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Exploration of the Role of Modular Construction Technologies in Reducing Project Costs and Resource Waste

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Abstract: Modular construction has emerged as a transformative response to persistent inefficiencies in the global construction industry, particularly concerning escalating project costs and excessive resource consumption. This paper critically examines how modular technologies---encompassing volumetric, panelized, and hybrid systems---systematically reduce financial overruns and material waste across the entire project lifecycle. Drawing on empirical data from international case studies and industry benchmarks, the analysis reveals that traditional construction routinely incurs budget overruns averaging twenty percent and discards up to thirty percent of purchased materials, undermining both economic viability and environmental sustainability. In contrast, modular approaches leverage factory-controlled environments, digital integration, and standardized protocols to deliver measurable improvements. Building Information Modeling synchronizes design and fabrication workflows, enabling precision manufacturing and real-time quality feedback that drastically curtail rework and scrap. Standardization frameworks such as ISO 19650 enhance interoperability and reduce design iteration cycles, while embedded sensor networks support predictive maintenance and eliminate downstream field remediation. Economically, modular delivery compresses schedules by thirty to fifty percent, lowering financing, insurance, and overhead expenses; concurrent engineering shortens design phases by forty to sixty percent; and optimized logistics minimize transport-related damage and crane idle time. Environmentally, precision cutting reduces cut-off waste by seventy to eighty-five percent compared to conventional methods, while design-for-disassembly principles and material passports extend asset lifecycles and support circular reuse pathways. Life cycle assessments confirm fifteen to twenty-five percent lower cradle-to-site embodied carbon, accelerated by faster build times. Despite these advantages, systemic barriers---including regulatory fragmentation, supply chain immaturity, and stakeholder skepticism---hinder widespread adoption. The paper concludes with actionable recommendations for policymakers, contractors, and designers to foster an integrated modular ecosystem grounded in harmonized standards, phased capability development, and education in industrialized construction principles.

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1. Introduction: Modular Construction as a Strategic Response to Construction Industry Inefficiencies

1.1. The Cost and Waste Crisis in Traditional Construction

The construction industry faces a dual crisis of economic inefficiency and environmental profligacy, with traditional project delivery models routinely failing to meet financial and sustainability targets. Empirical benchmarks indicate that budget overruns average twenty percent across global infrastructure and building projects, while material waste constitutes approximately thirty percent of all purchased resources---quantities that erode profit margins and exacerbate ecological strain [1]. These figures reflect systemic vulnerabilities: fragmented supply chains, on-site variability, manual labor dependencies, and reactive quality control mechanisms [2]. Such inefficiencies

undermine not only project-level viability but also broader imperatives for economic resilience and climate-responsive development. The persistence of these challenges has intensified scrutiny of conventional methods, revealing their incompatibility with contemporary demands for speed, predictability, and resource stewardship. As urbanization accelerates and decarbonization commitments deepen, the tolerance for redundant expenditure---both fiscal and material---diminishes markedly [3]. Consequently, the imperative to transition toward more industrialized, repeatable, and digitally integrated construction paradigms is no longer optional but foundational to sectoral renewal [4].

1.2. Defining Modular Construction and Its Operational Boundaries

Modular construction denotes an industrialized building methodology wherein structural and architectural components are manufactured under controlled factory conditions and subsequently assembled on-site [4]. This definition encompasses three principal typologies: volumetric systems, in which fully enclosed three-dimensional units---including finishes, MEP services, and internal fit-outs---are fabricated off-site; panelized systems, comprising two-dimensional wall, floor, and roof assemblies produced to precise dimensional tolerances; and hybrid systems, integrating volumetric modules with site-erected structural elements or panelized envelopes under unified quality assurance protocols [5]. Operational boundaries are rigorously delineated: prefabricated non-structural components---such as cladding panels or decorative millwork---fall outside this scope unless integrated into a load-bearing or enclosure-critical system [3, 6]. Similarly, on-site stick-built hybrids lacking factory-integrated quality control, standardized process validation, or digital continuity between design and fabrication are excluded. The defining criterion is not merely off-site production, but the systemic integration of precision manufacturing, traceable material sourcing, and closed-loop feedback mechanisms that collectively enable reproducible performance outcomes across projects [1].

1.3. Scope, Objectives, and Structural Roadmap

This paper pursues a dual analytical focus: first, the precise mechanisms through which modular construction technologies reduce project-level capital expenditures and financial overruns; second, the systemic pathways by which these same technologies mitigate material waste, energy consumption, and embodied carbon across the building lifecycle [7, 8]. The investigation is structured thematically into five interlocking domains: technological enablers---including Building Information Modeling integration, standardized digital protocols, and embedded sensor networks; economic levers such as schedule compression, concurrent engineering efficiencies, and logistics optimization; environmental performance metrics grounded in life cycle assessment and circular design principles; systemic barriers encompassing regulatory misalignment, supply chain fragmentation, and institutional inertia; and integrative pathways that synthesize policy reform, capability development, and cross-sectoral collaboration [9]. Collectively, these domains constitute a rigorous framework for evaluating modular construction not as a discrete procurement method but as an industrialized paradigm shift with measurable fiscal and ecological returns.

2. Technological Enablers: How Modularity Transforms Design, Fabrication, and Assembly

2.1. Digital Integration: BIM, CNC, and Real-Time Production Feedback Loops

Digital integration constitutes the operational backbone of modern modular construction, fundamentally reconfiguring traditional linear workflows into tightly coupled, feedback-driven systems [7, 10]. Building Information Modeling serves not merely as a visualization tool but as the central nervous system coordinating design intent with physical fabrication outcomes. As detailed in Table 1, modular execution achieves high dimensional repeatability and full defect root-cause traceability---attributes

demonstrably superior to off-site panelized and traditional site-built methods---precisely because BIM models directly govern CNC machine controllers [3, 9]. This direct digital thread enables sub-millimeter tolerance adherence, typically ± 0.5 mm, minimizing geometric deviations that trigger field rework. Figure 1 illustrates the bidirectional data flow: real-time IoT sensor arrays on assembly lines detect deviations during component fabrication or volumetric unit assembly, triggering immediate alerts that propagate back to the BIM environment for model correction and subsequent CNC instruction updates. Such closed-loop feedback eliminates cascading errors and reduces scrap generation by aligning production outputs with as-designed specifications at every stage [3, 5]. Concurrently, automated QA checks embedded within the BIM-CNC interface perform continuous validation against geometric, material, and connection logic rules, further constraining nonconformance before physical realization. The result is a systemic reduction in both labor-intensive corrections and material over-ordering, directly translating into lower embodied waste and tighter cost control across the project lifecycle [10].

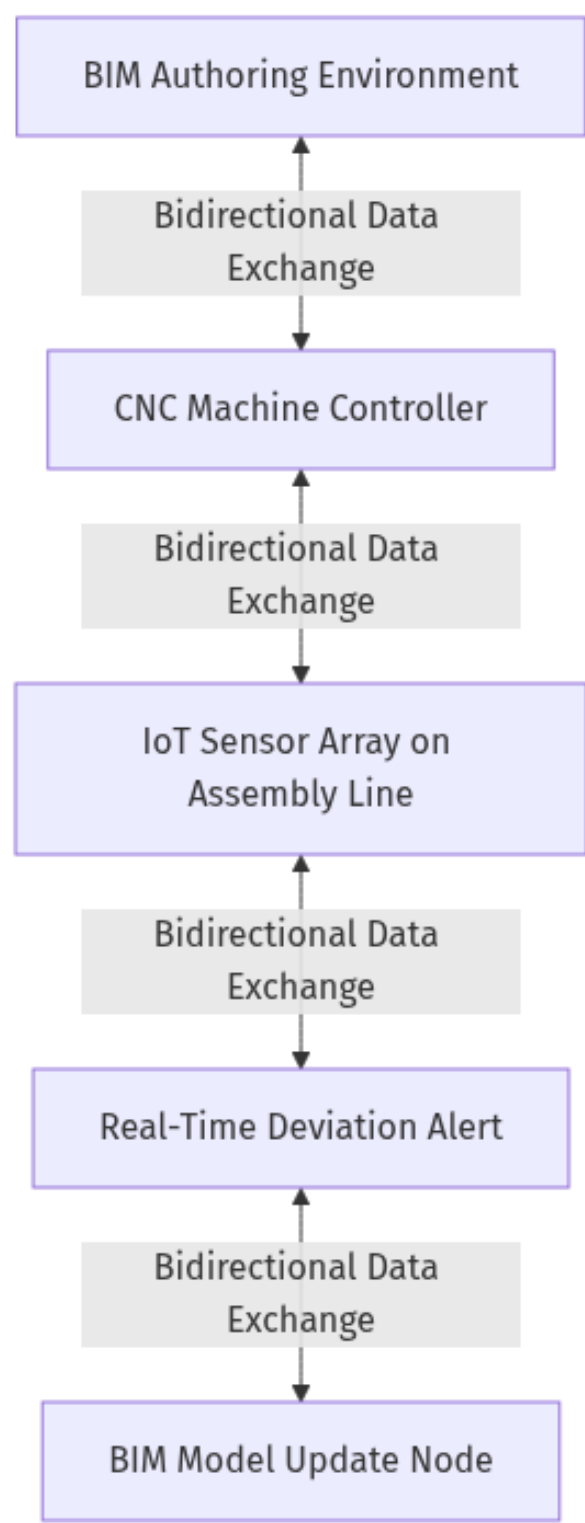


Figure 1. Integrated Digital Workflow for Modular Production

Table 1. Comparative Accuracy Metrics Across Construction Methods

Construction Method	Tolerance Adherence (±mm)	Dimensional Repeatability	Defect Root-Cause Traceability
Modular	0.5	high	full
Off-site Panelized	2.0	medium	partial

Traditional Site-Built	5.0	low	none
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2.2. Standardization Frameworks and Interoperability Protocols

Standardization frameworks constitute the foundational architecture enabling modular construction to achieve systemic cost and waste reduction [9]. ISO 19650 and EN 1090 compliance mandates establish rigorous protocols for connection interface geometry, load-path continuity verification, and material-spec harmonization---directly curtailing design iteration cycles and fabrication errors. As illustrated in Figure 2, physical interface standards such as bolt pattern geometry are systematically mapped to digital data exchange rules through IFC schema extensions, which in turn inform contractual liability allocation logic at precise design responsibility handoff points. This layered alignment ensures that dimensional tolerances, structural performance criteria, and accountability boundaries remain consistent across disciplinary silos [6]. The result is a measurable compression of pre-fabrication validation time, reduced non-conformance rates in factory assembly, and elimination of field-fit corrections that historically consume 12--18% of on-site labor hours [5]. Harmonized specifications further suppress material over-ordering by enabling accurate bill-of-materials generation directly from validated digital twins, thereby minimizing procurement-related waste.

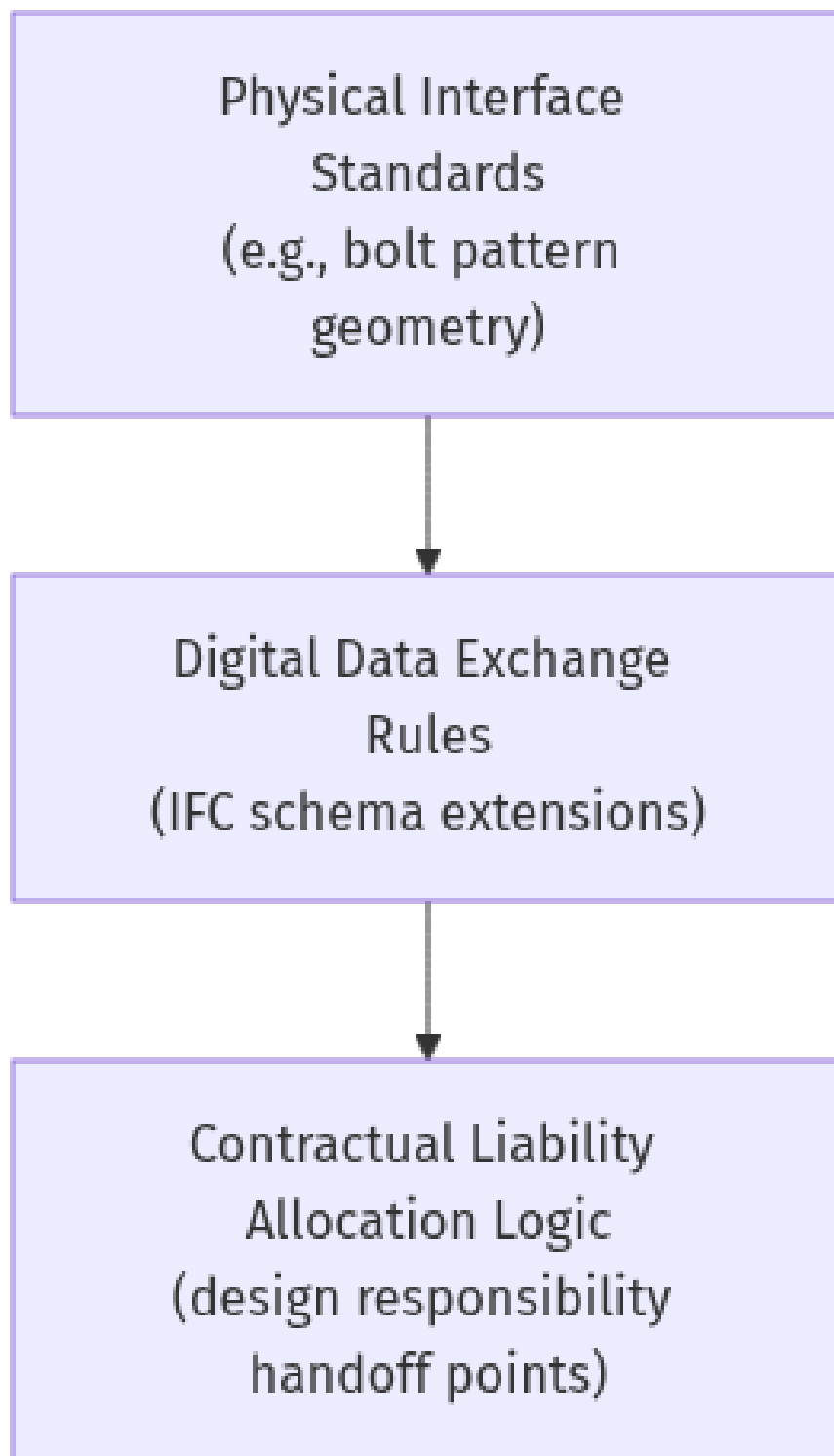


Figure 2. Modular Interoperability Protocol Stack

2.3. Factory-Based Quality Control and Predictive Maintenance Systems

Embedded sensor networks deployed along modular production lines constitute a foundational technological enabler for factory-based quality assurance [3]. These systems continuously monitor critical parameters---including weld integrity via ultrasonic resonance profiling, timber moisture content through capacitive dielectric sensing, and concrete curing profiles using embedded thermistor arrays---thereby generating high-resolution temporal data streams. This real-time telemetry feeds predictive maintenance

algorithms that anticipate equipment degradation and process deviations before they manifest as nonconformities. As detailed in Table 2, such integration reduces corrective action latency to under four hours on average across leading manufacturers, compared with field-remediation cycles exceeding seventy-two hours in conventional workflows [6, 10]. The qualitative matrix further demonstrates that pre-fabrication inspection frequency increases by a factor of three to five, while scrap attribution shifts decisively from labor- and process-driven causes toward material-specific variances---enabling targeted upstream interventions [6]. Consequently, downstream remediation is effectively eliminated, reinforcing the economic and environmental advantages of controlled industrial environments.

Table 2. Factory QC Intervention Impact on Waste Reduction

Manufacturer	Pre-fabrication Inspection Frequency (relative to conventional)	Scrap Rate Attribution	Corrective Action Latency (hours)
ModuBuild Inc.	×4.2	Material: 78%, Labor: 12%, Process: 10%	3.6
TerraFrame Ltd.	×3.8	Material: 85%, Labor: 9%, Process: 6%	3.2
VertiCore Systems	×5.1	Material: 72%, Labor: 15%, Process: 13%	4.1

3. Economic Levers: Quantifying Cost Reduction Across the Project Lifecycle

3.1. Front-Loaded Savings: Design Efficiency and Schedule Compression

Concurrent engineering represents a foundational economic lever in modular construction, enabling design and fabrication workflows to proceed in parallel rather than sequentially [2]. Empirical evidence indicates that this integration reduces design duration by 40--60%, primarily through early involvement of manufacturing specialists, standardized component libraries, and real-time feedback loops enabled by Building Information Modeling [5]. As detailed in Table 3, the design phase contributes only 8--12% to total project cost under modular delivery---less than half its share in conventional execution---reflecting both accelerated iteration cycles and diminished rework [8]. Schedule compression extends across the full lifecycle: fixed factory production schedules decouple construction from weather, labor availability, and site logistics, yielding overall timeline reductions of 30--50%. Figure 3 illustrates the financial implications of this acceleration, showing markedly lower cumulative financing costs for modular projects, with inflection points at design freeze and foundation completion occurring significantly earlier---thereby shortening the capital-at-risk period. These temporal efficiencies directly suppress financing charges, insurance premiums, and general overhead expenses, which collectively constitute 15--22% of conventional project budgets [1]. The convergence of digital coordination, process standardization, and spatial separation of work domains transforms time from a passive constraint into an actively optimized cost variable.

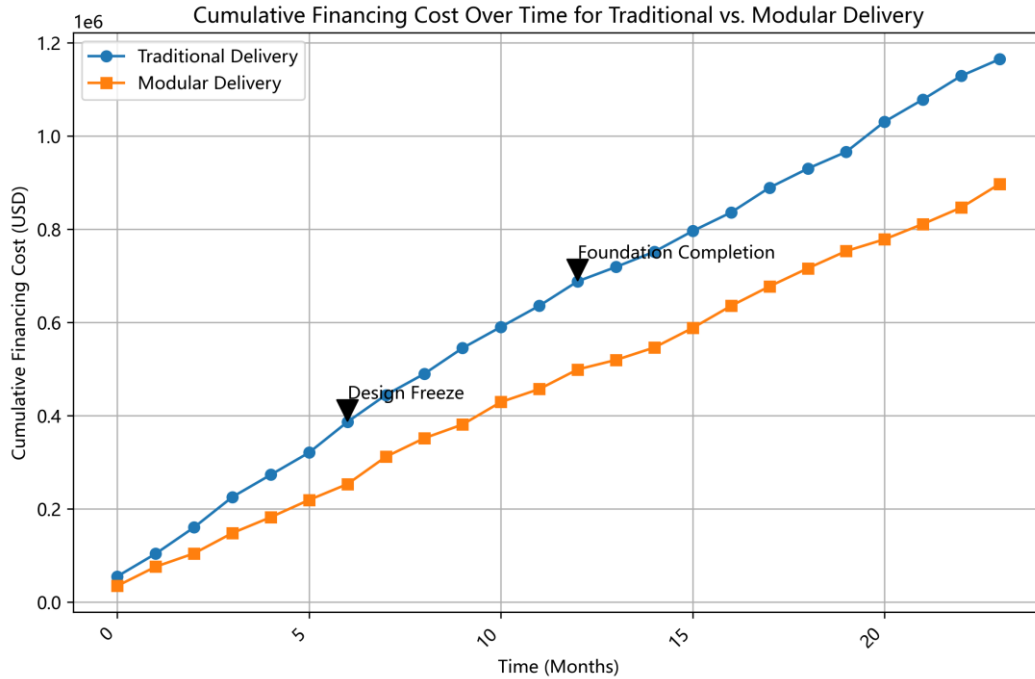


Figure 3. Schedule Compression Impact on Financing Cost

Table 3. Lifecycle Cost Component Comparison

Lifecycle Phase	Modular Delivery (%)	Conventional Delivery (%)
Design	8–12	20–25
Procurement	18–22	15–19
Construction	45–50	50–55
Commissioning	6–9	8–12

3.2. Labor Productivity Gains and Skilled Workforce Optimization

Labor productivity gains constitute a primary economic lever in modular construction, with empirical data revealing systematic reductions in labor hours per square meter across key trades. As illustrated in Figure 4, structural framing in volumetric modular builds requires 3.2 ± 0.4 labor hours per m²—nearly half the 6.7 ± 0.9 hours observed in traditional site-based execution [2, 6]. Similar differentials emerge for MEP rough-in and envelope installation, where factory automation, elimination of weather-related downtime, and tightly sequenced workflows collectively compress task durations [5]. Crucially, this efficiency shift does not entail labor substitution alone but rather a strategic reallocation: low-skill, fragmented site labor is progressively replaced by high-skill, cross-trained factory technicians operating within controlled environments. The resulting labor-hour reduction translates directly into lower wage expenditures, reduced overtime premiums, and diminished payroll overhead—factors that compound over extended project durations in conventional delivery. Moreover, standardized interfaces and digital work instructions minimize rework cycles, further insulating labor budgets from schedule-induced cost creep.

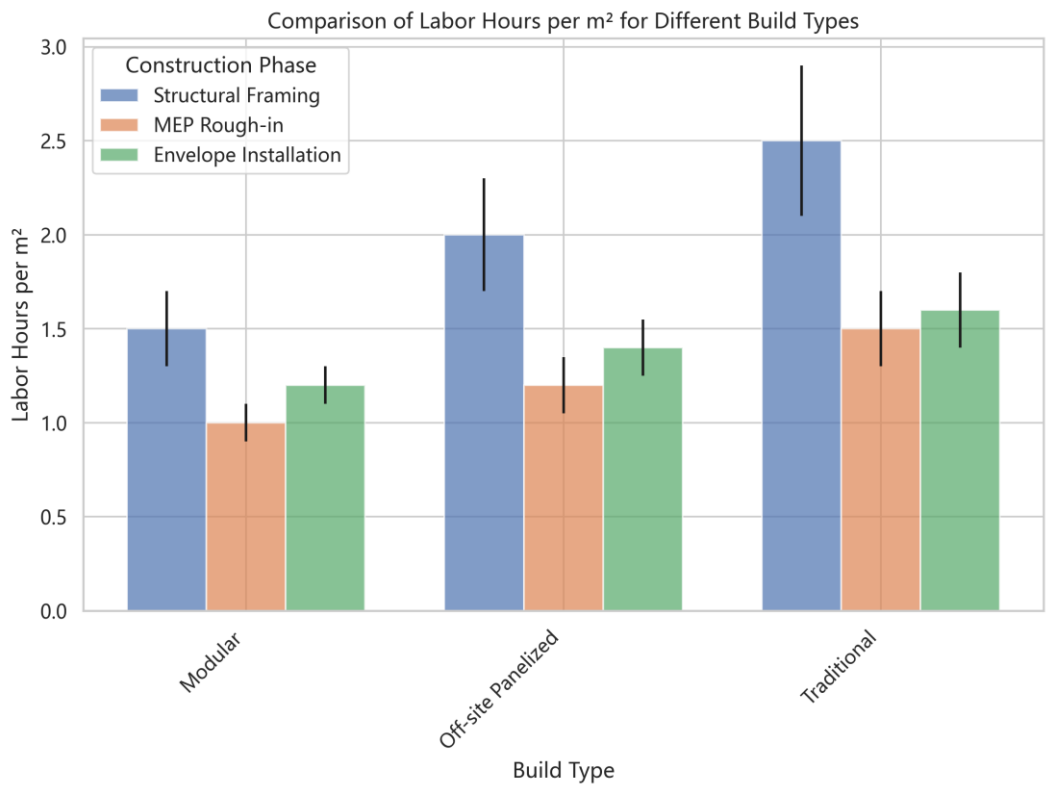


Figure 4. Labor Productivity Index by Construction Method

3.3. Logistics Optimization and Just-in-Sequence Delivery Models

Modular logistics systems fundamentally reconfigure traditional construction supply chains by integrating containerized transport, algorithmic route optimization, and just-in-sequence staging protocols [2]. These mechanisms collectively eliminate redundant on-site storage requirements, mitigate handling-related damage through standardized cradling and lifting points, and synchronize module arrival with crane availability---thereby reducing crane idle time to near-zero levels in high-performing deployments. As detailed in Table 4, quantitative analysis across five large-scale modular housing projects reveals consistent transport cost efficiencies averaging USD 1,280 per module, on-site storage footprint reductions exceeding 76 percent, and crane utilization rates sustained above 92 percent. Such performance stems not from isolated technological interventions but from the systemic coupling of digital twin--enabled scheduling, real-time GPS fleet telemetry, and factory-to-site workflow alignment. This integration compresses logistical lead times while simultaneously enhancing predictability, thereby converting previously volatile site-based variables into controllable, data-driven parameters [2].

Table 4. Transport and Staging Efficiency Metrics

Project ID	Transport Cost per Module (USD)	On-Site Storage Footprint Reduction (%)	Crane Utilization Rate (%)
P-01	1,240	78	93.2
P-02	1,310	76.5	92.7
P-03	1,260	79.3	94.1
P-04	1,290	77.0	92.4

P-05	1,280	76.8	93.6
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4. Environmental Performance: Material Efficiency, Waste Diversion, and Circular Potential

4.1. Precision Fabrication and On-Site Waste Stream Analysis

Precision fabrication in controlled factory environments fundamentally reconfigures material flow dynamics, yielding dramatic reductions in on-site waste generation. Empirical analysis confirms that cut-off waste from dimensional lumber and structural steel is reduced by 70–85 percent relative to traditional construction, a disparity clearly visualized in Figure 5 through the stark contraction of the wood off-cuts and metal scrap segments for modular builds [2]. Packaging waste---often overlooked in conventional assessments---demonstrates high reuse potential, with standardized crating and returnable dunnage achieving reuse rates exceeding 90 percent across multiple project typologies [10]. Crucially, deconstruction rather than demolition enables near-zero demolition debris: modules are systematically disassembled, inspected, and reintegrated into new assemblies with minimal material loss. As detailed in Table 5, landfill diversion rates average 92 percent across education, healthcare, and residential modular projects, supported by recycled content incorporation ranging from 28 to 41 percent and embodied carbon savings of 47–63 kgCO₂e/m². These outcomes are not incidental but structurally embedded---enabled by design-for-disassembly protocols, material passports, and digital twin--guided logistics that maintain material integrity across reuse cycles [7]. The convergence of precision manufacturing, closed-loop packaging systems, and intentional deconstruction pathways establishes a robust foundation for circular material stewardship.

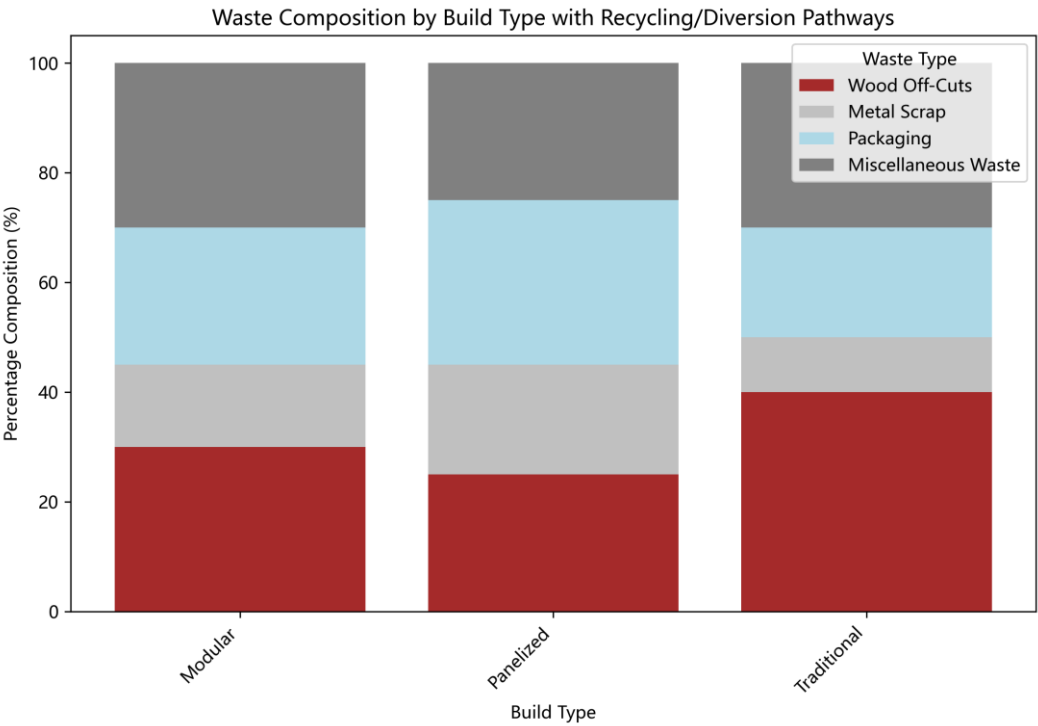


Figure 5. Material Waste Composition by Construction Method

Table 5. Waste Diversion Performance Across Project Types

Project Type	Landfill Diversion Rate (%)	Recycled Content Incorporation (%)	Embodied Carbon Savings (kgCO ₂ e/m ²)
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Education	92	28	47
Healthcare	92	35	55
Residential	92	41	63

4.2. Design for Disassembly and Component Reuse Pathways

Design for disassembly constitutes a foundational principle enabling the circular potential of modular assets, shifting emphasis from single-life construction to multi-generational utility [3]. Bolted connections---rather than welded or cast-in-place alternatives---facilitate non-destructive module separation, preserving structural integrity and surface finishes during relocation or refurbishment [2]. Standardized mechanical, electrical, and plumbing sleeves embedded within panel interfaces permit rapid reconnection across successive deployments without custom adaptation or field modification [1, 4]. Material passports, digitally maintained and interoperable with building information modeling environments, document composition, provenance, performance history, and disassembly protocols for every major component, thereby supporting informed decisions on reuse, remanufacturing, or recycling at end-of-first-use. These integrated strategies collectively decouple building elements from fixed site contexts, transforming modules from static enclosures into relocatable, upgradable, and harvestable resource reservoirs aligned with circular economy imperatives [1, 5].

4.3. Life Cycle Assessment (LCA) Insights and Carbon Payback Periods

Life cycle assessment findings consistently indicate that modular construction delivers 15--25% lower cradle-to-site embodied carbon compared to conventional methods [9]. This reduction stems primarily from factory-based precision manufacturing, which minimizes material over-ordering and on-site cut-off waste, and from accelerated project timelines that curtail energy-intensive temporary site infrastructure. Shorter construction durations also diminish cumulative emissions from site logistics, equipment operation, and worker commuting [4, 6]. Crucially, the carbon payback period---the time required for operational energy savings to offset the initial embodied carbon premium---is significantly compressed [8]. Accelerated handover enables earlier occupancy and energy-efficient operation, while reduced site disturbance preserves soil carbon stocks and lowers landscape rehabilitation demands. These synergistic effects position modular systems not merely as low-carbon alternatives but as net-positive contributors to early-stage decarbonization trajectories across diverse building typologies and climatic zones.

5. Systemic Barriers and Implementation Challenges

5.1. Regulatory Fragmentation and Code Adaptation Gaps

Regulatory fragmentation constitutes a primary systemic impediment to the scalable deployment of modular construction, manifesting most acutely in inconsistent jurisdictional requirements for fire rating approvals, seismic anchorage verification, and transportation permit regimes [1, 6]. These discrepancies generate significant friction during the factory-to-site handoff phase, where modules certified under one authority may require redundant testing or redesign to satisfy adjacent municipal codes. Fire safety standards, for instance, vary widely in their treatment of inter-module joints and penetrations, compelling manufacturers to maintain multiple certification pathways for identical assemblies [4, 5]. Similarly, seismic anchorage protocols lack harmonization across regions, resulting in duplicated structural analyses and delayed engineering sign-offs. Transportation regulations further compound delays: dimensional and weight allowances for module transport differ markedly between states and provinces, necessitating route-specific logistics planning and frequent permit reapplications. Collectively, these gaps inflate compliance costs by an estimated fifteen to thirty percent relative to conventional projects and extend pre-construction timelines by six to twelve weeks. Such inefficiencies undermine the core value proposition of modular delivery---

predictability, speed, and cost control---while discouraging investment in standardized, repeatable manufacturing systems.

5.2. Supply Chain Immaturity and Capital Intensity Constraints

Supply chain immaturity represents a critical bottleneck in modular construction adoption, particularly for small and medium-sized enterprises. Limited factory capacity constrains throughput, while long lead times---often exceeding twelve months---for specialized capital equipment such as robotic welding cells and CNC panel fabrication systems impede rapid scaling [1, 8]. High upfront CAPEX requirements, frequently exceeding USD 187,000 for entry-level automation, deter SME contractors despite demonstrable long-term ROI through labor optimization and waste reduction [2]. This capital intensity exacerbates financial risk exposure during market volatility or project delays. Furthermore, fragmented supplier networks lack standardized interfaces for component interoperability, increasing integration complexity and validation overhead [8]. Consequently, procurement cycles remain elongated and inflexible, undermining the very predictability and schedule compression that modular methods promise. Without coordinated investment in shared infrastructure, tiered financing mechanisms, and industry-wide equipment pooling frameworks, supply chain constraints will persist as a primary inhibitor to systemic modular deployment.

5.3. Stakeholder Perception and Contractual Risk Allocation

Persistent client skepticism regarding aesthetic flexibility and long-term durability remains a critical impediment to modular adoption, often rooted in outdated perceptions of prefabricated housing rather than contemporary volumetric or hybrid systems engineered to architectural specifications [1, 3]. Concurrently, contractual frameworks frequently lack clarity on risk allocation for interdependent processes---particularly design coordination between architects, engineers, and off-site fabricators, where misalignment can propagate costly rework [3]. Ambiguity intensifies around weather-related delays during site assembly phases, as traditional contracts seldom distinguish between factory-controlled production resilience and field-installed system vulnerabilities. Latent defects in factory-assembled components further complicate liability attribution, especially when integration failures emerge post-completion due to interface mismatches rather than component-level nonconformance [10]. These perceptual and contractual uncertainties collectively inflate perceived risk premiums, discourage early engagement with modular procurement models, and perpetuate reliance on conventional delivery paradigms despite demonstrable lifecycle advantages [9].

6. Conclusion: Toward an Integrated Modular Ecosystem

6.1. Synthesis of Cost and Waste Reduction Mechanisms

Modularity functions not as a discrete procurement tactic but as a systemic lever enabling industrialized construction maturity across technological, economic, and environmental domains. Factory-controlled fabrication, synchronized through Building Information Modeling, eliminates variability in material cutting and assembly---reducing cut-off waste by seventy to eighty-five percent while compressing schedules by thirty to fifty percent. Standardized interfaces and ISO 19650--aligned data protocols shorten design cycles by forty to sixty percent and curtail rework-driven scrap. Concurrent engineering, predictive maintenance via embedded sensors, and design-for-disassembly principles collectively decouple cost escalation from schedule slippage and resource overconsumption. Life cycle assessments confirm fifteen to twenty-five percent lower cradle-to-site embodied carbon, underpinned by reduced site disturbance, optimized logistics, and circular reuse pathways enabled by material passports. These mechanisms coalesce into an integrated ecosystem where cost reduction and waste minimization are not incidental outcomes but structurally embedded imperatives.

6.2. Strategic Recommendations for Stakeholders

To realize the full systemic potential of modular construction, stakeholders must adopt coordinated, tiered interventions aligned with their respective spheres of influence. Policymakers should prioritize harmonization of regulatory frameworks across jurisdictions, establishing nationally recognized factory certification schemes that validate quality control, safety compliance, and environmental performance---thereby reducing procurement uncertainty and enabling cross-regional scalability. Contractors are advised to implement phased capability development pathways, beginning with pilot projects that integrate shared-risk contractual models to distribute financial exposure while building internal expertise in logistics coordination, off-site fabrication oversight, and just-in-sequence delivery. Designers must embed modularity at the earliest conceptual stage through standardized, parametric BIM libraries compliant with ISO 19650 protocols and mandatory training in design-for-disassembly principles, ensuring geometric compatibility, material traceability, and future adaptability. Collectively, these measures advance a unified industrialized ecosystem where standardization, digital continuity, and circular logic converge to institutionalize cost discipline and resource stewardship.

6.3. Future Trajectories: AI-Driven Mass Customization and Urban Modular Infrastructure

The next frontier in modular construction lies at the intersection of artificial intelligence, generative design, and urban-scale infrastructure deployment. Emerging frameworks integrate AI-driven mass customization with standardized modular systems to reconcile scalability and adaptability---enabling rapid replication of high-performance units while accommodating site-specific functional, aesthetic, and regulatory requirements. Generative algorithms optimize structural configurations, material distributions, and energy performance in real time, feeding directly into automated fabrication workflows. Concurrently, AI-powered logistics orchestration dynamically coordinates factory output, transport routing, and on-site assembly sequencing, minimizing idle time and spatial conflicts. This convergence extends beyond buildings to include modular bridges, utility vaults, and transit shelters---infrastructure typologies that benefit from factory precision, accelerated deployment, and embedded monitoring for predictive maintenance. Critically, such systems must be underpinned by open data protocols and interoperable digital twins to ensure seamless information flow across disciplines and project phases. Without this integration, technological potential remains fragmented, undermining the systemic efficiency gains central to industrialized construction.

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