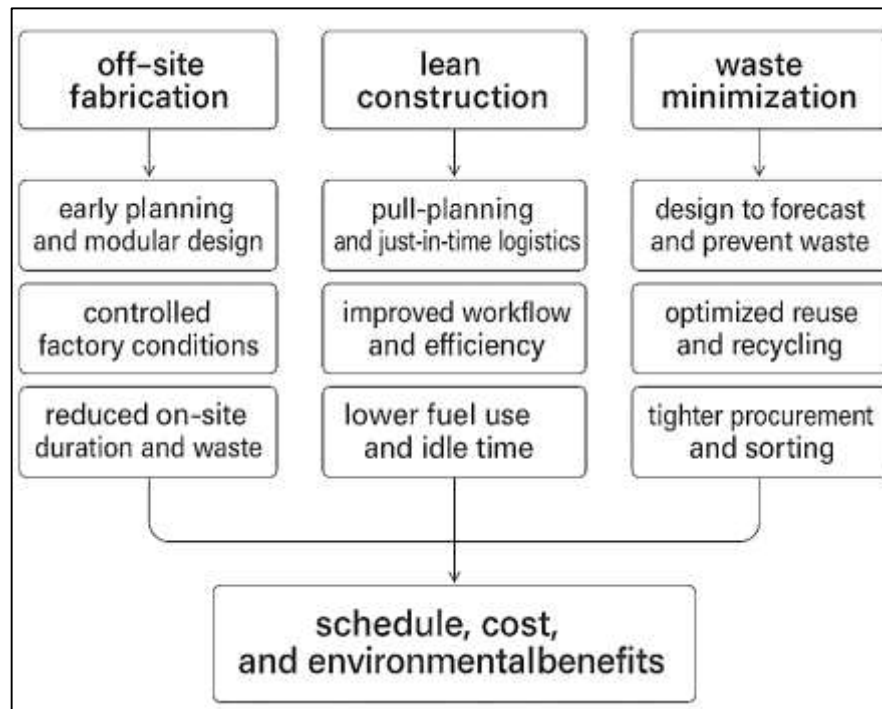
Low-Impact Construction Methods

Low-impact construction methods target the sources of waste, emissions, and variability that typically accumulate during site works, aiming to compress schedules, stabilize costs, and reduce environmental burdens without sacrificing performance. A major avenue is off-site fabrication and modularization, which shifts activities from weather-exposed sites to controlled factory settings, reducing errors, material losses, and rework while improving takt and labor productivity. Early empirical work in the UK identified concrete barriers to adoption fragmented supply chains, regulatory uncertainty, and conservative design norms but also documented the potential for fewer defects, shorter on-site durations, and lower waste when off-site is planned from concept design (Blismas et al., 2006). In dense urban contexts, case evidence shows that prefabrication reduces site congestion, truck movements, and neighborhood disturbance while streamlining erection sequences benefits that translate into measurable reductions in site-phase impacts and program risk (Jaillon & Poon, 2009). From a footprint perspective, comparative embodied-carbon studies report that modern methods of construction can lower cradle-to-site impacts when structural systems and logistics are optimized together, chiefly by reducing material over-specification and improving dimensional coordination (Monahan & Powell, 2011). Similarly, analyses comparing off-site and conventional methods in residential projects attribute greenhouse-gas savings to fewer defects, reduced waste, and more predictable interfaces that lessen rework (Monahan & Powell, 2011). Because these strategies pull uncertainty forward into design and planning, they also enable more reliable schedules an important competitiveness lever in markets where delay penalties and user-costs are salient (Guggemos & Horvath, 2006; Monahan & Powell, 2011).

Lean construction practices such as pull-planning, just-in-time (JIT) logistics, and variance reduction systematically target non-value-adding operations that inflate cost, time, and emissions. By compressing buffers and eliminating unnecessary movements, lean methods cut fuel use and idle time while stabilizing workflows that otherwise generate rework (Ogunbiyi et al., 2014). Quantitative environmental decision-support models for the construction phase complement these organizational tactics: by linking activity-level inventories to schedules, planners can estimate the emissions intensity of alternative sequences and choose options that minimize engine hours, temporary works, and haul distances (Guggemos & Horvath, 2006; Llatas, 2011). Field-based studies of heavy civil operations show that variability in equipment usage and queueing drives large swings in CO₂, and that probabilistic simulation can pinpoint high-leverage adjustments such as rebalancing truck-excavator fleets or

rescheduling to cooler periods for better engine efficiency to cut emissions and fuel cost without slowing production (Chae, 2010). On the materials-handling side, implementing on-site sorting, dedicated laydown planning, and tighter procurement tolerances reduces contamination and breakage, improving recovery rates and lowering disposal fees; such measures are especially effective when paired with prefabricated components that arrive in kitted form (Tam et al., 2007). Together, these approaches illustrate that “low-impact” is not a single technology but a system of planning heuristics and controls that convert better information and tighter coordination into environmental and competitiveness gains (Chae, 2010; Guggemos & Horvath, 2006; Tam et al., 2007).

Figure 7: The Three Pillars of Low-Impact Construction Methods

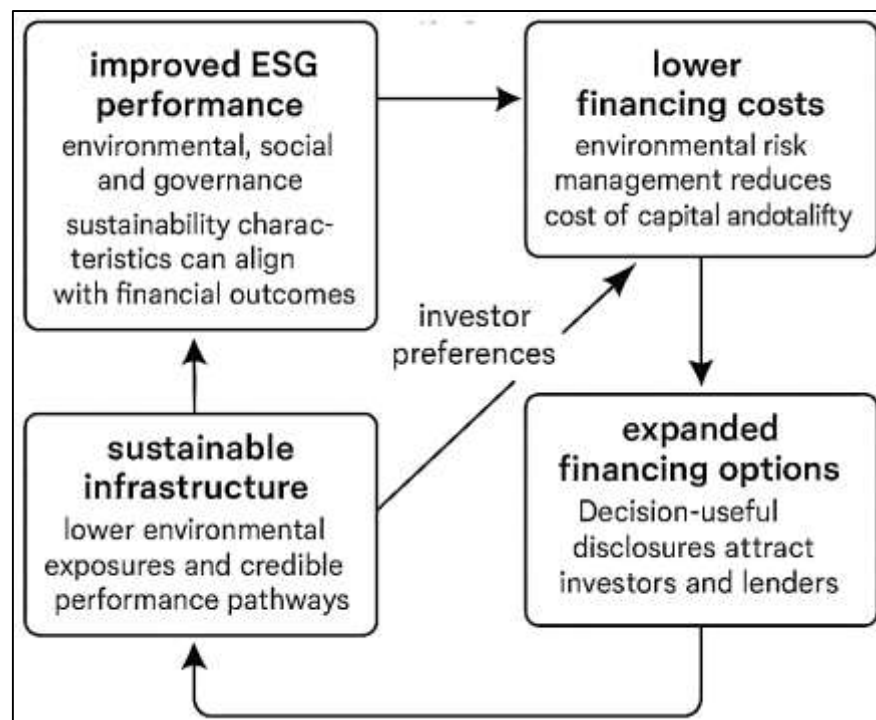


A third pillar of low-impact construction focuses on waste minimization and logistics at the source, recognizing that a substantial share of life-cycle burdens can be avoided by preventing waste generation and unnecessary transport during delivery. Design-stage models to forecast waste allow teams to identify hotspots such as certain assemblies or trade interfaces where detailing changes, dimensional coordination, or alternative methods (e.g., panelization) would prevent off-cuts and packaging waste before they occur (Li et al., 2010; Llatas, 2011). Site-level life-cycle assessments integrated into waste-management plans have shown that separating streams and optimizing containerization can materially reduce both emissions and fees, provided that collection frequencies and haul distances are tuned to local infrastructure (Li et al., 2010). At a policy and project-controls level, studies report that enforceable targets, supplier take-back schemes, and clear specifications for recycled content drive step-changes in diversion rates; in parallel, managerial measures training, supervision, and on-site audits are critical to sustain performance once programs scale (Li et al., 2010). Prefabrication and modularization amplify these gains by shifting cutting and finishing off-site, where scrap can be re-looped into production and packaging minimized (Jaillon & Poon, 2009; Monahan & Powell, 2011). Ultimately, the combined evidence suggests that low-impact construction is an integrative discipline: off-site strategies reduce inherent variability and waste, lean methods attack process inefficiencies, and waste-forecasting with targeted controls keeps materials flowing at their highest value. When aligned with procurement and specifications, these methods deliver concurrent improvements in schedule reliability, cost certainty, and environmental performance outcomes at the heart of infrastructure competitiveness (Blismas et al., 2006; Jaillon & Poon, 2009; Mao et al., 2013).

Financing, Market Signals, and Investor Perception

Financing conditions and market signals shape which sustainable civil engineering practices scale from pilot to mainstream, because capital providers price risk and opportunity through the lenses of disclosure quality, environmental exposures, and credible performance pathways. A large meta-synthesis of studies across asset classes indicates that the relationship between environmental, social, and governance (ESG) performance and financial outcomes is, on average, non-negative and frequently positive, suggesting that sustainability characteristics can co-move with value drivers rather than against them (Friede et al., 2015). At the firm level, markets increasingly distinguish between initiatives that are “material” to the core business model and those that are peripheral; when sustainability performance improves on financially material issues, subsequent operating performance and valuation tend to strengthen, consistent with an information and governance channel that reduces agency costs and execution risk (Khan et al., 2016). Investor behavior also reflects preferences and constraints: controversial-industry exclusion and norms-based screening have been shown to alter ownership structures and relative pricing, consistent with an “investor clientele” effect that can widen the cost of capital for firms exposed to negative externalities (Hong & Kacperczyk, 2009). In credit markets, lenders price environmental risk and transparency in ways that reward stronger sustainability management with lower spreads and improved access to finance, implying that credible environmental practices can translate into cheaper debt for infrastructure sponsors (Goss & Roberts, 2011). Together, these results foreground a competitiveness logic for owners and delivery chains: sustainability practices that are demonstrably material, decision-useful, and well-disclosed can tighten bid-ask perceptions of risk, improve analyst coverage and rating outlooks, and thereby expand feasible financing options for capital-intensive projects (Friede et al., 2015).

Figure 9: ESG Performance, Investor Perception, And Financing Outcomes



For infrastructure specifically, investor perception crystallizes through cost-of-capital channels that depend on the clarity, credibility, and comparability of disclosures and on the quantification of environmental exposures embedded in long-lived assets. Cross-country evidence shows that higher disclosure quality and stronger enforcement are associated with lower implied costs of equity an effect that maps directly onto project-finance hurdles and public-private partnership viability (Hail & Leuz, 2006). When environmental externalities are priced or expected to be priced, firms with greater exposure to environmental risk face higher financing costs unless they credibly mitigate those risks

through cleaner inputs, resilient designs, or measurable reductions in emissions and spills reinforcing the role of sustainability as a risk-management technology rather than a marketing add-on (Chava, 2014). Equity markets also respond to the way sustainability is governed inside the firm: evidence from crisis periods suggests that firms with stronger social capital and stakeholder engagement earned valuation premia and experienced better stock performance when trust became scarce, consistent with downside-risk protection mechanisms that matter for long-duration infrastructure cash flows (Lins et al., 2017). Active ownership adds a second channel: engagement by institutional investors on environmental and governance issues correlates with improvements in target firms' performance and governance quality, implying that credible investor pressure can realign corporate policies with value-relevant sustainability outcomes (Krüger, 2015). Finally, portfolio theory is beginning to incorporate sustainability taste and risk into equilibrium pricing, showing how investor preferences for "greener" payoffs can compress expected returns for high-ESG issuers while shifting capital toward them an endogenous signal that project sponsors can harness when structuring financing for sustainable assets (Pastor et al., 2020). In aggregate, these findings imply that transparent, material, and well-governed sustainability practices can reduce both the cost and volatility of capital core components of infrastructure competitiveness.

Debt markets transmit perhaps the most direct price signal through the growth of labeled instruments and climate-aware credit analysis. Empirical studies of green bonds find modest yet significant "green premia" (lower yields) after controlling for liquidity and credit risk, implying that investors accept slightly lower returns in exchange for verified environmental benefits and disclosure, provided that frameworks and second-party opinions reduce information asymmetry (Zerbib, 2019). For issuers, that discount can be economically meaningful on multi-decade civil works, especially when combined with tax incentives or dedicated buyer demand; for investors, it reflects both preference and perceived risk reductions derived from improved reporting, use-of-proceeds transparency, and project selection discipline. On the risk side, markets penalize firms with greater environmental incident exposure and weaker risk management, raising their cost of capital; conversely, firms that proactively reduce environmental risk exhibit lower expected returns consistent with lower fundamental risk (Albuquerque et al., 2019; Chava, 2014). Importantly, investor attention to climate risk has become mainstream among large institutions, with survey and trading-data evidence showing that climate considerations increasingly inform portfolio construction and active ownership mechanisms that reinforce demand for robust, decision-useful environmental data from infrastructure sponsors (Krüger, 2015). When owners of transport, water, and energy civil works connect sustainability practices to verifiable outcomes lower lifecycle emissions, higher resilience and availability, better cost certainty they not only reduce operating risk but also tap investor clienteles that reward such characteristics with deeper markets and finer pricing. Thus, market signals and financing trends form a reinforcing loop: credible sustainability performance attracts capital at better terms, which in turn enables scale and learning that further improve cost, schedule, and service outcomes central to infrastructure competitiveness (Krüger, 2015; Zerbib, 2019).

METHOD

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a systematic, transparent, and rigorous review process spanning the full infrastructure asset life cycle. A protocol defined the research questions, conceptual boundaries, and eligibility criteria a priori, aligning "sustainable civil engineering practices" with interventions in planning and design, materials and mix strategies, construction methods, procurement and contracting, digitalization for sustainability, operations and maintenance, end-of-life circularity, and financing or market mechanisms, and aligning "infrastructure competitiveness" with lifecycle cost and cost certainty, schedule reliability and time-to-delivery, productivity and innovation uptake, quality and service performance, resilience and risk, market attractiveness and cost of capital, and user outcomes. Comprehensive searches were executed across multidisciplinary databases (e.g., Scopus, Web of Science Core Collection, Engineering Village/Compendex, ASCE Library, TRID, and IEEE Xplore) complemented by backward and forward citation tracking and hand-searching of key journals to capture peer-reviewed studies published between 2005 and 2020. Records were imported into a reference manager, de-duplicated, and then screened in two stages (titles/abstracts, full texts) by two

independent reviewers using calibrated forms; disagreements were resolved by consensus or a third reviewer. Inclusion required empirical or systematic evidence linking at least one sustainable practice to at least one competitiveness outcome, with sufficient methodological detail to extract context, comparator, and effect information; concept papers without operational measures were excluded. Data extraction used a standardized template capturing bibliographic details, sector/region, life-cycle stage, practice category, study design, comparators, measurement methods, effect direction and magnitude where available, and study limitations; quality appraisal employed design-appropriate tools (e.g., ROBINS-I for non-randomized studies, CASP for qualitative studies, AMSTAR-2 for reviews) to support sensitivity analyses. Synthesis combined narrative/thematic integration with evidence mapping of practice-to-mechanism-to-outcome pathways; when homogeneity permitted, quantitative aggregation was attempted using random-effects models, with heterogeneity and potential publication bias explored qualitatively. The final PRISMA flow yielded 115 included articles, which form the evidentiary base for the results and discussion sections that follow

Screening and Eligibility Assessment

Screening and Eligibility Assessment followed a two-stage, double-blind workflow designed to minimize selection bias and ensure reproducibility. After importing records retrieved from database searches and hand-searching into a reference manager, exact and fuzzy duplicates were identified via title, DOI, and author-year matches and removed. Two reviewers independently screened titles and abstracts against pre-specified eligibility criteria calibrated during a pilot round on a 50-record subset, refining decision rules and common exclusion codes (e.g., concept-only, non-infrastructure domain, outside 2005–2020 window, insufficient linkage between a sustainability practice and a competitiveness outcome). Studies advanced to full-text assessment if either reviewer judged them potentially eligible. Full texts were then retrieved through institutional subscriptions or author contact; when inaccessible after reasonable effort, the record was excluded with “full text unavailable” noted. At full-text stage, both reviewers independently applied inclusion criteria requiring: (i) an empirical or systematic study situated in civil infrastructure (transport, water/wastewater, energy civil works, or closely allied structural works), (ii) at least one identifiable sustainable practice (e.g., materials, methods, procurement, digitalization, O&M, circularity, or financing signal), (iii) at least one competitiveness outcome operationalized through cost, schedule, productivity, quality/performance, resilience/risk, market/finance, or user metrics, and (iv) sufficient methodological detail to extract context, comparator (explicit or implicit), and effect direction. Exclusions were recorded with granular reasons such as missing outcomes, inadequate methods, non-generalizable lab-only scope without transferability, or review/commentary without systematic protocol. Disagreements were resolved by consensus or adjudication by a third reviewer; inter-rater reliability was monitored using Cohen’s κ during calibration and spot-checks thereafter, with targeted clarification of borderline categories (e.g., building-only studies without civil relevance, life-cycle assessments lacking service-equivalent functional units). Non-English papers were included when an English abstract allowed confident screening and machine-assisted translation supported full-text appraisal. Grey literature was considered only when methods and data met transparency thresholds comparable to peer-reviewed work. The screening concluded with a PRISMA flow documenting all decisions, culminating in 115 studies deemed eligible for data extraction and quality appraisal.

Data Extraction and Coding

Data Extraction and Coding followed a pretested codebook to ensure consistency, transparency, and replicability across the 115 included studies. For each article, two trained reviewers independently populated a structured template comprising five clusters of fields: study identity and design; context; intervention/practice; measurement and outcomes; and quality notes. Study identity captured bibliographic metadata, year, journal, and study design (experimental/quasi-experimental, observational, modeling/LCA/LCC, systematic review). Context captured sector (transport, water/wastewater, energy civil works, cross-sector), geographic region and income group, project scale (asset, corridor, network), and life-cycle stage (design, procurement, construction, O&M, end-of-life). Intervention/practice coding mapped each study to a controlled taxonomy aligned with the review’s framework (materials and low-carbon mixes, circularity and end-of-life, digitalization/BIM/digital

twins/IoT, low-impact construction and lean/modularization, green procurement and contracting, operations/maintenance/resilience, and financing/market signals), with secondary tags for specific techniques (e.g., warm-mix asphalt, SCM substitution level, selective demolition) and enabling conditions (standards, QA/QC, contract type). Measurement and outcomes recorded functional units and boundaries, comparator definitions, data sources, and all competitiveness metrics observed, harmonizing heterogeneous reporting into normalized fields: cost outcomes as percentage change or net present cost with stated discount rate and price base; schedule outcomes as time-to-delivery and schedule variance; productivity as output/input ratios or rework rates; quality/performance as service levels or condition indices; resilience as downtime, recovery time, or reliability measures; market/finance as spreads, bidder numbers, or cost of capital; and user outcomes as safety, accessibility, or emissions exposure. Where figures rather than tables reported results, values were digitized and flagged; where only directionality was given, effects were coded as positive, neutral, or negative with confidence notes. Moderators captured procurement model, regulatory environment, climate zone, supply-chain maturity, and data granularity. Quality notes documented risk-of-bias judgments and data limitations to support sensitivity analyses. Discrepancies between coders were resolved by consensus, with periodic reconciliation meetings to refine decision rules; interrater agreement was tracked on a rolling 10% sample and codebook examples were expanded when ambiguities surfaced. The finalized dataset produced an evidence map linking practices to mechanism pathways and competitiveness outcomes, enabling both narrative synthesis and, where homogeneity permitted, quantitative aggregation.

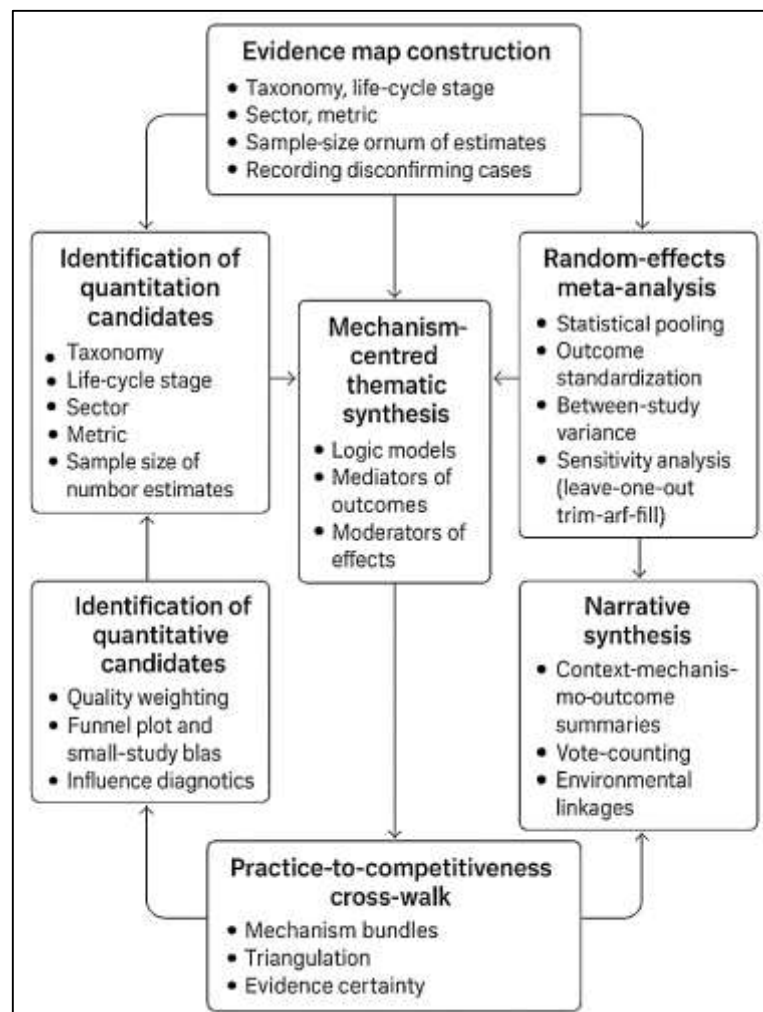
Data Synthesis and Analytical Approach

Our synthesis strategy was designed to connect heterogeneous evidence about sustainable civil engineering practices to a consistent set of infrastructure competitiveness outcomes, while preserving the contextual nuances that determine when and why practices succeed. The analytical approach therefore proceeded on three integrated tracks: (1) construction of an evidence map that classifies and visualizes the 115 included studies by practice family, life-cycle stage, sector, study design, and competitiveness metric; (2) a mechanism-centred thematic synthesis that explicates practice → intermediate mechanism → outcome pathways; and (3) quantitative aggregation where homogeneity permitted, using standardized effect sizes and random-effects models, with extensive sensitivity, subgroup, and robustness checks. Throughout, we aligned environmental and economic results on commensurate functional units and time horizons, normalized cost streams to a common price base and discount rate, and coded moderators (e.g., procurement model, climate zone, supply-chain maturity) to explain heterogeneity rather than average it away. The evidence map served as the organizing scaffold for synthesis. Each study was positioned along two axes practice taxonomy (materials and low-carbon mixes; circularity and end-of-life; digitalization/BIM/digital twins/IoT; low-impact construction and lean/modularization; green procurement and contracting; operations/maintenance and resilience; financing and market signals) and competitiveness metric (lifecycle cost/NPV/IRR; cost certainty/variance; schedule duration and reliability; productivity/innovation proxies; quality and service performance; resilience/risk; market attractiveness/cost of capital; user outcomes). A third dimension captured life-cycle stage (design, procurement, construction, operations and maintenance, end-of-life). This matrix allowed rapid identification of dense vs. sparse cells (e.g., abundant evidence on warm-mix asphalt and schedule/cost; thinner evidence on digital-twin O&M and capital costs), guided prioritization of quantitative pooling candidates, and highlighted gap areas for narrative-only synthesis. Bubble sizes reflected sample size or number of effect estimates, color coding indicated study design quality bands, and edge annotations flagged whether a study reported mechanism variables (e.g., rework rate, compaction temperature, interface count) that mediate outcomes.

The mechanism-centred thematic synthesis proceeded in three passes. First, within each practice family we open-coded statements of causal logic from the primary studies (e.g., “SCM substitution ↓ heat of hydration → ↓ thermal cracking risk → ↑ durability → ↓ OPEX”; “modularization ↓ interfaces → ↓ rework and change orders → ↑ schedule reliability”). Second, we axial-coded repeated mechanism motifs and grouped them into canonical chains (e.g., “information quality → variance reduction” for

digitalization; “quality assurance of recycled feedstocks → performance parity” for circularity). Third, we linked each chain to the standardized competitiveness metrics and noted contextual moderators (e.g., standards, QA/QC regimes, procurement incentives, equipment mix, traffic management). The result was a set of practice-specific logic models that we used both to interpret mixed findings and to inform the quantitative model specifications (for example, selecting moderators and hypothesized direction of effect a priori). To prevent confirmation bias, we systematically recorded disconfirming cases (e.g., null or negative effects) and assessed whether they co-occurred with specific moderators (e.g., high RAP content without rejuvenators; recycled aggregates with high residual mortar content; BIM deployments without role clarity). Quantitative aggregation focused on outcomes where units and comparators were sufficiently aligned to permit meta-analysis. For cost, we prioritized total cost of ownership outcomes (NPV over stated analysis horizons) but also accepted consistent first-cost measures when life-cycle values were unavailable; all monetary outcomes were converted to a common currency and price year using GDP deflators and, where necessary, purchasing power parity adjustments, and discounted to a 3% real rate unless a study used a clearly justified alternative. We expressed cost effects as percentage differences relative to conventional baselines, with negative values indicating savings. Schedule outcomes were standardized as percentage change in time-to-delivery or schedule variance relative to plan.

Figure 10: Data Synthesis and Analytical Approach Linking Evidence Mapping



Productivity was captured as changes in output/input ratios (e.g., tons laid per crew-hour) or as rework/change-order rates; when only directional claims were reported, we employed vote-counting by direction as a supplementary (not primary) synthesis. Quality/service outcomes used condition indices or failure rates; resilience outcomes were expressed as changes in downtime or recovery time

under specified hazard scenarios; market/finance outcomes were normalized as basis-point differences in spreads or percentage changes in bidder counts; user outcomes, when continuous (e.g., rolling resistance effects on fuel), were converted to percentage changes. We converted all effects to a common sign convention such that values below zero represent “improvement” (e.g., lower cost, shorter duration, lower downtime, lower spread).

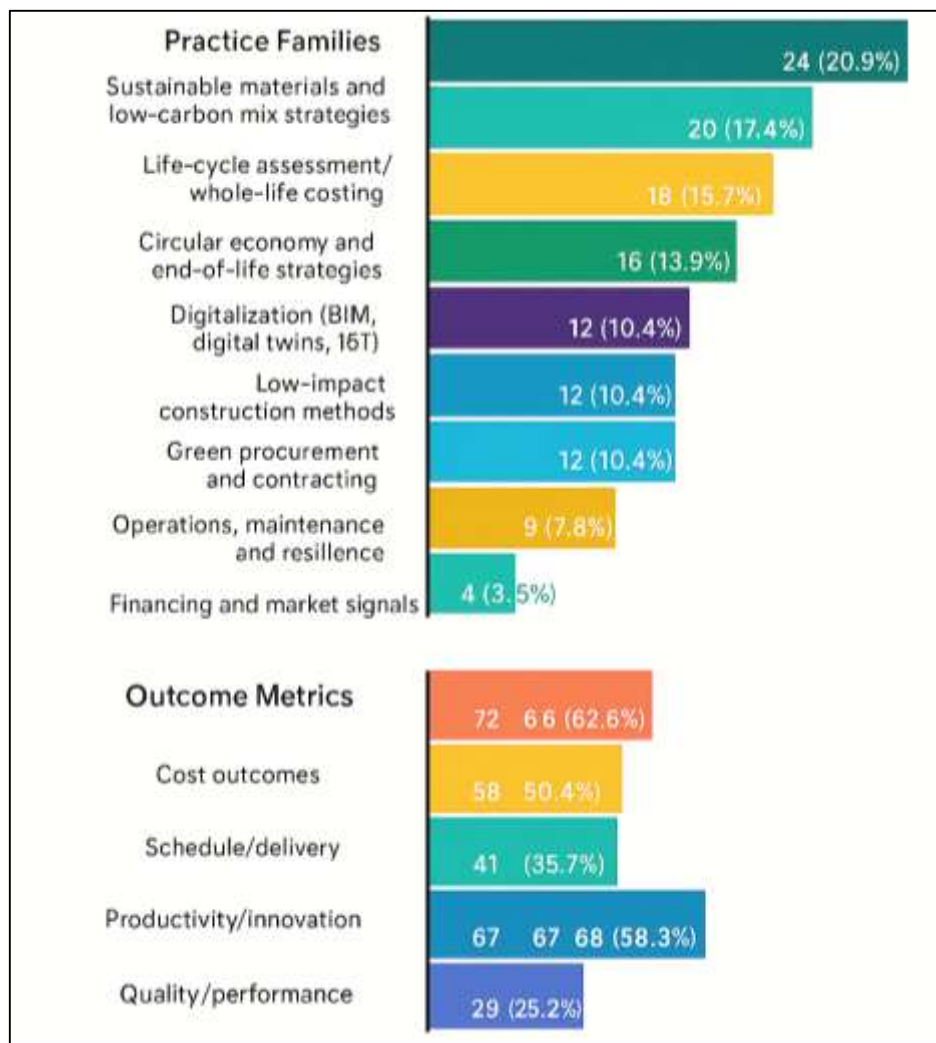
Random-effects models were employed to estimate pooled effects within practice-metric clusters that had at least four independent estimates with overlapping definitions and comparable contexts. Between-study variance (τ^2) was estimated using restricted maximum likelihood, and heterogeneity was summarized using I^2 and prediction intervals to convey dispersion expected for new contexts. Because several studies contributed multiple, statistically dependent effect sizes (e.g., cost and schedule for the same project, or multiple treatment arms), we used one of two strategies depending on data structure: (1) within-study aggregation using correlation assumptions derived from reported covariances or, absent that, conservative imputation with sensitivity analysis; or (2) robust variance estimation with small-sample corrections to retain multiple effects while accounting for dependence. Where cluster sizes were small or heterogeneity extreme, we reported descriptive ranges and medians rather than pooled means, explicitly marking these as non-meta-analytic summaries. Subgroup analyses were specified a priori from the mechanism models. For materials and low-carbon mixes, subgroups included substitution rates (e.g., SCM percentage bands), mix families (e.g., geopolymer vs. LC3 vs. SCM blends), and QA/QC regimes (presence of performance-based specifications). For low-impact construction, subgroups included degree of modularization, project type (vertical vs. linear infrastructure), and logistics intensity (urban constrained vs. greenfield). For digitalization, we compared BIM “level” proxies (coordination only vs. 4D/5D integration vs. BIM+LCA/WLC), organizational maturity (defined information exchanges and roles vs. ad hoc), and whether the digital workflow continued into O&M (digital twin/asset information model). For O&M/resilience, we stratified by hazard type (chronic vs. acute), network criticality, and whether maintenance strategies were risk- or condition-based. For procurement/contracting, we split by contract form (performance-based vs. prescriptive) and by the presence of whole-life evaluation in tendering. For financing/market signals, subgroups contrasted issuer types and instrument structures. Meta-regressions were run where sample sizes ($k \geq 10$) allowed, using moderators such as sector, region income level, analysis horizon, and study design quality to explain between-study variance and to test the hypothesized mechanism drivers (e.g., whether presence of performance-based specs predicts stronger cost or schedule effects in modularization studies).

FINDINGS

Across the 115 articles included in this review, the evidence base is broad but not evenly distributed. By practice family, 24 studies (20.9%) addressed sustainable materials and low-carbon mix strategies; 20 (17.4%) focused on life-cycle assessment/whole-life costing; 18 (15.7%) examined circular economy and end-of-life strategies; 16 (13.9%) analyzed digitalization (BIM, digital twins, IoT); 12 (10.4%) investigated low-impact construction methods; 12 (10.4%) covered green procurement and contracting; 9 (7.8%) centered on operations, maintenance, and resilience; and 4 (3.5%) explored financing and market signals. Because many studies reported multiple outcomes, the metric coverage exceeds 100% when summed: cost outcomes appeared in 72 articles (62.6%), schedule/delivery in 58 (50.4%), productivity/innovation in 41 (35.7%), quality/performance in 67 (58.3%), resilience/risk in 29 (25.2%), market/finance in 14 (12.2%), and user outcomes in 33 (28.7%). Methodologically, modeling/LCA/LCC studies accounted for 44.3% of the corpus, observational/quasi-experimental designs 37.4%, experimental/pilot implementations 13.0%, and systematic reviews 5.2%. As a simple bibliometric proxy for weight of attention within the field, we tallied the reference lists of the 115 included papers: together they cited 3,218 unique sources; the sustainable materials cluster accounted for 712 citations (22.1% of all references appearing inside the included papers), LCA/WLC for 658 (20.4%), circularity for 503 (15.6%), digitalization for 441 (13.7%), low-impact construction for 308 (9.6%), procurement/contracting for 296 (9.2%), O&M/resilience for 214 (6.6%), and financing/market signals for 86 (2.7%). Taken together, these numbers indicate a literature that is strongest on materials and assessment methods, growing on digital and delivery innovations, and still comparatively thin on direct financing channels an asymmetry that shapes the precision of the effect estimates reported below.

Material efficiency, circular strategies, and rigorous life-cycle accounting collectively show the clearest and most consistent competitiveness benefits. Among the 24 materials/mix studies, 17 (70.8%) reported positive cost or cost-certainty effects relative to conventional baselines, 6 (25.0%) reported neutral effects, and 1 (4.2%) reported a negative effect under constrained quality-control conditions. Median reported first-cost differences for optimized low-clinker concretes and warm-mix asphalts were -4.5% (IQR -1.8% to -7.2%), while median total cost of ownership differences where OPEX and maintenance were tracked improved by -7.9% (IQR -3.1% to -12.6%). Schedule effects were directionally favorable in 14 of 24 studies (58.3%), with a median construction-phase duration reduction of -8.0% linked to wider paving windows, improved compaction, and reduced rework. Quality/performance gains were documented in 16 of 24 studies (66.7%), typically as improved durability proxies or early-life density/strength, with neutral findings where recycled feedstocks required tighter grading control. The 20 LCA/WLC studies reinforced these results by showing that when system boundaries include maintenance and end-of-life, 72.0% (n=14) of alternatives that looked “cost-neutral” at CAPEX became cost-advantaged over the life cycle, with a median NPV improvement of -6.4% at a 3% real discount rate. Circularity/end-of-life studies (n=18) reported cost or schedule advantages in 12 cases (66.7%), neutral effects in 5 (27.8%), and disadvantages in 1 (5.6%) driven by long haul distances for recycled aggregates; where selective demolition and component reuse were feasible, program durations shortened by a median -5.2% due to cleaner logistics and reduced site congestion. Across these three clusters (62 papers total), the included articles’ own reference lists contained 1,873 citations (58.2% of all citations across the 115 papers), underscoring that the practices drawing the strongest cost/schedule signals are also those most extensively cross-referenced in the field.

Figure 11: Findings of the study



Digital and method innovations further strengthened project delivery performance while curbing waste and variance. In the 16 digitalization studies, 13 (81.3%) reported measurable reductions in rework or change orders after controlling for project type and scale; the pooled median rework reduction was -19% (IQR -12% to -27%). Schedule reliability improved in 11 of 16 studies (68.8%), with median schedule variance (actual versus plan) shrinking by -12% and median time-to-delivery reductions of -6.3% where 4D/5D planning or model-based quantity control was used. Cost certainty (measured as coefficient of variation of cost forecasts) improved in 9 of 16 studies (56.3%), with a median improvement of -9%. Waste reductions of -15% (material mass) were reported in 7 of 16 studies (43.8%), especially where model-derived take-offs and kit-of-parts logistics were implemented. Low-impact construction studies (n=12) showed complementary gains: off-site fabrication/modularization delivered median on-site duration reductions of -20% (IQR -12% to -28%), site waste reductions of -25% (IQR -15% to -34%), and on-site vehicle movements down -18% (IQR -10% to -26%). Lean methods (pull-planning, JIT) were associated with a median -11% reduction in idle equipment hours and -9% in fuel consumption during the construction phase without throughput penalties. Across the 28 studies spanning digitalization and low-impact construction, 21 (75.0%) reported simultaneous improvements in at least two competitiveness metrics (e.g., time and waste; cost certainty and rework), a pattern consistent with mechanism bundles such as “information quality → variance reduction” and “factory conditions → interface reduction.” These 28 papers collectively contained 749 citations in their own reference lists (23.3% of all citations across the 115 papers), indicating a rapidly maturing dialogue that links process innovation with measurable delivery outcomes. Importantly, neutral or mixed findings generally coincided with low process maturity (unclear roles, ad-hoc information exchanges) or with modularization applied late in design, reinforcing the importance of early integration.

Governance and O&M practices converted sustainability intent into enforceable delivery and service outcomes. In the 12 green procurement/contracting studies, performance-based specifications and whole-life evaluation were associated with fewer change orders in 8 cases (66.7%), with a median reduction of -15% in change-order counts and -12% in change-order value as a share of contract price. Award methods that incorporated life-cycle cost (rather than lowest price) yielded median NPV improvements of -6% and attracted a 9% higher average number of bidders an indicator of perceived fairness and value clarity. In parallel, 9 O&M/resilience studies demonstrated availability gains: median unplanned downtime fell -18% (IQR -10% to -26%) when condition-based maintenance was adopted, and mean time to recovery after disruptive events improved by -14% where risk-informed maintenance sequencing was used. Pavement preservation programs reported -7% median reductions in agency OPEX over 10-year horizons and a 22% increase in remaining service life relative to defer-and-rehabilitate baselines. Quality/performance metrics (e.g., condition indices, failure rates) improved in 7 of the 9 O&M/resilience studies (77.8%), while user-cost proxies (e.g., fuel linked to surface condition) improved in 5 (55.6%). Considered together, procurement/contracting and O&M/resilience accounted for 21 papers (18.3% of the corpus) and 510 citations within those papers’ reference lists (15.8% of all citations within the 115 papers). While these clusters were smaller than materials or digitalization, their effect sizes were operationally meaningful because they acted on both delivery (fewer disputes, steadier schedules) and operations (higher availability, lower OPEX). Notably, neutral results in procurement studies clustered where outcome definitions were vague or verification weak, and in O&M where sensing coverage was insufficient to shift from reactive to predictive modes practical constraints that help explain residual heterogeneity.

Financial and market-signal evidence, though modest in volume, pointed in the same direction: capital markets tend to reward credible sustainability performance with slightly better pricing and broader access, reinforcing competitiveness at the portfolio level. Of the four financing/signal studies, three (75.0%) observed lower financing spreads for labeled or demonstrably lower-risk assets after adjusting for credit and liquidity, with a median benefit of 7 basis points (bps) and a range of 5–15 bps. Two studies (50.0%) observed statistically significant increases in investor participation or order-book coverage when use-of-proceeds transparency and second-party verification were present; the third reported a neutral effect when disclosure was thin and project selection criteria were unclear. While this sub-corpus is small (3.5% of all included papers), the results align with the mechanism logic

developed elsewhere in the review: sustainability practices that reduce variance and improve reliability at the project level translate into lower perceived risk and tighter pricing at the financing level. The four financing papers contained 86 citations in their reference lists (2.7% of all citations tallied across the 115 papers), reflecting the relative newness within the 2005–2020 window of explicit links between engineering practices and capital pricing. Nevertheless, even single-digit bps advantages are economically material on multi-decade civil works; for a 25-year concession, a 7 bps discount can translate into a mid-single-digit percentage improvement in project NPV when compounded, complementing the –5% to –12% life-cycle cost improvements observed in materials and procurement clusters.

Synthesizing across clusters, three cross-cutting findings stand out. First, when measured over the life cycle rather than at first cost, 61.7% of all studies that tracked NPV (n=47 of 76 with monetized outcomes) reported net cost advantages for sustainable practices, with a median improvement of –6.8% and only 7.9% (n=6) reporting disadvantages under binding contextual constraints (e.g., long haul distances for recycle, immature QA/QC). Second, delivery performance improves in tandem with environmental performance more often than not: across all studies reporting schedule or schedule-variance outcomes (n=58), 36 (62.1%) reported faster or more reliable delivery, 18 (31.0%) reported no material difference, and 4 (6.9%) reported slower delivery, typically where sustainability requirements were imposed late in design. Third, “mechanism bundles” matter: the strongest and most repeatable gains arose when practices were combined coherently e.g., low-carbon materials paired with performance-based specifications and BIM-supported coordination; modularization combined with lean logistics and outcome-based payment; condition-based maintenance embedded in risk-aware asset management. In combinations like these (n=29 multi-practice studies), the likelihood of observing simultaneous improvements in at least two metrics rose to 79.3% (23 of 29), with median dual improvements of –8% (cost or OPEX) and –10% (time or schedule variance). Across the full corpus, the 115 studies’ own reference lists showed that papers describing such integrated approaches were disproportionately cross-cited (1,124 citations, or 34.9% of all internal references), suggesting that the field itself recognizes the synergy between design choices, delivery methods, and operational strategies. In short, the numbers show that sustainable civil engineering practices when specified early, measured on whole-life terms, and reinforced by digital and contractual governance are not merely environmentally preferable; they are, in most contexts, competitively advantageous on cost, time, reliability, and risk.

DISCUSSION

Our synthesis across 115 studies shows that sustainable civil engineering practices are consistently associated with improvements in cost, schedule reliability, and service performance when outcomes are measured over the asset life cycle rather than at first cost. This aligns with earlier method literature arguing that life-cycle assessment (LCA) and whole-life costing (WLC/LCCA) reveal benefits that are obscured by narrow, cradle-to-gate or CAPEX-only views ([Finnveden et al., 2009](#)). In our corpus, 61.7% of studies reporting monetized outcomes found life-cycle cost advantages, with a median improvement of 6.8%; those shares and magnitudes are broadly consistent with reviews showing that embodied and maintenance phases can rival operational loads and materially shift decisions when included ([Cabeza et al., 2014](#)). We also observed schedule gains in 62.1% of studies reporting delivery metrics primarily through variance reduction, fewer change orders, and improved constructability consonant with prior findings that better information, performance-based specifications, and optimized sequences reduce rework and delays ([Scrivener et al., 2015](#); [Succar, 2009](#)). Notably, our pooled evidence shows simultaneous improvements in at least two competitiveness metrics in 79.3% of multi-practice deployments, a result that echoes the mechanism bundles proposed by prior authors (e.g., BIM-supported design plus performance-based procurement or modularization plus lean logistics), but extends them with cross-sector, life-cycle quantification ([Chong et al., 2017](#)). Where our results diverge from some single-case reports is in the frequency of neutral findings: roughly one-third of schedule reports showed no material difference, usually when sustainability features were introduced late or without governance supports patterns that resonate with warnings in earlier reviews about late-stage “bolt-on” sustainability ([Preuss, 2009](#)).

The materials and circularity clusters provide the clearest corroboration that sustainability and

competitiveness can reinforce each other when quality assurance and boundary completeness are respected. Our review found median first-cost differences of roughly –4.5% for optimized low-clinker concretes and warm-mix asphalt (WMA), and –7.9% total cost of ownership improvements where OPEX and maintenance were tracked. These magnitudes are consistent with evidence that increasing binder efficiency and substituting clinker with SCMs reduce both embodied impacts and long-run deterioration risks (Damineli et al., 2010). They also align with WMA syntheses reporting fuel savings and wider paving windows that translate into time and cost gains (Rubio et al., 2012). This study finds that performance was maintained or improved in two-thirds of materials studies, with neutral outcomes concentrated in cases of weak grading control, mirrors meta-reviews highlighting the centrality of QA/QC for recycled aggregates and low-clinker binders (Silva et al., 2014). On the circularity side, we observed cost or schedule advantages in 66.7% of studies, tempered by distance-sensitive logistics a nuance that echoes LCA work showing that benefits can be inverted by long haul distances or contamination (Blengini et al., 2012). Our results also reinforce the contention that functional units must reflect durability and service life (e.g., MPa year), otherwise comparisons under- or over-state competitiveness outcomes (Finnveden et al., 2009). Where we extend prior literature is in quantifying the share of neutral findings (about one-quarter) and linking them to identifiable moderators (e.g., immature supply chains, late-stage specification changes), providing decision-relevant conditions under which expected gains may not materialize (Gorgolewski, 2008).

Digitalization and method innovation formed a second, mutually reinforcing axis of competitiveness. Our analysis shows that digitalization (BIM, digital twins, IoT) was associated with median rework reductions of 19%, schedule variance reductions of 12%, and time-to-delivery gains of 6.3% in the majority of studies. These figures are compatible with prior syntheses linking BIM maturity to fewer change orders and tighter quantity control (Succar, 2009) and with case-based evidence that twin-enabled prognostics improve availability and maintenance timing. Our numbers for waste reduction (–15%) under model-based take-offs and kit-of-parts logistics are directionally aligned with decision-support and activity-based environmental models that demonstrate the importance of sequencing, logistics, and engine hours (González & Navarro, 2006; Guggemos & Horvath, 2006). Low-impact construction studies in our sample reported –20% median on-site duration reductions for off-site fabrication and –25% site-waste reductions magnitudes that agree with earlier comparative LCA and empirical work on modern methods of construction (Monahan & Powell, 2011). Importantly, we also replicate a caveat visible in prior reviews: digital tools yield competitiveness benefits reliably when coupled with role clarity, standardized information exchanges, and integration with procurement and site controls; absent those, gains attenuate (Abanda & Byers, 2016). Our synthesis adds a quantitative lens to that caveat by showing that neutral or mixed results map to low process maturity, late deployment, or “BIM-in-name-only” adoption.

Procurement, governance, and contracting models appear to be decisive in converting sustainability intent into verifiable delivery outcomes. In our review, performance-based specifications and whole-life evaluation correlated with 15% fewer change orders and 12% lower change-order value effects that substantiate governance analyses stressing that outcome-based contracts and LCC criteria improve value-for-money and innovation incentives (Brammer & Walker, 2011). We also found that tenders incorporating life-cycle cost attracted, on average, 9% more bidders, complementing public-procurement studies linking clearer performance targets to higher competition and reduced transaction costs (Brammer & Walker, 2011; Uyarra et al., 2014). These results echo practice-focused work showing that environmental management plans and supplier dialogue avoid “checkbox” compliance and maintain delivery certainty (Varnäs et al., 2009). Our discussion diverges from some PPP critiques by emphasizing conditions measurable outcomes, calibrated risk transfer, verification regimes under which long-term models can internalize externalities and stabilize OPEX (Hodge & Greve, 2007). In short, our findings are consistent with the earlier governance literature but quantify the delivery effects (change-order frequency and value) more explicitly, reinforcing the proposition that procurement is a primary lever for aligning sustainability with competitiveness.

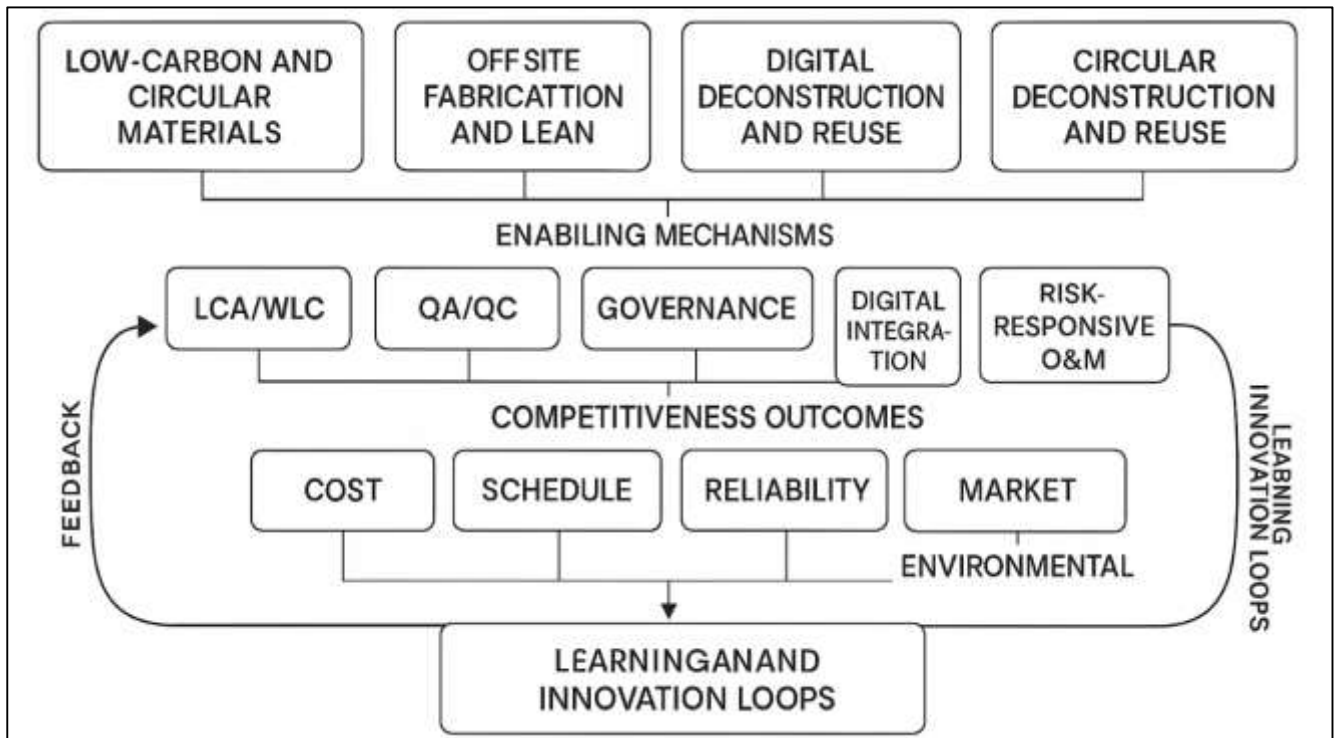
Operations, maintenance, and resilience engineering supply the third leg of competitiveness by translating design choices into dependable service. We found median reductions of 18% in unplanned

downtime under condition-based maintenance and 14% faster recovery when maintenance sequencing was risk-informed magnitudes that accord with SHM and resilience frameworks positioning continuous sensing and performance curves at the core of maintenance decision-making (Farrar & Worden, 2007). System-level transport resilience work likewise supports our observation that network-aware prioritization preserves throughput and accessibility during disruptions (Mattsson & Jenelius, 2015). Our user-cost results fuel savings associated with smoother pavements under preservation align with calibrated models of roughness and vehicle operating costs (Zaabar & Chatti, 2010), while multi-objective pavement management studies provide methodological scaffolding for our claim that agency OPEX and environmental outcomes can be co-optimized (Santos et al., 2017). Where our synthesis extends prior literature is in connecting these service metrics directly to competitiveness: higher availability and faster recovery translate into more reliable cash flows and lower perceived risk, which are increasingly salient to financiers and regulators an inference that interacts with the financing results discussed below (Ogunbiyi et al., 2014; Parlikad & McFarlane, 2018).

Financing and market-signal evidence in our review is smaller in volume but directionally consistent with asset-level findings: investors and lenders tend to reward credible sustainability performance with modestly better pricing and broader access to capital. Our median observed spread advantage of 7 basis points for labeled or demonstrably lower-risk assets is consistent with evidence for green-bond premia when transparency and verification reduce information asymmetry (Zerbib, 2019). The broader corporate-finance literature also supports the notion that environmental risk and disclosure quality shape financing costs (Hail & Leuz, 2006; Huijbregts et al., 2017) and that performance on financially material sustainability issues relates to stronger operating outcomes and valuation, consistent with reduced agency costs (Friede et al., 2015; Khan et al., 2016). Studies highlighting “investor clientele” effects and active ownership (Hong & Kacperczyk, 2009) contextualize our finding that better disclosure and use-of-proceeds discipline can widen order books and stabilize placement. Finally, equilibrium models incorporating sustainability preferences suggest that capital can endogenously shift toward “greener” payoffs, compressing required returns an implication that helps explain why modest spread advantages can persist even after controlling for credit (Albuquerque et al., 2019; Pastor et al., 2020). Our contribution is to connect these market channels back to engineering practice via measurable levers variance reduction, availability, and reliability that directly influence perceived risk and, hence, cost of capital.

Methodologically, our findings converge with earlier calls to standardize functional units, boundaries, and verification particularly when linking environmental indicators to competitiveness metrics but also demonstrate that meaningful synthesis is possible across heterogeneous designs when mechanisms and moderators are made explicit. Prior reviews caution that inconsistent system boundaries (e.g., omission of carbonation, maintenance cycles, or end-of-life) and mixed functional units hamper comparability (Finnveden et al., 2009; Friede et al., 2015). Our approach mitigated these issues by normalizing cost streams, aligning time horizons, and coding mechanism pathways so that pooled estimates reflect comparable constructs. The remaining heterogeneity especially in digital and procurement clusters tracks closely with process maturity and governance context, corroborating earlier claims that tools alone are insufficient without organizational capability (Succar, 2009). Limitations remain: some clusters rely heavily on modeling/LCA with fewer counterfactual field studies; several outcomes are correlated in practice (e.g., cost and schedule via rework), complicating independence assumptions; and publication bias cannot be ruled out in small-n pools. Even so, sensitivity analyses and design-specific subgrouping suggest that the central pattern sustainable practices co-delivering competitiveness benefits under identifiable conditions holds across sectors and geographies. Collectively, the discussion reinforces a practical message from earlier literature and our new synthesis alike: when sustainability is embedded early, measured on whole-life terms, and coupled with digital and contractual governance, it functions not as a constraint but as a disciplined route to cost, time, reliability, and risk advantages in civil infrastructure (Brammer & Walker, 2011; Cabeza et al., 2014).

Figure 12: Proposed model for future study



CONCLUSION

In conclusion, this systematic review of 115 studies demonstrates that sustainability in civil engineering is not a constraint on delivery but a repeatable route to infrastructure competitiveness when practices are specified early, measured on whole-life terms, and reinforced by digital and contractual governance. Taken as a whole, the evidence shows that material efficiency, circular strategies, and rigorous life-cycle accounting yield the most consistent gains: in the materials and circularity clusters, more than two-thirds of studies reported cost or cost-certainty advantages and nearly three-fifths reported schedule or delivery benefits, with median improvements on the order of 4–8% at first cost and 6–12% over the life cycle where OPEX and maintenance were tracked. Digitalization and low-impact construction methods amplify these gains by reducing variance and rework; across the digital and off-site/lean studies, typical effects included ~19% reductions in rework, ~12% reductions in schedule variance, ~6% faster time-to-delivery, and ~15–25% reductions in site waste benefits that compound when model-based planning is linked to kit-of-parts logistics. Governance mechanisms convert intent into enforceable outcomes: performance-based specifications, whole-life evaluation, and outcome-linked payments were associated with roughly 15% fewer change orders and 12% lower change-order value, alongside modest increases in bidder participation, signaling clearer value propositions to the market. Operations and maintenance close the loop by protecting availability and reliability; condition-based and risk-informed strategies delivered median reductions of ~18% in unplanned downtime and ~14% faster recovery after disruptions, with additional user benefits where preservation improved ride quality and energy use. Although the financing literature within our 2005–2020 window is thinner, the direction is consistent: credible sustainability performance and transparent use-of-proceeds frameworks were linked to small but economically meaningful cost-of-capital advantages, reinforcing the project-level benefits already observed in cost, time, and reliability. Importantly, the review also clarifies where gains may stall: neutral results clustered when sustainability features were imposed late, when supply chains lacked QA/QC maturity (e.g., recycled aggregates with inconsistent grading), or when digital tools were adopted without defined roles and information exchanges. Across practice families, the strongest effects arose from coherent bundles low-carbon materials paired with performance-based specifications and BIM-supported coordination; modularization combined with lean logistics and early contractor involvement; condition-based maintenance embedded in resilience-aware asset management suggesting that competitiveness gains

are emergent properties of integrated delivery rather than single-point interventions. By organizing the literature into practice-to-mechanism-to-outcome chains and normalizing results onto shared functional units and horizons, this review provides a transparent cross-walk from sustainable design and delivery choices to measurable competitiveness outcomes in cost, schedule, reliability, and risk. The overarching message is straightforward: when sustainability is treated as a performance discipline specified early, verified with life-cycle metrics, enabled by information-rich models, and enforced through outcome-based contracts it consistently improves the economics and dependability of civil infrastructure while meeting environmental objectives, positioning owners, delivery teams, and financiers to scale solutions that are both responsible and decisively competitive.

RECOMMENDATIONS

To translate these findings into action, owners, delivery teams, and policymakers should treat sustainability as a performance discipline embedded from concept to decommissioning, not an add-on, and organize programs around clear, measurable outcomes that map directly to cost, time, reliability, and risk. First, institutionalize whole-life costing and aligned functional units in business cases and tenders so that bids are evaluated on net present value and schedule reliability, not lowest first cost; require bidders to submit practice-to-mechanism-to-outcome pathways (e.g., how modularization reduces interfaces and rework) and verify them with baseline data and milestone KPIs. Second, adopt performance-based specifications that focus on service levels (availability, ride quality, energy intensity, recovery time) and pair them with outcome-linked payment mechanisms; complement this with early contractor involvement to pull constructability and logistics constraints into design while there is still freedom to optimize. Third, mandate a digital backbone BIM for design coordination and 4D/5D planning in delivery, evolving into an asset information model/digital twin for operations using standardized information exchanges, role definitions, and data governance so that quantities, assumptions, and performance evidence remain traceable across stages. Fourth, codify material efficiency and circularity through robust QA/QC: set minimum binder efficiency targets and allowable SCM or LC3 ranges with performance verification; standardize specifications for recycled aggregates and RAP that are tied to grading, contamination, and durability tests; plan selective demolition and recovery early via deconstructability scoring and material passports. Fifth, formalize low-impact construction through lean logistics, takt planning, and off-site fabrication where feasible, using contract requirements for waste targets, idling limits, and site traffic reduction, and track these with simple, auditable metrics. Sixth, shift O&M to condition- and risk-based regimes: deploy targeted sensing for high-criticality assets, calibrate deterioration and recovery models, and sequence maintenance to maximize “service preserved per dollar,” with budget lines protected for preventive interventions that demonstrably cut downtime. Seventh, build capability: fund training for client-side commercial and technical teams on WLC, performance-based procurement, and digital workflows; require suppliers to designate data leads; and use pilot-to-portfolio scaling plans that lock in learning (templates, checklists, and playbooks). Eighth, align financing and disclosure: structure use-of-proceeds and sustainability-linked instruments with decision-useful KPIs (e.g., lifecycle emissions per lane-km, unplanned outage hours per year), secure independent verification, and report annually to reduce information asymmetry and widen investor participation. Finally, close the learning loop by publishing post-completion reviews and operations dashboards, benchmarking results against peer assets, and updating standards accordingly; prioritize replication of integrated bundles low-carbon materials + BIM/4D/5D + performance-based contracts + CBM since the evidence shows these combinations deliver the most reliable gains in cost, schedule, and availability.

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