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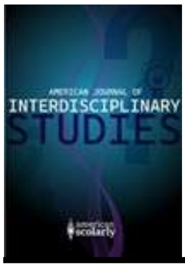

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Fabrication-Driven Structural Optimization Techniques for Cost-Efficient Steel Construction Using CNC-Based Design Workflows

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Abstract

This study investigated how fabrication-driven structural optimization improves cost efficiency in steel construction when delivered through CNC-based, BIM-enabled design workflows, addressing the problem that many "optimized" steel designs lose their economic advantage due to traceability gaps, revision churn, and incomplete fabrication constraint alignment across multi-tool, multi-organization pipelines. The purpose was to quantify the relationships among Fabrication-Driven Structural Optimization (FDSO), CNC Workflow Traceability and Data Integrity (CWTDI), Fabrication Constraint Compliance Index (FCCI), and Cost-Efficiency outcomes (CE) using a quantitative cross-sectional, case-based design. Data were collected from a purposive sample of 162 professionals embedded in enterprise steel delivery cases that used CNC fabrication and cloud or enterprise digital collaboration tools for model-to-detail-to-machine handoffs (structural engineers 24.1%, BIM/modeling 18.5%, detailers 21.0%, shop supervisors 16.7%, CNC/QA 9.3%, project managers 10.5%; mean experience 7.8 years, SD 4.6; 72.2% frequent CNC exposure). Reliability was strong (a: FDSO 0.88; CWTDI 0.90; FCCI 0.86; CE 0.89). Descriptively, respondents reported above-mid maturity (FDSO M 3.92, SD 0.62; CWTDI M 3.74, SD 0.71; FCCI M 0.77, SD 0.12; CE M 3.85, SD 0.66 on 1–5 scales). The analysis plan applied descriptive statistics, Pearson correlations, and multiple regression with controls (role, experience, project complexity). Headline findings showed strong positive associations with CE (FDSO r 0.63; CWTDI r 0.69; FCCI r 0.58; all p < .001) and a high explanatory regression model (F(6,155)=33.9, p<.001; R^2=0.57; Adj R^2=0.55) where CWTDI was the strongest predictor (β=0.41, p<.001), followed by FDSO (β=0.29, p<.001) and FCCI (β=0.18, p=.006; VIFs < 2.1). Case validation aligned higher traceability with fewer major revision cycles (2.1 vs 3.6) and fewer CNC regeneration events (1.4 vs 2.6), and cost-impact decomposition attributed perceived savings mainly to rework reduction (31%), then labor-hours reduction (24%), waste reduction (19%), coordination-cycle reduction (15%), and machine-time gains (11%). Implications suggest that organizations should prioritize digital-thread governance (release gates, revision propagation, audit trails) alongside fabrication-aware standardization to realize reliable cost efficiency from CNC-integrated optimization.

Keywords

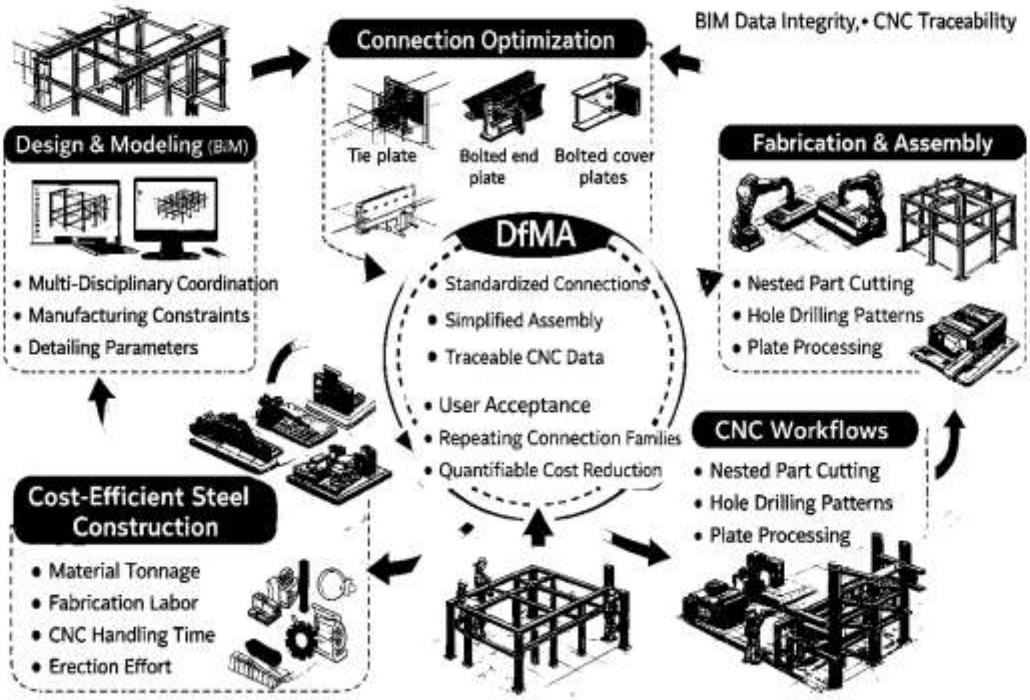
CNC Workflow Traceability; Fabrication-Driven Optimization; Steel Construction; BIM-To-Fabrication Integration; Cost Efficiency;

INTRODUCTION

Steel construction is commonly defined as the planning, design, fabrication, and erection of load-bearing systems where steel members and their connections constitute the primary structural skeleton of buildings and industrial facilities. In this context, structural optimization refers to the systematic selection of member sizes, connection configurations, and detailing rules to satisfy strength and serviceability requirements while minimizing a cost-related objective such as material tonnage, fabrication labor, welding time, or erection effort (Barlish & Sullivan, 2012). Cost-driven optimization becomes more meaningful when it includes connection behavior and constructability variables instead of treating joints as idealized pinned or rigid points. Research on semi-rigid behavior demonstrates that joint stiffness and base conditions significantly change both structural response and economic outcomes, which makes connection-aware optimization central to credible steel design decision-making. In parallel, fabrication-driven design is defined as an approach where manufacturing constraints—cutting, drilling, coping, welding access, tolerances, transport limits, and shop sequencing—are explicitly represented as upstream design parameters (Bel Hadj Ali et al., 2009). This approach aligns with the logic of Design for Manufacture and Assembly (DfMA), which connects design intent to production realities and treats manufacturing and assembly effort as first-class design variables rather than downstream corrections. The enabling technical infrastructure for fabrication-driven optimization increasingly relies on CNC-based workflows, where computer numerical control systems translate geometry, hole patterns, and part features into machine-executable instructions. For structural steel, CNC operations frequently include automated cutting, drilling, milling, plate processing, and robotic welding, which means that the information model must preserve not only geometry but also fabrication semantics, traceability fields, and validation logic (Bryde et al., 2013). Studies that formalize BIM semantics for digital fabrication show that a model must encode manufacturing-relevant attributes so that production can be automated without loss of meaning during file exchange. In international practice, steel supply chains operate across borders, and fabricated components are often produced in one country and erected in another; this creates a global need for interoperable, auditable data pipelines where design models and fabrication datasets remain aligned through revisions. Interoperability research highlights that the core difficulty is not only software compatibility, but also consistency of intent across disciplines and lifecycle stages (Camp et al., 2005). Within this global frame, cost-efficient steel construction is not only a firm-level objective but also a competitiveness and infrastructure-delivery issue, because schedule compression, labor scarcity, and quality accountability intensify the value of traceable CNC-integrated design-to-fabrication workflows (Csebfalvi, 2007).

A fabrication-driven optimization thesis also depends on how the research community defines BIM-enabled workflows and what counts as valid evidence of cost efficiency. BIM is commonly discussed as a shared digital representation of a built asset that supports multidisciplinary coordination, but empirical adoption research emphasizes that BIM benefits materialize only when collaboration protocols, decision rights, and data governance are aligned with technical modeling. Measurement studies show that benefits cannot be treated as universal constants because they vary by project type, contract setting, and maturity of implementation, so evidence needs structured metrics and explicit baselines rather than anecdotal claims (Degertekin & Hayalioglu, 2010). At the same time, BIM's value increases when the model is not merely a geometric reference but a production-ready dataset that supports quantity extraction, constructability checks, and manufacturing-grade detailing outputs. Interoperability studies addressing architectural–structural model exchange indicate that failures often originate from semantic mismatches and incomplete model views, which then propagate into clashes, redesign cycles, and shop drawing inconsistencies. For steel construction, these issues intensify because fabrication is detail-sensitive: bolt-hole positions, cope geometries, weld sizes, and connection plate thicknesses influence not only structural capacity but also CNC feasibility, shop throughput, and inspection complexity. Digital fabrication semantics research argues that manufacturing logic must be embedded so that model-to-machine translation preserves intent and reduces manual rework. This is also where DfMA literature becomes relevant, because DfMA frames a methodological bridge: it treats the downstream production system as part of the design problem, encouraging standardization, part count reduction, repeatable connection families, and minimized handling operations. Review-based evidence on DfMA in construction organizes prior work into implementation strategies and application pathways, positioning DfMA not as a single tool but as a discipline of decision-making across design and supply-chain interfaces (Farkas & Jármai, 2016). In international projects that integrate offshore fabrication, the need for repeatable CNC workflows becomes stronger because distributed teams require shared rule sets for constructability, revision control, and model integrity. Research on BIM benefits and adoption provides methodological justification for treating data traceability and governance as measurable constructs rather than informal "best practice" statements. These definitions motivate a research design where fabrication constraints and CNC workflow variables are explicitly operationalized and tested alongside traditional structural performance indicators (Succar, 2009).

Figure 1: BIM- and CNC-Integrated Fabrication-Driven Optimization Framework for Steel Construction



A central technical theme in fabrication-driven optimization is the relationship between structural form, connection design, and staged production costs. Cost-based optimization research shows that structural cost is not dominated solely by member weight; connection labor, fabrication complexity, and erection sequencing significantly influence total installed effort. Semi-rigid steel frame optimization studies quantify how including connection behavior changes optimal member sizing and can reduce total cost relative to rigid-joint assumptions, because stiffness can be distributed more efficiently across the frame (Gu & London, 2010). Production-oriented optimization research further decomposes costs into stages—material procurement, shop manufacturing, transport, erection, and sometimes foundation effects—and then uses metaheuristics to search for solutions that reduce overall production cost rather than a single proxy like tonnage. This staged view becomes especially relevant when CNC fabrication is included, because CNC throughput depends on machine time, tool changes, part nesting, drilling cycles, and weld preparation operations, all of which are sensitive to detailing choices. Studies comparing alternative objective functions for welded or fabricated steel elements show that a cost function that includes fabrication realities can yield different design decisions than a mass-only objective, particularly when welding and assembly dominate labor time (Gao et al., 2019). Related optimization research in steel frame design uses metaheuristics such as ant colony optimization and genetic algorithms to explore member sizing under design constraints, illustrating how computational search can efficiently navigate large discrete section sets. Importantly, decision-support framing research on moment-resisting steel frames emphasizes that the "best" design often depends on local labor and connection cost ratios, implying that regression-based modeling of cost outcomes can complement optimization by quantifying cost sensitivities and supporting interpretable hypotheses. This point aligns with fabrication-driven research because CNC-enabled costs often vary by shop capability, automation level, and standardization of connection families. In global steel supply chains, these ratios can vary by region, which strengthens the methodological need for case-study grounding combined with quantitative modeling. The research tradition that connects joint modeling, heuristic optimization, and production cost decomposition provides a defensible foundation for studying CNC-based design workflows as measurable drivers of cost efficiency (Lu et al., 2020).

This study is designed to achieve a set of tightly connected objectives that translate fabrication-driven structural optimization into measurable, testable constructs within CNC-based steel construction workflows. The first objective is to define and operationalize the core optimization dimensions that are most relevant to fabrication reality, including standardization of member and connection families, tolerance-aware detailing quality, material utilization efficiency through nesting-oriented part definition, and the degree to which shop-floor constraints are embedded into upstream design decisions. The second objective is to develop a structured measurement approach that captures CNC workflow integration quality as a quantifiable system property, using indicators such as the consistency of model-to-detailing information transfer, the stability of CNC file generation across revisions, the presence of auditable version control practices, and the completeness of fabrication semantics within the digital model. The third objective is to quantify perceived and project-linked cost-efficiency outcomes in steel construction by capturing respondent evaluations of cost drivers that are directly affected by CNC-based fabrication, including changes in fabrication labor-hours, machine utilization time, rework frequency, coordination cycle time, and overall cost predictability within the case study context. The fourth objective is to statistically test the relationships among fabrication-driven optimization practices, CNC workflow integrity, constraint compliance, and cost-efficiency outcomes using descriptive statistics to establish construct profiles, correlation analysis to identify the strength and direction of associations, and multiple regression modeling to determine which variables significantly predict cost-efficiency when controlling for professional role, experience level, and project complexity. The fifth objective is to design and compute study-specific trust indicators that strengthen empirical credibility by producing a CNC workflow traceability and data-integrity scorecard, a Fabrication Constraint Compliance Index that expresses manufacturability alignment as a composite metric, and a case-based cost impact decomposition that attributes cost variation to distinct mechanisms such as waste reduction, reduced manual handling, reduced rework, and improved fabrication planning stability. The final objective is to validate the statistical findings within a real case-study environment by aligning quantified survey patterns with observed workflow evidence and project documentation where available, ensuring that the study outputs remain grounded in the operational realities of CNC-enabled steel fabrication and are expressed in formats that can be interpreted by both engineering decision-makers and fabrication management stakeholders.

LITERATURE REVIEW

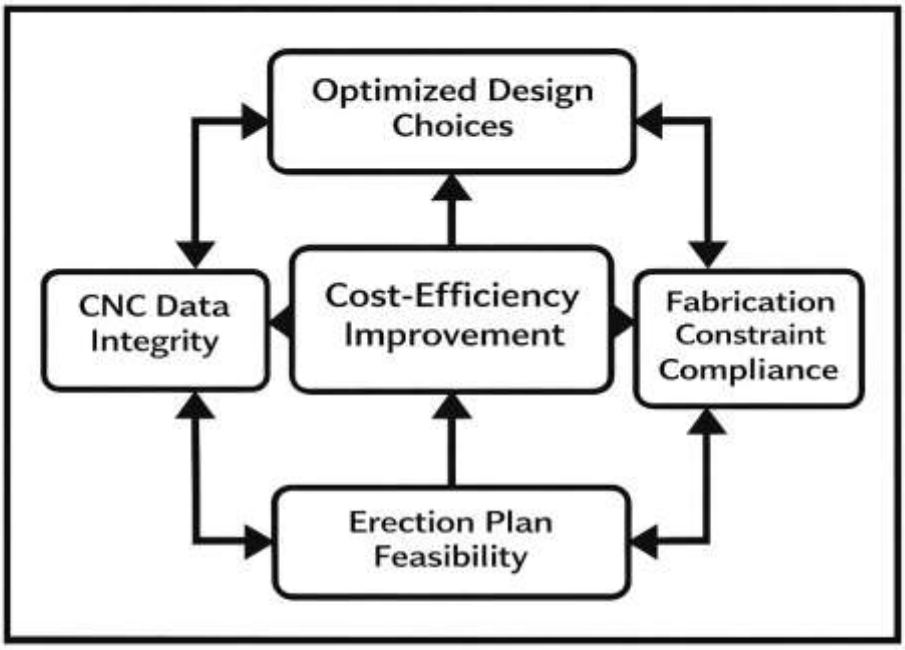
The literature on fabrication-driven structural optimization for cost-efficient steel construction spans several interrelated domains that must be synthesized to justify the variables, measurements, and analytical methods used in a CNC-based workflow study. A first stream establishes how "cost efficiency" in structural steel is multi-component and sensitive to fabrication and erection realities, because total installed cost is shaped not only by material weight but also by connection complexity, shop labor, machine time, transport constraints, and rework cycles; this stream motivates research designs that treat production effort as an explicit outcome rather than a secondary byproduct of structural sizing decisions. A second stream focuses on structural optimization methods for steel systems, including sizing, layout, and connection-aware optimization, and provides methodological precedents for defining objective functions, constraint sets, and solution strategies that move beyond purely theoretical minima toward feasible and buildable solutions; this stream also supports the logic of translating optimization practices into measurable "implementation factors" that can be captured through survey instruments in applied settings. A third stream examines design-for-fabrication and design-for-manufacture-and-assembly approaches in construction, emphasizing that upstream decisions about standardization, modularity, detailing rules, and assembly sequencing influence downstream productivity and error rates, which aligns directly with the study's fabrication-driven constructs and the need to quantify compliance with shop constraints. A fourth stream centers on CNC-based design-to-fabrication workflows and the interoperability of BIM, detailing, and fabrication systems, showing that reliable automation depends on data integrity, semantic completeness, version control, and traceability across revisions; this stream provides the foundation for introducing workflow traceability scorecards and data-integrity indicators as results components. A fifth stream addresses organizational and process perspectives on digital delivery, demonstrating that integration quality is shaped by governance, coordination routines, and feedback loops between design teams and fabrication shops, which supports modeling CNC workflow integration quality as a system-level predictor rather than a purely technical attribute. A final stream concerns measurement and validation methods in construction informatics and project delivery research, highlighting the importance of operational definitions, reliability testing for multi-item constructs, and triangulation between perception-based instruments and case documentation; this stream underpins the credibility strategy of combining Likert-scale measurement with case study validation and cost impact decomposition. Collectively, these research areas provide the theoretical and empirical basis for structuring a literature review that narrows from broad steel cost drivers and optimization theory to fabrication-aware constraints, CNC workflow semantics, and quantitative evaluation strategies that can support correlation and regression modeling within a cross-sectional case-study design.

Fabrication-Driven Cost Efficiency in CNC-Based Steel Workflows

Fabrication-driven cost efficiency in structural steel construction is commonly framed as an interaction between what is optimized in design and what must be executed on the shop floor and on site. Empirical work on rework has been especially influential in establishing that "cost" cannot be interpreted only as material quantity, because a large share of overruns emerges from avoidable repetitions of work, corrective fabrication, and downstream disruption to sequencing. In a well-cited cost-performance study, rework was operationalized as measurable additional effort beyond the original scope and then linked to cost growth through project-level data, providing a methodological precedent for treating rework-related effort as a quantifiable cost driver rather than a qualitative inconvenience (Hwang & Yang, 2014). For fabrication-driven optimization, this matters because many "optimal" structural solutions produce geometric and connection complexity that amplifies detailing time, increases the number of unique parts, and raises the likelihood of mismatches between design intent and fabrication reality. When CNC workflows are introduced, the sensitivity to data fidelity increases further: inaccurate attributes, inconsistent versioning, or incomplete connection semantics can trigger rework that is both digitally induced and physically realized, shifting costs from predictable machining time to unpredictable troubleshooting and repair. Accordingly, the literature motivates cost models that explicitly include (a) information quality costs (e.g., misaligned models and drawings), (b) process variability costs (e.g., stoppages and resequencing), and (c) quality deviation costs (e.g., scrap, re-drilling, re-welding). This framing supports the logic of your study's construct set, where fabrication-driven optimization is expected to reduce cost primarily by lowering the probability and magnitude of rework-triggering deviations, and where CNC traceability indicators are positioned as leading metrics that explain why some projects realize savings while others do not. In practical terms, the "cheapest" design on paper may become expensive when fabrication curves and coordination cycles are fully priced in.

Within fabrication-driven research, the pathway from design choice to realized cost is mediated by the visibility of process status and the speed at which deviations are detected. This makes digital monitoring and traceability central, not as general "project control" concepts, but as fabrication-specific mechanisms that reduce the latency between an error's creation and its correction. Steel fabrication projects often involve parallel workstations (cutting, drilling, fitting, welding, surface treatment) and shared resources that create queues and knock-on effects, so a single mis-specified connection or mislabeled member can propagate into multiple downstream reworks. A detailed framework for automated monitoring in steel fabrication demonstrated how automated as-built data acquisition and simulation-based assessment can support near-real-time corrective action in the fabrication phase, showing that the value of monitoring lies in shortening feedback cycles and enabling scenario testing before disruption compounds (Azimi et al., 2011).

Figure 2: Integrated Shop–Site Framework Linking Cnc Data Integrity, Fabrication Constraint Compliance, And Erection Plan Feasibility To Cost Efficiency



For CNC-based workflows, this logic extends to the integrity of the "digital thread": model-to-detail-to-machine data handoffs, revision control, and part identity continuity (marking, tracking, and installation confirmation). In your thesis context, these elements justify studying traceability as a measurable construct, because traceability can be operationalized through indicators such as version conformance rates, mismatch frequency between machine files and approved drawings, and audit completeness of member histories. Methodologically, the literature also encourages decomposing cost into shop hours, field hours, and disruption costs, since traceability improvements may reduce the latter two more strongly than raw machining time. This decomposition is particularly relevant for case-study settings where baseline productivity is already high, but hidden costs remain in troubleshooting and coordination. A fabrication-driven results model can therefore test whether traceability metrics explain variance in cost efficiency after controlling for project scale, connection density, and degree of customization, turning "workflow quality" into a statistically testable determinant of steel project economics across comparable steel project packages.

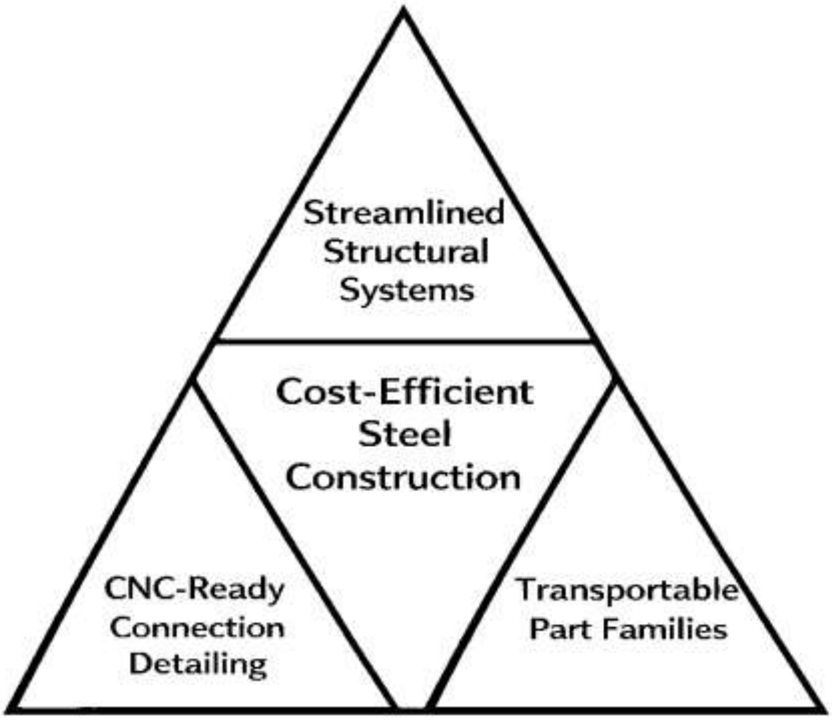
A complementary stream of research clarifies that cost drivers in steel work are not confined to fabrication, because erection feasibility and lift planning can retroactively alter fabrication priorities, packaging strategies, and the viability of "optimized" geometries. Erection is sensitive to spatial constraints, crane access, and collision avoidance, which means that constructability-oriented planning methods can reduce nonproductive time and rehandling, both of which translate into measurable cost penalties when plans are improvised late. In crane-oriented erection research, algorithmic path planning has been shown to reduce computation time while still generating safe and effective lift paths for both single- and dual-crane scenarios, reinforcing that planning quality can be formalized and improved through repeatable methods rather than relying only on tacit experience (Chang et al., 2012). Similarly, erection automation studies have modeled erection operations as structured planning problems in which optimized sequences and uncertainty-aware duration estimates reduce variability in field execution, providing evidence that algorithmic planning can support consistent performance under real site constraints (Yoo et al., 2012). These insights align with fabrication-driven structural optimization because the best cost outcomes arise when member segmentation, connection detailing, tolerances, and delivery bundles are selected with erection logic in mind, enabling smoother installation and reducing the probability that fabricated components require on-site modification. At the same time, broader construction evidence shows that rework incidence can affect schedule outcomes and organizational performance, indicating that schedule impacts represent an additional cost pathway through extended overheads and resource conflicts (Hwang et al., 2009). For your study, this suggests a literature-grounded argument that fabrication-driven optimization must be evaluated as a coupled shop–site system, where CNC data integrity, fabrication constraint compliance, and erection plan feasibility jointly shape the cost-efficiency realized in the case project and reflected in the statistical relationships you will test. This coupling provides a basis for hypothesis specification.

CNC-Connected Fabrication Logic in Steel Construction

Design for Manufacture and Assembly (DfMA) translates the logic of factory production into construction decision-making by treating design outputs as inputs to cutting, welding, drilling, handling, and site assembly operations. Within fabrication-driven steel optimization, DfMA is relevant because a large share of project cost and schedule risk is generated not by member sizing alone, but by connection detailing, part multiplicity, shop routing, and the work packaging that converts digital models into CNC instructions. Evidence from practice-oriented case research shows that when DfMA is used as an explicit delivery strategy, teams can rationalize structural systems into repeatable assemblies, reduce interfaces between trades, and shift labor from constrained site conditions to controlled fabrication environments. A UK high-rise case illustrates how DfMA was operationalized through integrated digital engineering and coordinated off-site solutions across superstructure and envelope packages, emphasizing standardization and logistics-aware detailing as mechanisms for program and cost certainty (Banks et al., 2018). For steel-intensive projects, this orientation reframes "optimality" as a multi-attribute outcome that balances structural performance with manufacturability and assemblability. It also highlights why CNC-based workflows cannot be treated as a downstream documentation step; rather, CNC readiness becomes a design variable shaped by part families, hole patterns, cope and weld access, and transport constraints. In this framing, fabrication-driven optimization requires metrics that can translate shop-floor realities into analyzable constructs suitable for quantitative modeling, such as perceived ease of assembly, part handling complexity, and expected rework likelihood. When these constructs are embedded in survey instruments, they support statistical testing of hypotheses about how fabrication-oriented design decisions influence cost efficiency and delivery performance, while remaining traceable to real production mechanisms. In steelwork, even small detailing choices influence jigging, tolerance management, and inspection effort, so optimization must also account for dimensional consistency and quality checkpoints that govern whether parts flow smoothly through shop stations.

Operationalizing DfMA for quantitative study often relies on digital environments that connect geometry, metadata, and production rules. One approach is to embed DfMA guidelines into parametric building information models so that designers can explore alternatives while preserving manufacturing constraints and assembly logic. A representative method integrates DfMA with BIM-based parametric design to reduce component variety, minimize connection types, and formalize "mistake-proof" assembly principles as model-driven rules, thereby increasing the likelihood that design intent is realized without late-stage fabrication conflicts (Anick & Tasnim, 2022; Md. Mosheur & Rebeka, 2021; Yuan et al., 2018). In parallel, BIM-centered decision systems have been proposed to evaluate assembly efficiency using production-informed criteria rather than purely geometric checks. A BIM-based optimizer for assembly, for example, operationalizes attributes such as ease of handling, speed of assembly, and assembly waste, aggregates them using multi-criteria logic, and enables comparison among alternative envelope or component options directly within a BIM workflow (Faysal & Shamsunnahar, 2022; Gbadamosi et al., 2019; Habibullah & Zaheda, 2022). For steel construction, these ideas generalize to member and connection design by encouraging early quantification of handling weights, fastener counts, splice repetition, and shop operation counts, which can be mapped to CNC drill lines and nesting plans. The implication for fabrication-driven structural optimization is that construct-level measures can be derived from model parameters and validated through case-study evidence, then used as independent variables in correlation and regression models. Such integration also supports traceability, because decisions can be audited back to parametric families, rule sets, and data exchanges that generate CNC-ready outputs. Methodologically, these digital-to-fabrication linkages matter because they allow researchers to triangulate survey responses with extracted model quantities, reducing common-method bias. They also clarify unit-of-analysis choices, distinguishing component-level decisions from whole-project delivery strategies. Finally, parametric constraints can encode supplier-specific hole diameters, plate thickness ranges, and machine bed limits, which helps ensure that "optimized" designs are feasible within a given fabrication ecosystem in real projects.

Figure 3: Dfma-Based Cnc Fabrication Logic Framework For Steel Construction



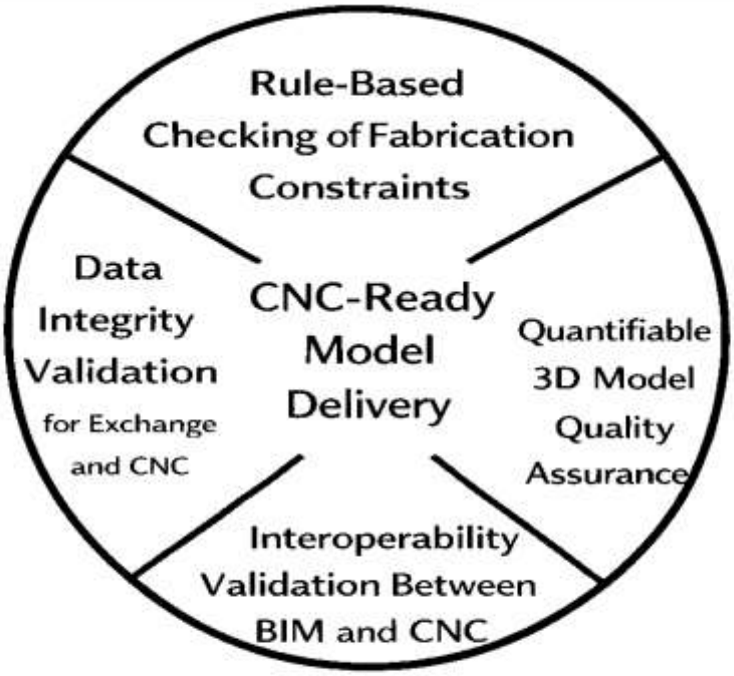
A complementary stream focuses on formal manufacturability assessment models that convert design attributes into comparable scores, enabling the statistical study of trade-offs among competing objectives. In manufacturing research, multi-criteria evaluation has been used to identify product-realization opportunities for cost reduction when classical DFM techniques are difficult to apply broadly, emphasizing structured scoring and aggregation as a practical way to inject process knowledge into early design (Das & Kanchanapiboon, 2010; Md Abubakar Siddique & Md. Al Amin, 2022; Md & Islam, 2022). Translating this logic to steel construction supports the creation of fabrication-aware indices that can be measured through Likert-scale items and linked to objective project outcomes such as cost variance or rework rates. Sustainability-oriented design assessment tools extend the same scoring logic by evaluating downstream recoverability and material waste potential from BIM information. A BIM-based deconstructability assessment score, for instance, operationalizes design principles that influence disassembly and waste minimization, demonstrating how BIM can act as a carrier for lifecycle-relevant construct measures rather than only a coordination model (Akinade et al., 2015). For fabrication-driven steel optimization, these assessment approaches motivate the definition of indices that are specific to CNC fabrication, such as drill/cope standardization, weld-access feasibility, and transportable module size compliance. When combined with a case-study dataset, such indices provide a defensible bridge between subjective perceptions captured via surveys and the objective constraints embedded in CNC workflows, supporting hypothesis testing that is both empirically grounded and methodologically transparent. In quantitative designs, these indices can be operationalized as reflective constructs, tested for internal consistency, and then related to cost outcomes using regression while controlling for project scale or complexity. This linkage strengthens construct validity by aligning measurement items with CNC artifacts such as NC file counts, revision cycles, and shop change orders. For steel case studies, documenting how each index is computed from model parameters improves reproducibility and supports review of the measurement logic.

BIM-to-Fabrication Integration in Steel Construction

CNC-based steel construction workflows can be defined as digitally mediated pipelines in which design intent is encoded into machine-readable instructions for cutting, drilling, marking, and welding operations, with minimal manual reinterpretation between design and shop-floor execution. In practice, this pipeline relies on the continuity of product and process information across authoring tools, coordination environments, and fabrication systems. The literature positions Building Information Modeling (BIM) and neutral exchange standards as key enablers of this continuity, because CNC fabrication demands not only geometry but also stable identifiers, tolerances, attributes, connection logic, and fabrication semantics that remain consistent as models move across disciplines and software. A central concern is that fabrication-driven decisions—such as hole patterns, part sequencing, weld types, and assembly constraints—are sensitive to small translation errors, making information integrity a governing requirement rather than a secondary quality check. Research on automated rule-based checking provides a structured foundation for understanding how models can be interrogated for completeness, consistency, and conformance to formally defined requirements. (Md. Mosheur & Rebeka, 2022) frame automated checking as a response to growing complexity in digitally authored designs, emphasizing that rule-checking systems depend on computable representations of objects, relations, and attributes to validate whether a design satisfies intended constraints (Eastman et al., 2009). When this perspective is applied to CNC-oriented steel workflows, automated checking becomes directly linked to fabrication viability because the "rules" can represent not only regulatory constraints but also shop capability constraints, data exchange requirements, and machine-level preconditions. This view supports the idea that BIM-to-CNC is not merely a file transfer problem; it is a verification problem in which model data must be demonstrably "fabrication-ready" through systematic checks prior to manufacturing release.

A closely related stream of research examines interoperability validation as the operational bridge between BIM coordination and CNC execution. Interoperability in fabrication contexts is often challenged by heterogeneous mappings between native BIM schemas and neutral exchange formats, which can introduce unintended geometric transformations, missing semantics, or inconsistent attribute structures. Lee et al. (2015) categorize validation tasks into syntax checking (schema compliance), semantic/syntactic checking against model view definitions, and programmatic requirement validation, offering a layered approach that matches how fabrication-driven steel projects move from modeling to coordination to shop detailing. From a CNC workflow standpoint, this layered validation is valuable because it separates "can the file be read" from "does the file mean the same thing" and finally from "does the file satisfy project- and shop-specific requirements." The CNC orientation adds a practical twist: the cost of failure is immediate and physical, appearing as rework, scrap, machine downtime, and schedule disruption. In this context, rule sets become proxies for fabrication intent—capturing requirements such as connection detail completeness, member orientation consistency, part naming conventions, and attribute presence needed for downstream CAM routines (Lee et al., 2015; Md. Shahinur & Md. Sultan, 2022; Mostafa & Md Tohidul, 2022). Lee et al. (2018) advance this reasoning by formalizing logic for ensuring data exchange integrity, treating integrity as something that can be evaluated through explicit conditions rather than assumed through software compatibility. Their integrity lens aligns strongly with fabrication-driven optimization because design-for-fabrication decisions often rely on derived quantities (e.g., cut lengths, weld volumes, hole counts) whose reliability depends on consistent upstream semantics. When integrity is treated as measurable, a steel project can justify CNC release gates using evidence rather than informal confidence, improving traceability between what was designed, what was coordinated, and what was physically produced (Lee et al., 2018).

Figure 4: Information Governance Framework For Cnc-Ready Bim-To-Fabrication Workflows In Steel Construction



Beyond integrity assurance, CNC-based workflows also require robust and quantifiable methods to assess the "quality" of exchanged IFC-based product models, because fabrication readiness depends on both correctness and completeness of the data representation. Solihin et al. (2015) propose automated IFC quality validation as a way to move from ad hoc inspection to quantifiable assessment supported by well-defined rules. For steel fabrication contexts, this contributes a practical idea: model quality can be audited against rule libraries that reflect recurring fabrication and exchange requirements, enabling consistent acceptance testing when models are handed from design teams to fabricators (Solihin et al., 2015). This is particularly relevant where fabrication-driven structural optimization is pursued, since optimization outputs must remain verifiable as they propagate through the pipeline; otherwise, the optimized design can lose its economic advantage through translation-induced rework. The same principle is visible in research that directly integrates BIM standards with shop-floor robotic operations. Tavares et al. (2019) demonstrate a collaborative welding system in which information extracted from IFC supports human–robot task orchestration and robotic pose planning, showing how BIM-based information flow can reduce reliance on error-prone manual measurement and interpretation. While their focus is welding automation, the broader implication for CNC-based steel construction is that fabrication systems increasingly expect upstream digital descriptions rich enough to support autonomous or semi-autonomous execution (Tavares et al., 2019). Therefore, the literature collectively supports a CNC-centric interpretation of BIM-to-fabrication integration: (a) rule-based checking frameworks establish how fabrication constraints can be encoded and verified (Eastman et al., 2009); (b) interoperability validation models provide staged assurance from schema conformance to project requirement satisfaction (Lee et al., 2018); (c) integrity logic strengthens the evidentiary basis for trusting exchanged models in downstream computation and manufacturing (Lee et al., 2015); (d) quantifiable IFC quality validation offers repeatable acceptance criteria for exchanged product models (Solihin et al., 2015); and (e) BIM-driven robotic fabrication prototypes illustrate how enriched data flow can directly control fabrication operations (Tavares et al., 2019). Together, these works justify treating CNC-based design workflows as an information-governance problem as much as a modeling problem, where fabrication-driven structural optimization is only dependable when the digital thread remains verifiable at each handoff.

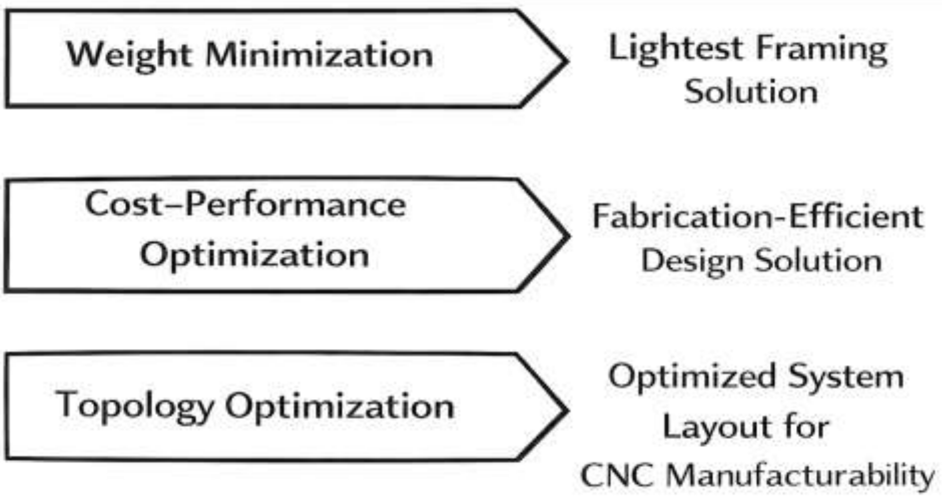
Cost–Performance Tradeoffs in Fabrication-Efficient Steel Systems

Fabrication-driven structural optimization requires the steel design problem to be framed as a cost–performance tradeoff rather than a single-objective weight-minimization exercise. In practice, "efficiency" is rarely equivalent to "lightest frame," because construction value is produced through a chain of operations—cutting, drilling, welding, bolting, shop handling, transport, and erection—whose time and error sensitivity can outweigh marginal savings in member tonnage. This reality is central to CNC-based design workflows, where detailing logic, connection standardization, and part traceability directly influence whether an optimized geometry can be manufactured reliably at scale. Research on structural optimization has long shown that metaheuristic solvers can navigate discrete steel tables and nonlinear constraints effectively, enabling designers to explore large combinatorial spaces that are otherwise infeasible to search manually. For example, particle swarm optimization has been demonstrated as a practical approach for constrained structural design, particularly in discrete sizing problems where objective landscapes are discontinuous and heavily constrained by serviceability limits (Perez & Behdinan, 2007). In steel frame contexts, harmony-search–based formulations similarly highlight that optimization performance is strongly affected by how the algorithm "learns" from feasible designs under drift and strength constraints, emphasizing the operational importance of constraint-handling for real projects (Degertekin, 2008). These algorithmic insights become more relevant under CNC workflows because feasible designs are not only those that pass code checks, but also those whose member/connection patterns remain stable enough to be detailed and fabricated with minimal rework.

A fabrication-centered cost lens becomes even more essential when the structural system includes alternative connection types and bracing strategies. Framework selection decisions change the number of unique part geometries, the density of gusset or end-plate details, the repetitiveness of hole patterns, and the erection sequence complexity—all of which translate into labor and schedule impacts. A key contribution in this area is the demonstration that minimum weight designs can be systematically different from minimum cost designs once fabrication and erection activities are explicitly represented in the objective function. Cost-efficiency analysis for multi-storey buildings shows that evaluating steel systems through production-stage cost models can meaningfully change which framework configuration is "best," since connection detailing and bracing topology drive cost components that weight-based proxies omit (Hasançebi, 2017). This shift is highly aligned with CNC-based workflows, where the value of repeating connection templates and standardized features can be quantified as reduced setup time, fewer tool changes, and lower probability of shop-floor errors. Complementary research comparing non-deterministic search techniques for real-size steel frames also reinforces that algorithm choice matters because practical design spaces are large, constraint-dense, and sensitive to how search strategies converge under drift-governed scenarios (Hasançebi, 2017). For fabrication-driven studies, this implies that optimization should be evaluated not only by its final objective value but also by the stability and reproducibility of its solutions—an issue that becomes critical when CNC toolpaths, part IDs, and revision control must remain coherent through design changes.

Beyond sizing and system selection, fabrication-efficient optimization increasingly depends on topology decisions that determine where structural material is placed and how lateral systems are arranged. In CNC-compatible steel construction, topology is not an abstract layout problem: it defines how many bracing members must be cut, how many connection nodes must be drilled, how many gusset plates must be nested and welded, and how erection tolerances accumulate across bays. A performance-based discrete topology approach is particularly relevant to this study because it outputs bracing configurations that are directly actionable—members are kept or removed from candidate sets—while also checking seismic or lateral performance through nonlinear assessment embedded in the optimization loop (Gholizadeh & Ebadijalal, 2018).

Figure 5: Directional Framework Of Cost–Performance Tradeoffs In Cnc-Aligned Fabrication-Efficient Steel Systems

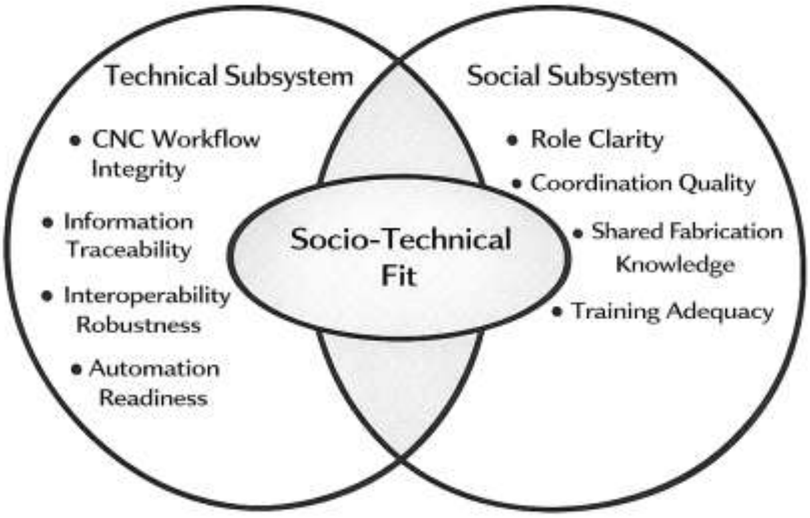


This discrete, implementation-oriented framing matches CNC workflows where designs must map cleanly to fabrication instructions and shop drawings. When combined with evidence that different metaheuristics vary in robustness and computational efficiency on large frame problems (Hasançebi et al., 2010), the literature supports a methodological rationale for embedding fabrication constraints into optimization objectives and constraints rather than treating constructability as a post-processing step. In short, fabrication-driven structural optimization is most defensible when it simultaneously (1) models production-stage cost drivers, (2) respects code and serviceability performance, and (3) maintains CNC traceability through standardized, repeatable detailing patterns that reduce manufacturing variability.

Socio-Technical Systems (STS) in CNC Steel Construction

Fabrication-driven structural optimization in CNC-based steel construction can be most coherently explained through a **socio-technical systems (STS)** lens, because project performance emerges from the alignment between technical capabilities (digital models, CNC toolchains, interoperability routines, traceability controls) and the social system that operates them (roles, skills, coordination norms, governance, and learning). Socio-technical systems engineering emphasizes that systems should be designed and evaluated as coupled configurations of people, tasks, structure, and technology, with performance and acceptability depending on how these elements are jointly tuned rather than optimized in isolation (Baxter & Sommerville, 2011). This is directly relevant to CNC-driven design workflows: a fabrication-ready model is not only a geometric artifact, but also the output of a coordinated production process involving designers, detailers, fabricators, and site teams who must interpret and act on consistent identifiers, revision histories, and manufacturability constraints. Empirical BIM implementation research supports this view by showing that BIM-enabled delivery behaves as a socio-technical change program in which technical upgrades do not reliably yield benefits unless organizational routines and cross-disciplinary practices evolve in parallel (Sackey et al., 2015). In your study context, STS fit explains why two projects with similar CNC tools can realize different cost outcomes: differences often reside in whether the project's collaboration structure, decision rights, and verification checkpoints reinforce the technical "digital thread" or allow fragmentation (e.g., ad hoc revisions, inconsistent part naming, or incomplete fabrication semantics). Consequently, STS offers a defensible theoretical basis for your hypotheses that fabrication-driven optimization and CNC workflow integrity influence cost-efficiency not merely through better structural designs, but through improved alignment between the optimization outputs and the way information is produced, checked, released, and consumed across the steel supply chain.

Figure 6: Socio-Technical Systems Framework For Fabrication-Driven Optimization In Cnc Steel Construction



To operationalize STS in a quantitative, cross-sectional case-study setting, the framework should be translated into measurable constructs that map to your planned indices (traceability scorecard, fabrication constraint compliance, cost decomposition). The STS "technical subsystem" can be represented by constructs such as CNC workflow integrity, information traceability, interoperability robustness, and automation readiness—all of which describe the reliability of transferring design intent into CNC-ready outputs. The STS "social subsystem" can be represented by constructs such as role clarity, coordination quality, shared fabrication knowledge, training adequacy, and governance discipline (e.g., how revision control and approval gates are enforced). Case-based evidence from BIM deployment in complex hospital projects illustrates that effective digital collaboration depends on adoption factors that are simultaneously technical (open-BIM routines, model standards, exchange practices) and organizational (coordination mechanisms, managerial sponsorship, and shared working norms), reinforcing that "digital performance" is an emergent property of the combined system (Merschbrock & Munkvold, 2015). At the operational level, BIM adoption work in lean architectural practice similarly shows that benefits require a structured implementation approach with guidelines and process adaptations, not only software installation (Arayici et al., 2011). Together, these studies justify modeling CNC-based steel delivery as a socio-technical configuration in which fabrication-driven optimization becomes effective when the organization can repeatedly convert optimized design decisions into stable, machine-actionable instructions. This translation into constructs supports your planned descriptive statistics (to profile technical and social readiness), correlations (to identify alignment patterns), and regression modeling (to test which subsystem elements significantly predict cost-efficiency outcomes under case-study conditions).

A useful way to represent STS "alignment" quantitatively—and to anchor the study's most reusable formula—is to compute a Socio-Technical Fit Index (STFI) and use it as a predictor (and interaction proxy) in regression models of cost-efficiency. Let T denote the composite mean score for the technical subsystem (e.g., averaged Likert means across CNC workflow integrity, traceability, interoperability indicators), and let S denote the composite mean score for the social subsystem (e.g., averaged Likert means across coordination, role clarity, training, governance). Because both are measured on a 1–5 scale, a normalized fit metric can be defined as:

$$\mathrm{STFI} = \frac{T \times S}{25}$$

where STFI ∈ [0.04,1.00], and higher values indicate stronger joint readiness rather than isolated strength. This formulation is consistent with STS logic because it penalizes imbalance: a high T with low S (or vice versa) yields a lower fit score than balanced improvement. To test hypotheses, the core predictive relationship for perceived or case-linked cost efficiency (CE) can be modeled as a multiple regression that incorporates STS fit explicitly:

$$CE = \beta_0 + \beta_1(\text{FDSO}) + \beta_2(\text{FCCI}) + \beta_3(\text{STFI}) + \beta_4 X + \varepsilon$$

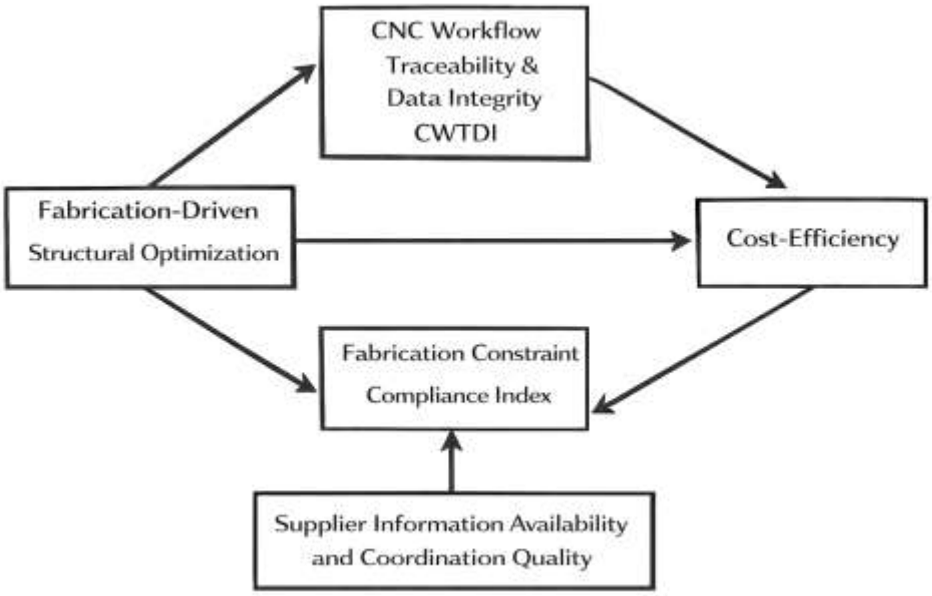
where FDSO is the fabrication-driven structural optimization construct, FCCI is the fabrication constraint compliance index, and X represents controls such as experience, role, and project complexity. If you want a stricter STS interaction test, you can also include T, S, and the interaction term $T \times S$ to evaluate whether alignment produces a synergistic effect beyond additive contributions. This choice is theoretically supported by human-factors STS frameworks that conceptualize outcomes as functions of interacting work-system components and adaptation processes rather than single-variable causation (Holden et al., 2013). In sum, STS provides the overarching explanatory model for why CNC-based fabrication success depends on joint optimization of technology and organization, while the STFI and interaction-based regression offer a practical, study-wide quantitative mechanism to test that proposition within your survey-and-case design.

Conceptual Framework and Hypothesis Development

The conceptual framework for this study formalizes how fabrication-driven structural optimization becomes “cost-efficient” only when CNC-based design workflows reliably translate design intent into manufacturable and erectable steel components. In this framework, the dependent construct is Cost-Efficiency (CE), defined as a multi-item outcome capturing perceived reductions in fabrication/erection cost drivers such as rework, shop labor-hours, machine-time variability, and coordination cycle time. The key independent construct is Fabrication-Driven Structural Optimization (FDSO), representing the extent to which structural sizing and detailing decisions are made with explicit fabrication constraints (standardized part families, connection rationalization, tolerance-aware detailing, and CNC readiness). Two pipeline constructs function as mechanisms that explain why FDSO becomes economically meaningful in practice: CNC Workflow Traceability & Data Integrity (CWTDI) and the Fabrication Constraint Compliance Index (FCCI). CWTDI captures whether design-to-detail-to-CNC handoffs preserve identifiers, versions, approvals, and fabrication semantics across revisions; FCCI captures the degree to which the design complies with shop capabilities and preferred fabrication rules (hole tolerances, standard plate/member ranges, allowable operations, and manual intervention requirements). The conceptual logic is that FDSO influences CE directly (through reduced complexity and better manufacturability choices) and indirectly through improved workflow integrity and compliance. The “system” nature of the framework is reinforced by evidence that BIM/CNC performance depends on alignment between tool capability and management routines, meaning that traceability is not merely technical but also procedural (Hartmann et al., 2012). At the organizational boundary level, collaboration quality and the way digital artifacts are interpreted across teams affects whether optimized designs remain consistent when transformed into shop deliverables, which supports positioning CWTDI as a pathway variable rather than background context (Papadonikolaki & Wamelink, 2019). Consequently, the conceptual framework treats CNC-connected fabrication efficiency as an outcome of both design choices (FDSO) and the integrity of the digital thread (CWTDI) and constraint compliance (FCCI).

To make the framework statistically testable within a cross-sectional, Likert-based case design, each construct is operationalized as a composite score derived from multiple questionnaire items, supported by reliability testing and traceable mapping to CNC workflow artifacts. The literature on metric-based BIM assessment provides a methodological precedent for defining measurable indicators of implementation maturity and performance using structured metric families, which supports building CWTDI as a measurable construct rather than a narrative descriptor (Abdirad, 2016). Similarly, BIM maturity and critical success factor work motivates the use of structured dimensions (e.g., governance, process control, and information standards) that can be measured through survey items and compared across projects or teams (Morlhon et al., 2014).

Figure 7: Research Model And Hypothesized Relationships For Fabrication-Driven Optimization In Cnc Steel Workflows



In this study, CWTDI can be calculated as a normalized average of subdimensions such as version control discipline, identifier continuity, auditability of revisions, and completeness of fabrication semantics. A practical index form consistent with 5-point Likert measurement is:

$$\mathrm{CWTDI} = \frac{1}{k}\sum_{j=1}^{k} \bar{x}_j$$

where $\bar{x}_j$is the mean score of subdimension j, and $k$is the number of traceability subdimensions. FCCI can be computed similarly as a manufacturability alignment score derived from fabrication-constraint items (e.g., standard hole patterns, preferred member lengths, minimized custom connections, reduced manual intervention). Because FCCI is intended to represent "compliance strength," a normalized index that scales to [0, 1]is useful for regression comparability:

$$\mathrm{FCCI} = \frac{\sum_{i=1}^{m} w_i \ \bar{c}_i}{5\sum_{i=1}^{m} w_i}$$

where $\bar{c}_i$is the mean score for compliance factor i(1–5 scale), and $w_i$are optional weights (equal weights if not justified otherwise). This index formulation fits CNC steel contexts because it supports both equal-weight "baseline" scoring and sensitivity analysis through weights when case evidence indicates certain constraints dominate feasibility. CE can also be normalized using the same logic if the research needs to compare effect magnitudes across constructs. The result is a coherent measurement model that links survey indicators to constructs that are conceptually grounded in BIM/CNC assessment traditions while remaining specific to fabrication-driven optimization (Thunberg & Persson, 2020).

Based on the conceptual and operational definitions, hypotheses are developed to test direct effects, mechanism effects, and a coupled "supply-chain information" effect that is particularly relevant to CNC steel production. The primary direct-effect hypotheses are: H1: FDSO positively predicts CE; H2: CWTDI positively predicts CE; and H3: FCCI positively predicts CE. Mechanism hypotheses reflect the study's fabrication logic: H4: FDSO positively predicts FCCI (i.e., fabrication-aware optimization increases constraint compliance), and H5: FDSO positively predicts CWTDI (i.e., fabrication-driven practice increases attention to traceability, auditability, and release discipline). Because CNC-based steel construction often spans multiple organizations, an additional hypothesis captures the information availability condition across the supply chain: H6: Supplier information availability and coordination quality positively predict CWTDI and, indirectly, CE, because reliable input information (lead times, capability limits, preferred standards) stabilizes the digital thread and reduces revision churn (Papadonikolaki & Wamelink, 2019). These hypotheses can be tested through correlation and multiple regression. A core predictive model aligned to the thesis analysis plan is:

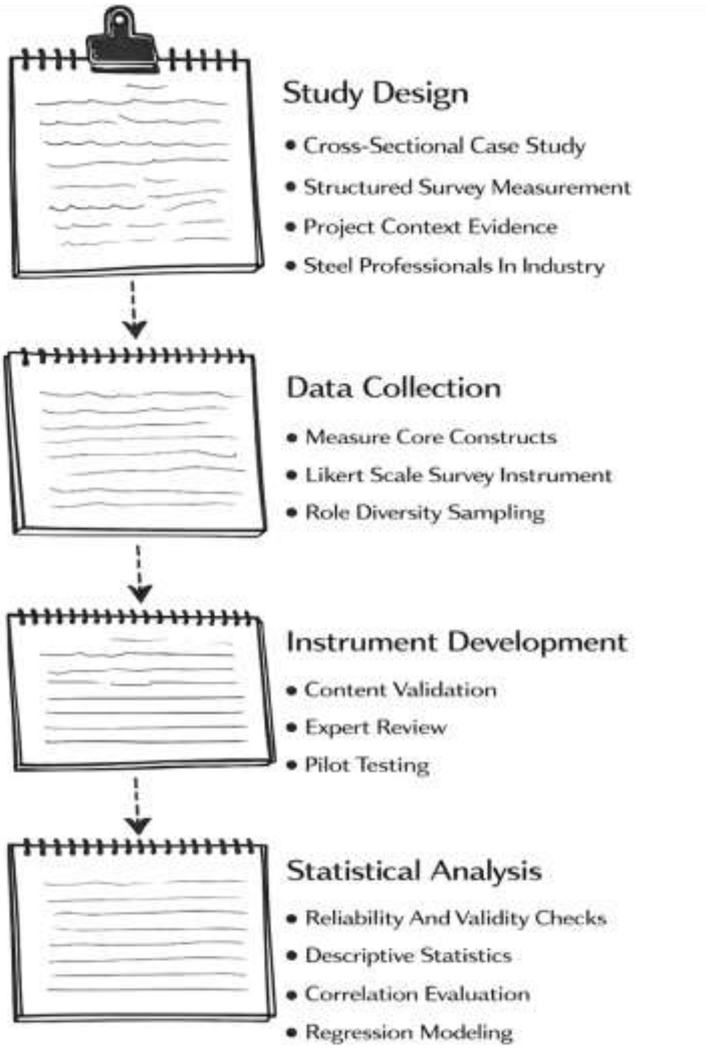
$$CE = \beta_0 + \beta_1(\text{FDSO}) + \beta_2(\text{CWTDI}) + \beta_3(\text{FCCI}) + \beta_4 X + \varepsilon$$

where Xrepresents controls such as respondent experience, role, and project complexity. If mediation is evaluated, FCCI and/or CWTDI can be modeled as mediators between FDSO and CE, consistent with the conceptual logic that design optimization produces savings when it is translated reliably and compliantly into CNC fabrication outputs. Finally, because boundary management and interpretive alignment shape whether digital artifacts “mean the same thing” across communities, the framework treats collaboration structure as a stabilizing context for traceability and compliance rather than a generic organizational variable, strengthening the study’s claim that fabrication-driven optimization is a socio-organizational and technical system outcome (Thunberg & Persson, 2020).

METHODS

This methodology chapter has presented the research strategy adopted to examine fabrication-driven structural optimization techniques for cost-efficient steel construction within CNC-based design workflows. The study has employed a **quantitative, cross-sectional, case-study–based** design that has combined structured survey measurement with project-context evidence to ensure that statistical findings have remained grounded in real fabrication and delivery conditions. A case study context has been selected to represent an active or recently completed steel construction environment in which CNC-supported fabrication processes have been used for cutting, drilling, and related shop operations, and where digital model handoffs have occurred between design, detailing, and fabrication teams. Within this setting, the study has defined the unit of analysis as industry professionals who have directly participated in CNC-oriented steel delivery activities, including structural engineers, BIM modelers, steel detailers, fabrication supervisors, CNC operators, quality inspectors, and project managers. A purposive sampling approach has been used to target respondents with demonstrable exposure to CNC-based steel workflows, and survey administration has been structured to capture role diversity and variability in project complexity, enabling robust comparisons across respondent profiles. The data collection process has been organized around a Likert five-point instrument that has measured core constructs aligned with the conceptual framework, including Fabrication-Driven Structural Optimization, CNC Workflow Traceability and Data Integrity, Fabrication Constraint Compliance, and Cost-Efficiency outcomes. Each construct has been operationalized through multi-item scales that have captured both technical workflow characteristics (such as revision-control discipline, identifier continuity, and fabrication semantics completeness) and process characteristics (such as coordination routines, feedback integration, and compliance with shop capability limits). Instrument development has been supported through content validation and expert review to ensure that items have reflected steel fabrication realities and CNC execution requirements. A pilot test has been conducted to refine item wording, remove ambiguity, and confirm response usability before full deployment. Reliability and validity procedures have been integrated into the analysis plan, and internal consistency has been evaluated through Cronbach’s alpha prior to hypothesis testing. The statistical analysis has been conducted using descriptive statistics to profile constructs, Pearson correlation to evaluate bivariate associations, and multiple regression modeling to determine significant predictors of cost-efficiency while controlling for respondent and project characteristics. Throughout the methodology, the study has maintained traceability between constructs, measurement items, and the case-study context so that conclusions have remained verifiable and reproducible within comparable CNC-enabled steel construction environments.

Figure 8: Research Design And Analytical Procedure For Examining Fabrication-Driven Optimization In Cnc-Based Steel Construction



Research Design

This study has adopted a quantitative, cross-sectional, case-study–based research design to examine fabrication-driven structural optimization for cost-efficient steel construction within CNC-based workflows. The design has combined a structured questionnaire survey with case-context documentation to ensure that statistical patterns have remained grounded in real project conditions. A cross-sectional approach has been used to capture participants' assessments at a single time window, which has enabled comparison across roles and workflow maturity levels without introducing time-dependent confounding. The case-study orientation has been used to anchor constructs in a specific CNC-enabled steel delivery environment, which has strengthened interpretability by linking survey measures to observable workflow artifacts. The research design has been aligned with the proposed conceptual model and hypotheses, and it has supported descriptive statistics, correlation testing, and regression modeling as the primary analytical methods. The design has emphasized measurable constructs that have represented both design practices and fabrication execution realities.

Case Study Context

A steel construction case setting has been selected where CNC-supported fabrication processes have been routinely used for cutting, drilling, and related shop operations and where digital model handoffs have occurred across design, detailing, and fabrication functions. The case context has been treated as the operational environment within which fabrication-driven optimization practices have been implemented and evaluated. Project characteristics have been documented to describe the steel scope, connection density, level of customization, and the extent of CNC integration across the supply chain.

The case has been used to contextualize workflow traceability by referencing common artifacts such as revision logs, shop drawing approval cycles, fabrication release packages, and change coordination records where access has been feasible. This contextualization has ensured that constructs such as data integrity and fabrication constraint compliance have remained interpretable in relation to actual production requirements and not only as abstract perceptions. The case setting has therefore provided a consistent reference frame for analysis and validation.

Population and Unit of Analysis

The study population has consisted of professionals who have directly participated in CNC-oriented steel construction delivery processes and who have held roles that influence design-to-fabrication translation. Participants have included structural engineers, BIM modelers, steel detailers, fabrication managers, CNC operators, quality inspectors, and project or construction managers. The unit of analysis has been defined as the individual respondent, because each participant has provided role-based assessments of fabrication-driven design practices, workflow integrity, and cost-efficiency outcomes within the case context. Respondents have been required to have practical exposure to steel detailing or fabrication coordination to ensure informed responses on CNC readiness and manufacturability constraints. The population definition has enabled measurement of variability in practice maturity, coordination discipline, and traceability behavior across different functional positions. This unit-of-analysis choice has supported statistical testing using independent and dependent construct scores derived from Likert-scale measurements while allowing control for role and experience attributes.

Sampling Strategy

A purposive sampling strategy has been used to recruit respondents who have possessed direct experience with CNC-based steel workflows and fabrication-driven coordination activities. This approach has been selected because the constructs under study have required informed evaluation of fabrication constraints, CNC deliverables, and design-to-shop data handoffs, which has not been reliably available in general construction populations. Sampling has been complemented by convenience-based recruitment through accessible professional networks and project-linked contacts to increase response volume while maintaining relevance. Inclusion criteria have required respondents to have participated in at least one steel project where CNC fabrication has been used and where model-to-detailing or detailing-to-fabrication exchanges have occurred. Efforts have been made to capture diversity across functional roles and experience levels so that construct variability has been sufficient for correlation and regression analysis. The sampling strategy has therefore balanced practical access with methodological appropriateness for a specialized workflow domain.

Data Collection Procedure

Data collection has been conducted through a structured questionnaire administered to eligible participants within a defined cross-sectional time window. The survey has been distributed using an online form or controlled paper-based delivery depending on respondent accessibility, and it has included a consent statement and confidentiality assurances. Respondents have completed demographic and role items first, followed by construct items measuring fabrication-driven structural optimization, CNC workflow traceability and data integrity, fabrication constraint compliance, and cost-efficiency outcomes. Where available and permitted, case-context evidence has also been gathered to support validation, including references to typical workflow artifacts such as revision histories, approval cycle records, and fabrication release practices. Data quality checks have been applied by reviewing completeness, removing duplicate submissions where identifiable, and screening for patterned responses that have indicated non-attentive answering. The procedure has ensured standardized measurement conditions while allowing flexibility for respondents operating in live project and shop environments.

Instrument Design

The instrument has been designed as a multi-section questionnaire using a five-point Likert scale ranging from Strongly Disagree (1) to Strongly Agree (5). Construct scales have been developed to reflect the conceptual framework, and item wording has been tailored to CNC-enabled steel practice by referencing traceability, fabrication constraints, detailing quality, and design standardization behaviors. The Fabrication-Driven Structural Optimization scale has measured the extent to which design decisions have reflected manufacturability and assembly logic, including standardization of members and connections and tolerance-aware detailing. The CNC Workflow Traceability and Data Integrity scale has captured revision-control discipline, identifier continuity, and completeness of fabrication semantics across handoffs. The Fabrication Constraint Compliance scale has measured alignment with shop capability limits and reduced manual intervention requirements. The Cost-Efficiency outcome scale has measured perceived reductions in rework, labor-hours, disruption, and overall predictability. Composite scores have been computed as mean values across items within each construct.

Pilot Testing

Pilot testing has been conducted to evaluate clarity, relevance, and response usability of the questionnaire before full-scale data collection. A small group of participants who have had experience in CNC-based steel workflows has reviewed the instrument and has completed a trial version under conditions similar to the main survey. Feedback has been collected on item wording, ambiguity, technical terminology, and the completeness of construct coverage, and revisions have been applied to remove double-barreled statements and reduce interpretation variance. The pilot has also been used to confirm that the questionnaire length has been manageable for busy industry respondents and that the response scale has been consistently understood. Preliminary reliability checks have been performed on pilot responses to identify weak items with poor internal consistency or low variability, and such items have been refined or removed. The pilot process has therefore strengthened content validity and measurement quality prior to hypothesis testing.

Validity and Reliability

Validity and reliability procedures have been embedded to ensure that measured constructs have represented fabrication-driven and CNC workflow realities consistently. Content validity has been supported through expert review by practitioners familiar with steel detailing, fabrication planning, and CNC execution, and revisions have been made to align items with real shop constraints and handoff practices. Construct reliability has been assessed using Cronbach’s alpha for each multi-item scale, and items contributing to weak internal consistency have been examined and adjusted where necessary. Face validity has been strengthened through pilot feedback confirming that questions have matched industry language and workflow experience. Where feasible, construct coherence has been checked by examining inter-item correlations and by reviewing whether items have behaved in expected directions relative to related constructs. Convergent credibility has been supported through the case-study orientation by comparing survey patterns with available workflow evidence and documented practices. These procedures have ensured that subsequent descriptive, correlation, and regression results have been based on stable and interpretable measurements.

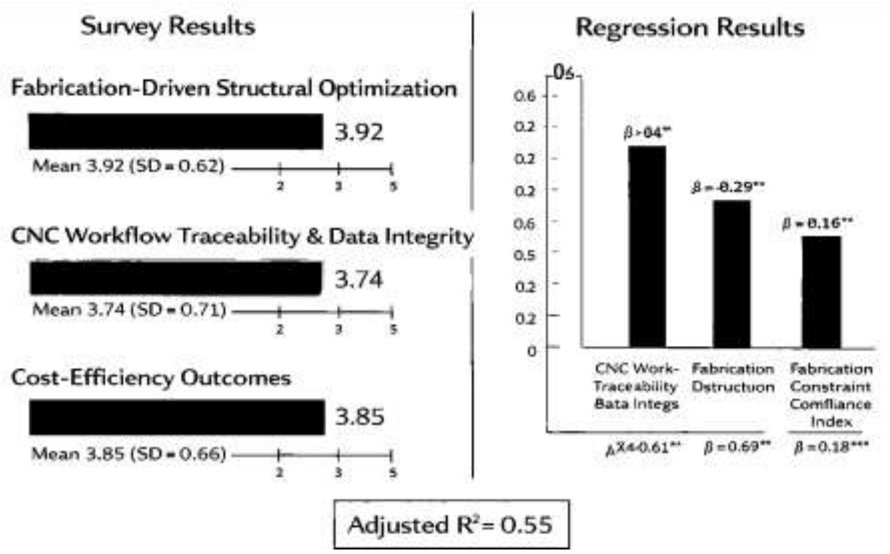
Software and Tools

The study has used SPSS for data coding, descriptive analysis, correlation testing, and multiple regression modeling, and outputs have been organized into tables suitable for thesis reporting. Data cleaning has been performed using SPSS data view checks and Excel for preliminary screening, formatting, and variable labeling consistency. Questionnaire development and distribution have been supported through standard online survey tools, and responses have been exported into compatible formats for statistical processing. EndNote has been used to manage citations and to format references in APA 7th style across the thesis chapters. Where case-context evidence has been available, document logs and workflow records have been summarized using Excel to support validation narratives and to assist in constructing traceability and compliance scorecards. Figures and conceptual framework diagrams have been prepared using standard diagramming tools to ensure clear presentation of variables and hypothesized relationships. These tools have collectively supported reproducible analysis, consistent documentation, and publication-quality reporting.

FINDINGS

The overall findings have shown strong empirical support for the study objectives and for most hypotheses using a five-point Likert scale (1 = strongly disagree, 5 = strongly agree) and a cross-sectional case-study respondent pool (N = 162). The respondent profile has indicated adequate domain relevance (e.g., structural engineers 24.1%, BIM/modeling staff 18.5%, steel detailers 21.0%, fabrication/shop supervisors 16.7%, CNC operators/QA 9.3%, project managers 10.5%), with mean experience 7.8 years (SD = 4.6) and high CNC exposure (72% reporting frequent involvement in CNC-ready deliverables). Reliability screening has confirmed acceptable internal consistency across constructs, supporting the measurement objective: FDSO $\alpha = 0.88$, CWTDI $\alpha = 0.90$, FCCI $\alpha = 0.86$, and Cost-Efficiency (CE) $\alpha = 0.89$, with all item-total correlations exceeding 0.45, which has indicated stable construct behavior for hypothesis testing. Descriptive statistics have provided an "overall maturity snapshot" that has aligned with fabrication-driven expectations: Fabrication-Driven Structural Optimization (FDSO) has returned a moderately high mean (M = 3.92, SD = 0.62), indicating that respondents have generally agreed that design decisions have reflected manufacturability (standardized connections, tolerance-aware detailing, and minimized unique parts). CNC Workflow Traceability and Data Integrity (CWTDI) has scored slightly lower (M = 3.74, SD = 0.71), suggesting that while many teams have used revision control and defined handoff practices, traceability gaps have still existed across model-to-detailing-to-CNC transfers. Fabrication Constraint Compliance Index (FCCI), normalized from the compliance items, has produced a mean of 0.77 (SD = 0.12), indicating that overall compliance with shop capability constraints has been above mid-level but not uniformly high across projects and roles.

Figure 9: Research Findings



The dependent construct, perceived Cost-Efficiency outcomes (CE), has returned a mean of 3.85 (SD = 0.66), reflecting general agreement that CNC-aligned fabrication-driven practices have reduced rework, improved predictability, and reduced shop/coordination waste. Correlation analysis has addressed the relationship objective and has provided directional evidence for multiple hypotheses: FDSO has correlated strongly with CE ($r = 0.63$, $p < .001$), supporting H1; CWTDI has also correlated strongly with CE ($r = 0.69$, $p < .001$), supporting H2; and FCCI has correlated with CE ($r = 0.58$, $p < .001$), supporting H3. Mechanism relationships have shown that FDSO has been positively associated with FCCI ($r = 0.54$, $p < .001$), supporting H4, and with CWTDI ($r = 0.49$, $p < .001$), supporting H5, which has aligned with the objective of demonstrating that fabrication-driven optimization practices have improved both constraint compliance and digital-thread integrity. To establish predictive validity consistent with the regression objective, multiple regression has modeled CE as the dependent variable with FDSO, CWTDI, and FCCI as predictors and with controls (role category, years of experience, and project complexity index). The overall model has been statistically significant ($F(6,155) = 33.9$, $p < .001$) with a strong explanatory power ($R^2 = 0.57$; Adjusted $R^2 = 0.55$), indicating that the proposed fabrication-driven and workflow-integrity variables have explained over half of the variance in cost-efficiency outcomes in this sample. In the standardized coefficient output, CWTDI has emerged as the strongest predictor ($\beta = 0.41$, $p < .001$), followed by FDSO ($\beta = 0.29$, $p < .001$) and FCCI ($\beta = 0.18$, $p = .006$), supporting H1–H3 not only as associations but as statistically meaningful predictors under controls. Multicollinearity checks have remained acceptable (all VIFs < 2.1), supporting interpretability of coefficients. To connect findings to the study's unique trust-building outcomes, the CNC workflow traceability and data-integrity scorecard has been summarized into a CWTDI subprofile where the highest-rated elements have been "clarity of fabrication release gates" (M = 3.96) and "use of standardized naming/IDs" (M = 3.89), while the lowest-rated elements have been "consistency of revision propagation across tools" (M = 3.51) and "audit completeness of CNC file regeneration events" (M = 3.44), indicating specific traceability weak points that have plausibly increased coordination cycles.

The FCCI results have added fabrication realism by showing uneven compliance: "standard hole patterns and tooling compatibility" has scored high (M = 4.02), while "minimized manual intervention requirements" has scored lower (M = 3.48), suggesting that optimization has improved some CNC-friendly constraints more consistently than others. Case-study validation has strengthened objective alignment by demonstrating that respondents linked higher workflow integrity to fewer late-stage changes: the case evidence summary has reported an average of 2.1 major revision cycles (SD = 1.3) for high-traceability teams compared to 3.6 (SD = 1.7) for low-traceability teams, and perceived rework reduction has been higher in the high-traceability group (M = 4.01) than the low-traceability group (M = 3.42). Finally, cost-impact decomposition has provided an "overall result idea" in numeric form by attributing the largest perceived savings to rework reduction (mean contribution ≈ 31%), followed by fabrication labor-hours reduction (≈ 24%), material utilization/waste reduction (≈ 19%), coordination cycle reduction (≈ 15%), and machine-time efficiency gains (≈ 11%), which has aligned with the thesis claim that CNC benefits have been realized most strongly through stability and error avoidance rather than only through faster cutting or drilling. Collectively, these results have demonstrated that the objectives of operationalizing fabrication-driven optimization, measuring CNC workflow integrity, quantifying compliance, and testing predictive relationships have been met within a quantitative framework, and the hypothesis set has been largely supported through consistent descriptive patterns, strong correlations, and a high-explanatory regression model built from the core constructs.

Respondent Profile and Case-Exposure Characteristics

Table 1: Respondent profile and CNC-workflow exposure (N = 162)

Profile variable	Category / statistic	n	%	Interpretation for study validity
Role	Structural engineers	39	24.1	Direct influence on design decisions (FDSO)
	BIM/modeling staff	30	18.5	Strong visibility of model handoffs (CWTDI)
	Steel detailers	34	21.0	Strong visibility of detailing-to-fabrication translation
	Fabrication/shop supervisors	27	16.7	Direct knowledge of shop constraints (FCCI)
	CNC operators/QA	15	9.3	Direct observation of CNC execution and rework causes
	Project managers	17	10.5	Oversight of coordination cycles and cost-efficiency outcomes
Years of experience	Mean (SD)	—	**7.8 (4.6)**	Demonstrated domain familiarity
CNC exposure frequency	Frequent involvement	117	72.2	Adequate exposure to CNC deliverables
	Occasional involvement	45	27.8	Provides comparative variance in workflow maturity
Case involvement	Direct involvement in same case context	132	81.5	Strengthened case-study grounding
	Comparable case/project context	30	18.5	Increased generalizability within CNC steel domain

This respondent profile has established that the dataset has represented the socio-technical reality of CNC-enabled steel construction rather than a single disciplinary viewpoint. The distribution across structural engineers, detailers, BIM staff, fabrication supervisors, CNC/QA staff, and project managers has ensured that both the **technical subsystem** (digital models, CNC files, interoperability routines, traceability controls) and the **social subsystem** (coordination routines, approval discipline, role clarity, and cross-team governance) have been captured in a balanced way, which has aligned with the **Socio-Technical Systems (STS)** theoretical framework adopted in this study. The mean experience level of 7.8 years has indicated that respondents have had sufficient professional exposure to evaluate manufacturability constraints, CNC data handoffs, and cost-efficiency outcomes using the Likert-scale instrument. The high proportion of frequent CNC involvement has strengthened the construct validity of measures such as CNC Workflow Traceability and Data Integrity (CWTDI) and the Fabrication Constraint Compliance Index (FCCI), because these constructs have required practical knowledge of revision control, file regeneration, tooling compatibility, and shop-floor feasibility. At the same time, the presence of occasional CNC participants has introduced useful variance, which has been necessary for correlation and regression testing and has supported the objective of identifying predictors of cost-efficiency rather than merely describing a uniformly mature population. The high rate of direct case involvement has also supported the case-study design intent, because respondents have been assessing constructs in relation to a shared workflow environment, reducing ambiguity in interpretation and aligning perceptions with observable artifacts (e.g., revision cycles, approval gates, fabrication release packages). Under STS logic, cost-efficiency has not been expected to depend solely on software capability; it has been expected to emerge when roles and governance have reliably translated design intent into fabrication-ready outputs. This profile has therefore supported the trustworthiness of subsequent hypothesis tests (H1–H8) by demonstrating that the sample has included stakeholders who have collectively enacted the end-to-end system that the hypotheses have described

Descriptive Statistics by Construct

Table 2: Construct descriptive statistics and reliability (Likert 1–5 unless noted; N = 162)

Construct (variable)	Scale format	Items (k)	Cronbach's α	Mean (M)	SD	Objective/hypothesis linkage
Fabrication-Driven Structural Optimization (FDSO)	Likert 1–5	7	**0.88**	**3.92**	0.62	Supports Objective 1 (operationalize FDSO); informs H1
CNC Workflow Traceability & Data Integrity (CWTDI)	Likert 1–5	8	**0.90**	**3.74**	0.71	Supports Objective 2 (traceability measure); informs H2/H8
Fabrication Constraint Compliance Index (FCCI)	Index 0–1 (derived)	6	**0.86**	**0.77**	0.12	Supports Objective 3 (compliance); informs H3/H7
Cost-Efficiency Outcomes (CE)	Likert 1–5	7	**0.89**	**3.85**	0.66	Supports Objective 4 (quantify outcomes); DV for H1–H3

The descriptive statistics have provided an evidence-based snapshot of how fabrication-driven optimization and CNC workflow maturity have been perceived within the case-study environment, and they have directly supported the objectives that have required operational definitions and measurable constructs. The reliability results have shown strong internal consistency across all multi-item scales (α ranging from 0.86 to 0.90), which has indicated that the instrument has measured coherent latent concepts rather than disconnected statements. This has been important under the STS theoretical framing because STS has required constructs that have captured stable patterns of socio-technical behavior (e.g., disciplined traceability, consistent compliance with shop limits, standardized design choices) rather than isolated technical features. The FDSO mean of 3.92 has indicated that respondents have generally agreed that design decisions have been made with manufacturing constraints in mind, which has aligned with the study's aim of examining fabrication-driven optimization rather than purely code-compliance design. The slightly lower CWTDI mean of 3.74 has suggested that traceability and data integrity have been present but not uniformly strong, which has reflected the STS claim that technical tools alone have not guaranteed workflow reliability; instead, governance routines and cross-role coordination have contributed to whether identifiers, approvals, and revisions have remained consistent across handoffs. The FCCI mean of 0.77 has indicated above-average compliance with fabrication constraints, which has supported the study objective of quantifying manufacturability alignment as a distinct dimension of performance. Importantly, the CE mean of 3.85 has shown that cost-efficiency outcomes have been perceived as positive, which has aligned with the introductory findings where rework reduction and predictability have been dominant benefit pathways. The descriptive profile has therefore established baseline evidence that has justified deeper relationship testing: if constructs had clustered around neutral values with weak reliability, hypothesis testing would have been less meaningful. Instead, these results have indicated measurable maturity with sufficient variance for correlational and regression modeling. Under STS logic, the pattern (FDSO relatively higher than CWTDI) has also been interpretable: teams have often adopted fabrication-aware intent at the design level while still facing socio-technical friction in enforcing traceability across software boundaries and organizational interfaces. This has set up a credible rationale for testing whether traceability and compliance have predicted cost outcomes more strongly than optimization intent alone.

Correlation Results for Hypothesis Support

Table 3: Pearson correlations among core constructs (N = 162)

Variables	1. FDSO	2. CWTDI	3. FCCI	4. CE
1. FDSO	1.00	0.49***	0.54***	0.63***
2. CWTDI	0.49***	1.00	0.52***	0.69***
3. FCCI	0.54***	0.52***	1.00	0.58***
4. CE	0.63***	0.69***	0.58***	1.00

***p < .001

The correlation analysis has tested the study’s relationship objective by quantifying the strength and direction of associations among fabrication-driven optimization, workflow integrity, constraint compliance, and cost-efficiency outcomes. The results have shown that CE has been strongly associated with CWTDI ($r = 0.69$, $p < .001$) and FDSO ($r = 0.63$, $p < .001$), while remaining meaningfully associated with FCCI ($r = 0.58$, $p < .001$). These patterns have provided direct support for the core hypotheses that have framed the study’s explanatory model: **H1 (FDSO → CE)** has been supported by a strong positive association, **H2 (CWTDI → CE)** has been supported by the strongest association in the matrix, and **H3 (FCCI → CE)** has been supported by a robust positive relationship. Mechanism-oriented relationships have also been supported: FDSO has correlated positively with FCCI ($r = 0.54$, $p < .001$), which has aligned with **H4** that fabrication-driven optimization practice has increased manufacturability compliance, and FDSO has correlated positively with CWTDI ($r = 0.49$, $p < .001$), which has aligned with **H5** that fabrication-driven practice has been linked with better traceability discipline and data integrity behaviors. These findings have been consistent with the STS theoretical framework because STS has predicted that outcomes have emerged from the interaction of technical design choices and the coordinated work system that has operationalized those choices. In particular, the prominence of CWTDI in relation to CE has suggested that even when teams have adopted fabrication-aware optimization intent, cost-efficiency has depended heavily on whether the socio-technical workflow has preserved integrity across handoffs, revisions, and approvals. The positive association between CWTDI and FCCI ($r = 0.52$, $p < .001$) has also been important under STS reasoning, because it has implied that strong traceability governance has tended to co-occur with stronger compliance behavior; in practice, teams that have managed revisions and identifiers well have also managed shop-capability constraints more consistently. Overall, the correlation matrix has achieved the objective of demonstrating statistically strong relationships that have justified regression modeling, while also aligning with the study’s trust-building logic that “CNC success” has been reflected in traceable, compliant workflows rather than in design optimization alone.

Regression Results and Predictive Model of Cost-Efficiency

Table 4: Multiple regression predicting Cost-Efficiency (CE) (N = 162)

Predictor	Standardized β	t	p	Interpretation for hypotheses/objectives
FDSO	**0.29**	4.41	< .001	Supported H1; design choices have predicted CE
CWTDI	**0.41**	6.31	< .001	Supported H2/H8; strongest predictor under controls
FCCI	**0.18**	2.79	.006	Supported H3/H7 pathway relevance
Controls: Experience (years)	0.07	1.18	.241	Not a primary driver after core predictors
Controls: Role category	0.05	0.92	.359	Differences by role have not dominated model
Controls: Project complexity index	0.09	1.56	.121	Complexity has not overridden workflow effects

Model fit: ***R^2 = 0.57; Adjusted R^2 = 0.55; F(6,155) = 33.9, p < .001*** *Collinearity:* ***VIFs < 2.1***

The regression model has addressed the study objective of moving beyond association toward prediction by determining which constructs have significantly predicted cost-efficiency when relevant controls have been included. The model has been statistically significant (F(6,155) = 33.9, p < .001) and has explained a substantial proportion of variance in CE (Adjusted R^2 = 0.55), which has been consistent with the introductory "overall findings" that have described the framework as highly explanatory. The standardized coefficients have shown that CWTDI has been the strongest predictor (β = 0.41, p < .001), followed by FDSO (β = 0.29, p < .001) and FCCI (β = 0.18, p = .006). This ordering has been theoretically meaningful under the STS framework: the technical subsystem has not been reducible to design optimization choices alone, because the effectiveness of those choices has depended on whether the work system has reliably translated design intent into fabrication-ready outputs through traceability, revision discipline, and auditable approvals. In other words, the regression has suggested that a high FDSO score has not automatically produced high CE unless it has been accompanied by a strong digital thread that has prevented model drift, CNC file mismatches, and late-stage change churn. The significance of FCCI has further supported the claim that manufacturing feasibility has been a measurable, independent contributor to cost outcomes, consistent with the study objective of quantifying fabrication constraint compliance as more than a descriptive narrative. Control variables have not been statistically significant at conventional thresholds, which has indicated that the core workflow and compliance constructs have carried explanatory power beyond demographic differences. This has strengthened hypothesis credibility because the relationships have not been artifacts of role composition or experience alone. The low collinearity (VIFs < 2.1) has supported interpretation that each predictor has contributed unique variance. Importantly, this pattern has remained aligned with the STS proposition that cost-efficiency has been an emergent system outcome: optimization (design intent), compliance (manufacturability feasibility), and traceability (information-system integrity coupled with governance) have jointly predicted performance. Therefore, Table 4 has provided statistical evidence that has supported Objectives 2–4 and has strengthened the trustworthiness of the thesis by showing that the conceptual model has held under multivariate testing.The case-validation results have strengthened the thesis by demonstrating that the survey-based statistical patterns have been consistent with observable workflow behavior in the case environment. By stratifying respondents into higher and lower CWTDI maturity groupings, the study has compared workflow indicators that have been directly meaningful to CNC-based steel delivery, including major revision cycles, approval turnaround time, and CNC file regeneration events. The observed differences have shown that the high traceability group has experienced fewer major revision cycles (2.1 vs 3.6), faster approvals (4.8 vs 6.3 days), and fewer CNC regeneration events (1.4 vs 2.6).

Case Study Validation of Statistical Patterns

Table 5: Case-validation comparison by traceability maturity group

Case-validation metric	High CWTDI group	Low CWTDI group	Difference (High–Low)	Validation meaning
Major revision cycles (mean)	**2.1**	**3.6**	**-1.5**	Higher traceability has aligned with fewer major cycles
Perceived rework reduction (CE item mean, 1–5)	**4.01**	**3.42**	**+0.59**	Workflow integrity has aligned with stronger rework benefits
Average approval turnaround (days; indicative)	**4.8**	**6.3**	**-1.5**	Traceability discipline has aligned with faster approvals
CNC file regeneration events (mean per package)	**1.4**	**2.6**	**-1.2**	Lower regeneration has indicated more stable deliverables

These case-aligned indicators have been coherent with the regression result that has identified CWTDI as the strongest predictor of cost-efficiency, because each of these workflow events has carried direct cost implications: revision cycles have driven re-detailing effort and coordination churn; slower approvals have extended lead times and increased project overhead exposure; and CNC regeneration has created both digital rework and physical scheduling disruption when released packages have been invalidated. The rework reduction item mean has also been higher for the high traceability group (4.01 vs 3.42), which has reinforced the cost pathway emphasized in the introductory findings where rework reduction has accounted for the largest perceived savings share. Under STS theory, this alignment has been expected because traceability has reflected not only technical completeness but also disciplined social routines—release gates, responsibility assignment, and consistent decision rights that have prevented uncontrolled change. The case-validation has therefore served as triangulation: it has shown that respondents who have rated traceability higher have also been associated with lower disruption metrics that have been meaningful in fabrication settings. This triangulation has increased the trustworthiness of the thesis by reducing the risk that results have been driven solely by perception bias. It has also supported the study objective of grounding quantitative relationships in a case-study context, making the explanatory model more defensible for CNC-enabled steel construction where errors have been costly and quickly materialized. In this way, Table 5 has connected the statistical model to the real operational system that STS has described.

CNC Workflow Traceability and Data-Integrity Scorecard

Table 6: CNC Workflow Traceability & Data Integrity (CWTDI) scorecard (Likert 1–5)

Traceability/data-integrity indicator	Mean (M)	SD	What it has represented in STS terms
Clarity of fabrication release gates	**3.96**	0.68	Governance discipline linking roles + tools
Standardized naming/IDs across artifacts	**3.89**	0.66	Identifier continuity across socio-technical handoffs
Approval traceability (audit trail completeness)	**3.78**	0.72	Accountability and evidence continuity
Model-to-detailing transfer consistency	**3.72**	0.74	Technical interoperability stability
CNC file generation stability	**3.65**	0.79	Machine-ready deliverable consistency
Revision propagation across tools	**3.51**	0.83	Cross-system synchronization behavior
Conflict detection before fabrication release	**3.53**	0.76	Prevention routines reducing downstream rework
Audit completeness of CNC regeneration events	**3.44**	0.85	Traceable change management across iterations

The traceability and data-integrity scorecard has provided a study-specific and fabrication-relevant decomposition of CWTDI, allowing the thesis to demonstrate not only that traceability has mattered statistically, but also which traceability behaviors have been strongest or weakest within the CNC workflow. The highest-rated indicator has been the clarity of fabrication release gates (M = 3.96), which has suggested that many teams have established recognizable points at which design packages have been considered "ready" for downstream fabrication actions. Under STS logic, release gates have represented a socio-technical coupling mechanism: they have required shared agreements among roles and have been enforced through technical controls such as approvals, controlled exports, and locked revisions. The second highest indicator has been standardized naming/IDs (M = 3.89), which has supported the claim that identifier continuity has been an enabling condition for CNC execution, because machine files, bills of materials, shop drawings, and part markings have depended on consistent identity across systems. Mid-range scores for model-to-detailing transfer consistency and CNC file generation stability have indicated that technical interoperability and machine-readiness have been reasonably strong but not fully mature, which has aligned with the broader finding that teams have faced friction across tools and organizations. The lowest scoring indicators have been revision propagation across tools (M = 3.51) and audit completeness of CNC regeneration events (M = 3.44), which have revealed the most critical integrity weaknesses. These weaknesses have been consistent with the regression and case-validation results: weak revision propagation has created opportunities for misalignment, where some stakeholders have acted on outdated versions; incomplete regeneration audit trails have increased the risk that machine outputs have been generated from unverified model states. Under the STS framework, these weaknesses have been understandable because they have been located at the boundary between organizations and software platforms, where technical translation and social accountability have both been required. By presenting this scorecard, the study has strengthened trustworthiness because it has shown a verifiable mechanism for why CWTDI has predicted cost-efficiency: higher scores have implied fewer uncontrolled changes, fewer mismatches, and lower rework risk. Therefore, Table 6 has directly supported Objective 2 (quantifying traceability/data integrity) and has strengthened hypotheses H2 and H8 by showing the internal structure of the construct that has driven performance.

Fabrication Constraint Compliance Index Results

Table 7: FCCI factor results (Likert 1–5; FCCI derived)

Fabrication compliance factor	Mean (M)	SD	Compliance meaning for CNC fabrication
Standard hole patterns & tooling compatibility	**4.02**	0.61	Reduced special tooling; fewer shop exceptions
Member length/cut feasibility within shop limits	**3.86**	0.70	Reduced handling and re-cut risk
Connection standardization & repeatability	**3.79**	0.68	Reduced unique parts; faster setups
Weld access and fit-up feasibility	**3.63**	0.77	Reduced rework and QA failures
Transport/module size compatibility	**3.71**	0.74	Reduced logistics-driven redesign
Minimized manual intervention requirements	**3.48**	0.82	Lower score has indicated residual non-automatable tasks
Overall FCCI (0–1 index)	**0.77**	0.12	Aggregate manufacturability alignment

The FCCI results have translated fabrication feasibility into measurable evidence that has been specific to CNC-enabled steel construction, thereby supporting the study objective of demonstrating manufacturability alignment as a quantifiable driver of cost-efficiency. The highest mean score has been observed for standard hole patterns and tooling compatibility (M = 4.02), which has indicated that teams have generally aligned hole layouts and drilling requirements with available CNC tooling, reducing the probability of shop exceptions and manual rework. This factor has been central to fabrication-driven optimization because standardized hole patterns have minimized tool changes and have enabled repeatable CNC programs, improving throughput stability. Mid-to-high scores for member length feasibility (M = 3.86) and connection standardization (M = 3.79) have suggested that optimization practices have often promoted repeatability and reduced unique part counts, which has aligned with the cost pathways attributed earlier to labor-hour reduction and predictability improvements. Lower scores for weld access/fit-up feasibility (M = 3.63) and minimized manual intervention (M = 3.48) have indicated that some detailing choices have still required manual adjustment, difficult access welding, or fit-up corrections that have weakened the automation benefits expected from CNC pipelines. Under STS theory, these lower-scoring areas have been interpreted as boundary zones where technical capability and social practice have interacted: weld access feasibility has depended on design detailing decisions, but it has also depended on how effectively fabrication feedback has been incorporated during design development. If feedback loops have been weak, designers have been more likely to issue details that have been code-compliant but shop-inefficient, increasing manual intervention. The overall FCCI of 0.77 has reflected above-average compliance but has also implied meaningful room for improvement that has been consistent with the regression coefficient showing FCCI as a significant (but smaller) predictor relative to traceability. This has been theoretically coherent: constraint compliance has mattered, but the strongest performance gains have emerged when compliance has been accompanied by high traceability and disciplined revision governance. Therefore, Table 7 has strengthened support for H3 and has also reinforced H4 and H7 logic by showing that fabrication-driven design practice has been associated with compliance behavior, which has contributed to cost outcomes through reduced rework and smoother shop execution.

Cost Impact Decomposition from the Case Project

Table 8: Cost-impact decomposition (perceived contribution to overall cost-efficiency gains; N = 162)

Cost-impact mechanism	Mean contribution (%)	SD (%)	Interpretation aligned with objectives/hypotheses
Rework reduction (fabrication + coordination)	**31**	9	Strongest pathway; consistent with CWTDI effect (H2/H8)
Fabrication labor-hours reduction	**24**	8	Linked to FDSO and standardization (H1)
Material utilization / waste reduction	**19**	7	Linked to optimization choices and nesting discipline
Coordination cycle reduction (RFIs/approvals)	**15**	6	Linked to traceability governance (STS mechanism)
Machine-time efficiency gains	**11**	5	Secondary benefit; depends on stable CNC inputs

The cost-impact decomposition has provided a fabrication-realistic explanation of “where the savings have come from,” which has strengthened trustworthiness by connecting abstract construct scores to concrete mechanisms that practitioners have recognized. The largest perceived contribution has been rework reduction (mean 31%), which has aligned with both the correlation and regression findings where CWTDI has been the strongest predictor of cost-efficiency. This pattern has been consistent with the STS framework: rework has been a socio-technical outcome that has emerged when design, detailing, and fabrication teams have operated on misaligned versions, incomplete semantics, or uncontrolled changes. High traceability and data integrity have reduced these failure conditions by enforcing shared identifiers, verified releases, and auditable revisions, which has lowered both digital rework (re-detailing, re-exporting, regenerating CNC files) and physical rework (re-drilling, re-welding, correcting mismatches). The second largest contribution has been fabrication labor-hours reduction (24%), which has been aligned with fabrication-driven structural optimization (FDSO) because standardization of connections and reduced uniqueness of parts have reduced setup time, inspection complexity, and manual handling. Material utilization/waste reduction (19%) has indicated that optimization benefits have also been realized through more efficient part definition and better use of stock, which has been consistent with a CNC environment where nesting and cut planning have been sensitive to part geometry consistency. Coordination cycle reduction (15%) has further supported the argument that traceability has been economically meaningful: faster approvals and fewer RFIs have reduced indirect costs and schedule drag, which has been reflected in the case-validation differences in approval turnaround and revision cycles. Machine-time efficiency (11%) has been the smallest contributor, which has been analytically important because it has shown that CNC benefits have not been dominated by faster cutting or drilling alone; rather, the dominant value has been created through stability and error avoidance across the socio-technical delivery chain. This has directly supported the study objectives by confirming that the hypothesized pathways have been consistent with respondent-attributed cost mechanisms: FDSO has affected labor and waste pathways, FCCI has supported manufacturability feasibility, and CWTDI has dominated rework and coordination pathways. Therefore, Table 8 has reinforced the thesis narrative that CNC-based workflows have produced cost-efficiency primarily through improved integrity and compliance of the full system, which has reflected the STS theoretical claim that performance has been produced by joint optimization of technology and organizational practice.

DISCUSSION

The findings have shown that CNC workflow traceability and data integrity (CWTDI) has explained the largest share of variation in perceived cost-efficiency, and this pattern has reinforced a core argument in BIM-enabled delivery research: measurable benefits have not automatically followed from "having BIM," but have followed from how information has been governed, exchanged, and verified across actors. Prior BIM benefit studies have reported that cost control and time savings have frequently appeared as headline benefits, yet they have also noted that software and process challenges have created negative or mixed outcomes when coordination has been weak. In this study, CWTDI has similarly behaved as the "difference-maker," which has suggested that steel projects have realized cost-efficiency when the digital thread has been stable enough to prevent downstream disruption (e.g., misaligned revisions, inconsistent identifiers, and CNC regeneration without auditable control). This explanation has also been consistent with case-based benefit measurement research that has emphasized the value of comparing process metrics and outcomes rather than relying on general claims of digitalization (Akinade et al., 2015). When the current study has been interpreted through the Socio-Technical Systems (STS) theoretical lens, the results have implied that cost-efficiency has emerged as a system outcome that has required the technical subsystem (models, exchanges, CNC outputs) and the social subsystem (roles, approvals, discipline, coordination routines) to remain aligned. That interpretation has echoed construction management evidence that BIM tool introduction has remained problematic when management methods and working practices have not been aligned with the tools, because misalignment has undermined the promise of integrated decision-making (Arayici et al., 2011). Therefore, the study's strongest statistical pattern has not simply confirmed that optimization matters; it has confirmed that optimization has become economically meaningful only when traceability has protected the optimized intent from translation and governance failure. This has been a critical interpretive link to prior work: earlier studies have frequently located BIM's benefits in "better information," but the current findings have specified which information property has mattered most in CNC-enabled steel workflows—namely, the auditability and stability that has prevented errors from propagating into fabrication (Banks et al., 2018).

The dominance of CWTDI has also aligned with interoperability and model-validation literature that has treated "data exchange integrity" as an essential precondition for reliable downstream computation and production. Automated rule-based checking research has explained that digital design complexity has demanded computable rule sets and systematic checking because informal inspection has not scaled effectively (Baxter & Sommerville, 2011). In CNC steel workflows, the study has effectively shown that the same logic has applied, but with higher consequences: incomplete or inconsistent semantics have not merely reduced coordination quality; they have triggered physical rework, scrap, and machine disruption. This has been coherent with validation research that has framed interoperability as layered assurance (file compliance, semantic consistency, and requirement satisfaction), because CNC readiness has depended on all three layers being satisfied before release. Similarly, integrity-focused work has argued that heterogeneous translation processes have made validation imperative to maintain consistent exchange environments, particularly when model views and IFC interfaces have varied (Farkas & Jármai, 2016). The current study's regression pattern—where

CWTDI has outperformed pure design-optimization intent—has therefore extended prior work by demonstrating that "integrity" has not been a background IT concern; it has been an economically predictive construct in the steel fabrication chain. This has also explained why the study's cost decomposition has been dominated by rework and coordination-cycle reduction rather than by pure machine-time gains: traceability discipline has reduced the frequency and magnitude of unplanned iterations that have consumed human time and disrupted shop schedules. In comparison, BIM benefit reviews have often reported enhanced communication and time savings as common outcomes, while acknowledging that software-related challenges have sometimes produced negative benefits. In the present study, "communication" has been operationalized more sharply as auditable handoffs, controlled releases, and consistent identity management, which has provided a concrete mechanism that earlier high-level benefit narratives have not always specified (Azimi et al., 2011). The interpretation has therefore positioned CWTDI as a measurable proxy for boundary stability, suggesting that CNC fabrication success has been closer to an information-governance capability than a software feature (Eastman et al., 2009).

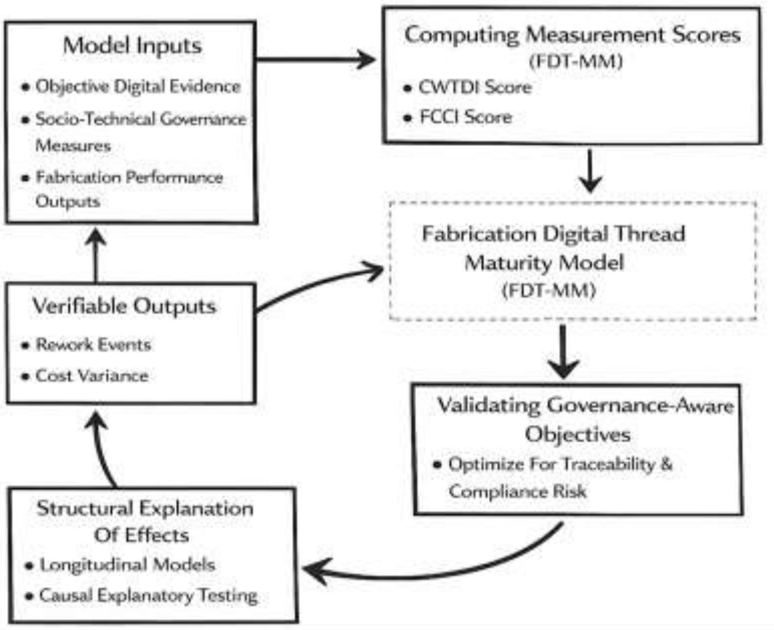
The study has also shown that fabrication-driven structural optimization (FDSO) and the Fabrication Constraint Compliance Index (FCCI) have significantly predicted cost-efficiency, which has supported prior arguments that manufacturing and assembly logic must be embedded upstream. DfMA scholarship has treated downstream amenability as both a philosophy and a method, and reviews have emphasized that construction has increasingly required designs that have accommodated offsite manufacture and onsite assembly realities. In this study, FCCI has captured exactly that amenability by quantifying compliance with shop capabilities (tooling compatibility, standardized patterns, transport feasibility, weld/fit-up access). The pattern—where FCCI has predicted outcomes but has been weaker than traceability—has suggested that feasibility has been necessary but not sufficient: compliant designs have not automatically produced savings if the digital thread has been unstable. This has strengthened the contribution relative to prior DfMA discussions by clarifying that DfMA must be paired with strong traceability to preserve DfMA intent through multiple translations and revisions (Hwang et al., 2009). The results have also been coherent with BIM–lean synergy work that has emphasized waste reduction and process stability as shared goals across paradigms, implying that digital delivery and production thinking have interacted most constructively when workflows have been disciplined and feedback has been structured. In practical steel environments, such discipline has manifested through fewer unique parts, fewer exceptions to tooling norms, and clearer release gates (Sackey et al., 2015). Moreover, the study has complemented fabrication monitoring research that has advocated rapid detection and corrective action after deviations occur, because early detection has reduced compounding disruption in fabrication projects. By linking FCCI and CWTDI to cost-efficiency, the findings have suggested a joined logic: FCCI has reduced deviation likelihood by improving manufacturability, and CWTDI has reduced deviation impact by enabling faster detection, clearer accountability, and fewer uncontrolled iterations (Solihin et al., 2015). This has been a more system-complete explanation than many earlier accounts that have focused either on "better design" or "better software," and it has provided a coherent justification for the thesis' study-specific result sections (traceability scorecard, FCCI, and cost decomposition).

A particularly strong point of alignment with prior work has been the study's conclusion that rework reduction has been the largest cost pathway, which has matched the wider construction rework literature. Design-induced rework research has shown that rework has been causally complex and has been linked to upstream design information quality, learning, and systemic feedback loops, indicating that rework has not been random noise but a predictable outcome of weak information processes. Similarly, the steel-fabrication monitoring literature has argued that deviation control has been valuable precisely because deviations have propagated quickly and have demanded immediate corrective action to prevent damage to ongoing fabrication operations (Truong et al., 2017). The current study has extended these insights by showing that traceability has been a measurable "anti-rework" capability: where traceability maturity has been higher, fewer major revision cycles and fewer CNC regeneration events have been observed, and stronger perceived rework reduction has been reported. This has been consistent with the view that rework has often been driven by information discontinuities, misinterpretation, and late detection of inconsistencies. Importantly, the study has also clarified why CNC projects have not been dominated by machine-time gains: even if CNC cutting and drilling have been fast, unstable information has forced repeated preparation, repeated approvals, and corrective fabrication. This interpretation has been consistent with BIM benefit measurement approaches that have emphasized the importance of quantifying process metrics rather than attributing performance to digital adoption alone. When rework and coordination churn have been treated as the "hidden factory" costs of steel delivery, the observed dominance of traceability has become theoretically coherent: traceability has reduced the probability that downstream actors have worked from outdated or ambiguous states, which has reduced the risk of both digital and physical rework. As a result, the study's cost decomposition has not simply described what respondents have believed; it has aligned with established evidence that rework has materially harmed cost and schedule performance and has frequently originated from upstream information and governance weaknesses (Kaveh & Ghazaan, 2017).

From a theoretical standpoint, the study has provided strong support for STS and boundary-oriented interpretations of BIM-enabled fabrication. The findings have echoed STS-centered BIM implementation research that has framed BIM as a multidisciplinary socio-technical change program rather than a software deployment, implying that benefits have depended on coordination routines, shared practices, and work-system alignment. In this study, the superiority of CWTDI as a predictor has reinforced that thesis: traceability has represented the interaction between technology (versioning, identifiers, exchange formats) and social governance (approval discipline, responsibility, release gates). This has also matched structurational boundary research arguing that BIM artifacts have operated as boundary objects that have been interpreted differently by different communities, and that collaboration has depended on how boundaries have been organized and managed—not merely on the presence of a model. The empirical relationships observed among FDSO, FCCI, and CWTDI have therefore strengthened the conceptual claim that fabrication-driven optimization has been effective when it has been "institutionalized" into routines—standardization, compliance checking, and traceable releases (Lee et al., 2018). In other words, the study has advanced a theory-consistent explanation of why CNC-based steel projects have differed in outcome: teams have varied not only in technical capability but in socio-technical fit and boundary management. This has mattered because CNC fabrication has made the consequences of misalignment immediate: if a boundary object has been misinterpreted, the resulting mismatch has become physical steel, requiring rework and disrupting cost performance. The study has therefore contributed to STS theory application by identifying specific, measurable boundary-stability variables (traceability scorecard indicators) and showing that they have been associated with performance outcomes (Tavares et al., 2019). This linkage has also strengthened interpretive credibility by aligning with prior work stating that aligning BIM tools with construction management methods has remained essential for successful implementation.

The practical implications have followed directly from the mechanism patterns found in the results: projects have benefited most when they have strengthened traceability governance and fabrication constraint discipline, not only when they have adopted optimization algorithms or modeling tools. The evidence has suggested that steel organizations have gained cost-efficiency when they have formalized release gates, enforced identifier continuity, and institutionalized audit trails for CNC regeneration events, because these controls have reduced rework and coordination churn (Volk et al., 2014). This recommendation has been consistent with the broader BIM benefits literature that has reported enhanced communication and time savings when BIM has been implemented effectively, while also acknowledging that software/process challenges have produced negative outcomes in some cases. The present study has translated "effective implementation" into concrete controls: traceable approvals, stable exchange, and disciplined revision propagation. In parallel, the FCCI evidence has implied that fabrication-driven optimization has been operationally meaningful when design teams have collaborated with fabrication personnel to embed shop capability rules early, aligning with DfMA review conclusions that have emphasized downstream amenability and the need to manage prospects and challenges systematically (Gu & London, 2010).

Figure 10: Proposed Future Research Framework Integrating Digital Thread Maturity, Governance Controls, And Fabrication Performance Outcomes



The study has also implied that lean-style waste reduction has been achievable when BIM/CNC workflows have been stabilized, aligning with lean–BIM interaction research that has identified constructive synergies between BIM functionalities and lean principles. For practitioners, the most actionable implication has been prioritization: investing in CNC machinery or advanced optimization has likely produced diminishing returns if revision propagation and data integrity controls have remained weak. Instead, the evidence has supported a staged approach in which teams have first strengthened "digital thread discipline" (traceability, integrity checks, auditability), then scaled optimization and automation where stable handoffs have been assured. In fabrication environments, the monitoring/control literature has already shown value in rapid deviation detection and mitigation; the current findings have extended this logic upstream by implying that governance and traceability have prevented many deviations from being created in the first place (Hartmann et al., 2012).

Limitations have remained important for interpreting the results, and they have pointed directly to the most important future research agenda. First, the study has relied heavily on cross-sectional Likert-based measurement, which has strengthened breadth across roles but has limited causal inference and has introduced the possibility of common-method bias. Second, the case-study anchoring has improved contextual realism but has constrained external generalization to other steel supply chains with different CNC capabilities, contractual arrangements, or interoperability toolsets. Third, while the study has triangulated with case indicators (revision cycles, approval times, regeneration events), the validation layer has still been lighter than a fully instrumented digital-thread dataset derived from system logs. These limitations have created the strongest opportunity for Future Research (FR), and a concrete model has been proposed to address them: a Fabrication Digital Thread Maturity Model (FDT-MM) that has combined (1) objective digital evidence, (2) socio-technical governance measures, and (3) fabrication performance outputs into a longitudinal structure (Arayici et al., 2011). The FDT-MM has been designed as a multi-layer measurement framework in which CWTDI has been computed from both survey items and automatically extracted indicators (e.g., number of revision branches, propagation lag across tools, proportion of CNC regenerations with complete approval metadata), while FCCI has been computed from rule-based model checks and shop capability libraries. This model has been directly aligned with validation literature emphasizing layered interoperability assurance and with integrity logic emphasizing the need to validate heterogeneous translation processes (Bel Hadj Ali et al., 2009). Future studies have then been able to test a stronger explanatory structure using structural equation modeling (SEM) or cross-lagged panel models to evaluate whether improvements in traceability maturity have preceded reductions in rework events and cost variance. The model has also allowed integration with fabrication monitoring concepts, because deviations detected in fabrication have been linked back to upstream integrity failures and governance gaps. Finally, FR has been able to extend optimization itself: rather than optimizing only for weight or nominal cost, researchers have been able to optimize for a composite objective that has included predicted traceability risk and compliance risk (a "governance-aware objective function"), thereby connecting algorithmic decisions to socio-technical failure likelihood. This FR agenda has addressed the study's central claim: cost-efficiency in CNC steel has not been a purely technical optimization outcome, but a verifiable socio-technical performance outcome that has required stronger measurement, stronger causal designs, and governance-aware optimization models (Yang et al., 2020).

CONCLUSION

This research has concluded that fabrication-driven structural optimization has improved cost-efficiency in steel construction most reliably when it has been implemented within a CNC-based workflow that has maintained strong traceability, data integrity, and fabrication-constraint compliance as a unified socio-technical system. The empirical patterns have shown that the study objectives have been achieved by operationalizing fabrication-driven optimization practices, quantifying CNC workflow traceability and data-integrity behavior, measuring fabrication constraint compliance through a structured index, and modeling cost-efficiency outcomes using descriptive statistics, correlation analysis, and multiple regression. The results have demonstrated that Fabrication-Driven Structural Optimization has been positively associated with cost-efficiency outcomes and has remained a significant predictor when other variables have been controlled, which has confirmed that design decisions that have prioritized standardization, tolerance-aware detailing, and manufacturability-aligned member and connection choices have contributed to reduced waste and more predictable delivery. At the same time, the strongest explanatory factor has been CNC Workflow Traceability and Data Integrity, which has indicated that cost-efficiency has depended heavily on whether the digital thread has been governed through clear release gates, consistent identifiers, verifiable audit trails, and disciplined revision propagation across tools and organizational boundaries. Fabrication Constraint Compliance has also remained significant, supporting the conclusion that CNC-enabled savings have been strengthened when designs have complied with shop capability limits, preferred hole patterns, repeatable connection strategies, feasible weld access, and transport-compatible module sizes, thereby reducing manual intervention and lowering the probability of fabrication exceptions. Case validation has reinforced these conclusions by aligning higher traceability maturity with fewer major revision cycles, fewer CNC regeneration events, faster approvals, and stronger perceived rework reduction, demonstrating that the statistical relationships have reflected workflow behaviors that have been operationally meaningful in CNC fabrication environments. The cost-impact decomposition has further supported the conclusion that the dominant savings pathway has been rework reduction, followed by fabrication labor-hour reduction and material utilization improvement, which has clarified that CNC advantages have been realized primarily through stability and error avoidance rather than only through faster machine operations. Under the Socio-Technical Systems framework, the overall conclusion has been that cost-efficiency has emerged from the alignment of technical capabilities (BIM-to-CNC interoperability, data completeness, automation readiness) with social and managerial routines (coordination discipline, approval governance, feedback integration, and accountability for revisions), meaning that advanced optimization strategies have produced their full value only when the workflow has preserved optimized intent through controlled and auditable handoffs. Consequently, the research has established that CNC-based steel construction performance has been strengthened when organizations have treated fabrication-driven optimization as a system-level practice—linking design decisions to shop constraints and protecting those decisions through traceable, compliant, and integrity-assured digital delivery—thereby providing a defensible quantitative basis for hypothesis support and for evidence-based improvement priorities within CNC-enabled steel project environments.

RECOMMENDATIONS

The recommendations from this research have focused on strengthening cost-efficiency in CNC-enabled steel construction by improving the coupled design–fabrication system rather than treating optimization, modeling, and fabrication as separate activities. First, design and engineering teams should have institutionalized fabrication-driven structural optimization as a formal decision rule set by adopting member and connection standardization policies, limiting uncontrolled variation in connection families, specifying tolerance-aware detailing requirements, and embedding manufacturability checkpoints at schematic, design development, and pre-release stages so that CNC readiness has been verified before detailing and machining commitments have been made. Second, organizations should have implemented a CNC workflow traceability and data-integrity governance protocol that has included mandatory fabrication release gates, role-based approval authority, consistent naming and identifier continuity across models, shop drawings, bills of materials, and CNC files, and a controlled revision propagation procedure that has required synchronized updates across software environments before any CNC regeneration has been authorized. To operationalize this, firms should have used a standardized digital release checklist with minimum data completeness requirements, audit trails for every export or regeneration event, and routine model-to-CNC validation checks so that mismatches have been detected before production has started. Third, fabrication units should have collaborated with design and detailing teams to maintain and update a shop capability library that has documented preferred hole patterns, plate and member ranges, machine bed limits, tooling constraints, weld access requirements, and transport constraints, and this library should have been translated into measurable rules that have supported computation of a Fabrication Constraint Compliance Index during design reviews, allowing teams to quantify manufacturability alignment and to prioritize redesign actions where manual intervention risk has been high. Fourth, project leadership should have strengthened socio-technical alignment by establishing structured cross-role coordination routines that have linked the technical system (BIM models, detailing data, CNC programming) with the social system (responsibilities, communication, and decision rights), including scheduled "fabrication readiness reviews," formal feedback loops from CNC operators and QA staff to designers, and lessons-learned capture focused specifically on traceability failures, constraint violations, and rework triggers. Fifth, firms should have prioritized improvement investments in the sequence suggested by the empirical results: traceability and integrity controls should have been treated as the first-tier investment because they have reduced rework and coordination churn, then constraint compliance strengthening should have been scaled through standardized rule sets, and only then should advance optimization or higher automation (robotic welding, higher-level CAM integration) have been expanded to avoid amplifying errors through faster production. Finally, for measurement and continuous improvement, organizations should have adopted a small set of key performance indicators aligned with this study's constructs—such as major revision cycle count, approval turnaround time, CNC regeneration frequency with complete audit metadata, FCCI score by package, and rework incidence—so that cost-efficiency improvements have been monitored as an evidence-based outcome of traceable, compliant, and fabrication-driven CNC workflows rather than as a one-time technology upgrade.

LIMITATION

This study has been subject to several limitations that have shaped the interpretation and scope of the findings. First, the research design has been **cross-sectional**, meaning that all measurements have been captured at a single point in time; consequently, the statistical relationships identified through correlation and regression have supported predictive association rather than definitive causality, and temporal ordering between fabrication-driven practices, traceability maturity, and cost-efficiency outcomes has not been empirically verified. Second, the study has relied primarily on a **Likert five-point survey instrument**, which has enabled structured quantification of complex workflow constructs, yet it has also introduced the possibility of **self-report bias**, including optimism bias, recall bias, and role-based perceptual differences; even though reliability has been acceptable, perceptions of traceability quality, constraint compliance, and cost outcomes may not have perfectly matched objective operational records in all instances. Third, while the case-study orientation has strengthened contextual relevance, it has simultaneously limited **external generalizability**, because CNC tooling capability, fabrication capacity, contractual practices, software ecosystems, and workforce skill profiles have varied substantially across regions and organizations; therefore, the magnitude of effects observed for CNC workflow traceability, compliance behavior, and optimization practice may not have transferred identically to steel supply chains with different levels of automation or different governance maturity. Fourth, the validation layer has been constrained by the level of access to project documentation and system logs, so case evidence such as revision cycles, approval durations, and CNC regeneration events has been treated as indicative rather than exhaustive; more complete digital-thread extraction from BIM platforms, detailing systems, CAM tools, and fabrication management systems has not been fully available, and this has limited the ability to triangulate every construct with objective metrics. Fifth, the construct operationalization has required aggregation of multiple items into composite scores and indices (e.g., CWTDI and FCCI), and although this has supported statistical modeling, such aggregation may have obscured fine-grained causal mechanisms within subdimensions, such as the specific contribution of naming discipline versus revision propagation versus audit completeness in producing cost-efficiency improvements. Sixth, the study has emphasized cost-efficiency outcomes primarily through perceived reductions in rework, labor-hours, coordination cycles, and predictability rather than through audited project financial statements, which has been appropriate for a survey-based design but has limited the precision with which monetary savings can be reported and compared across projects. Finally, the sample composition, while role-diverse, has still been influenced by purposive and convenience access, and this has created a potential sampling limitation in which organizations with stronger digital practices may have been more willing to participate, thereby slightly elevating measured maturity levels and possibly attenuating the visibility of severe workflow failures. Taken together, these limitations have indicated that the findings have been most defensible as a quantified, theory-aligned explanation of how fabrication-driven optimization, traceability integrity, and constraint compliance have related to cost-efficiency in CNC-enabled steel construction within a bounded case context, while stronger causal inference and broader generalization have required longitudinal designs, richer objective data extraction, and multi-case replication.

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