Decision-Support Framework for Evaluating Steel Connection Systems for Adoption in Construction

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Abstract –

Steel construction currently lacks systematic and validated frameworks that can be used to evaluate innovative systems against established alternatives before field deployment. This contributes to delayed adoption even where there are demonstrated performance advantages. This study presents the development of a conceptual decision-support framework for assessing steel connection systems. It compares an innovative intermeshed steel connection (ISC) with the existing bolted steel connection. The proposed framework integrates building information modeling (BIM) for constructability analysis, computer-vision-based ergonomic assessment for pose estimation, simulation-based performance evaluation, and multi-criteria decision analysis using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Using a simulated assembly scenario, the framework systematically evaluates connection systems across the parameters of worker safety (ergonomic risk), assembly efficiency, and construction cost. The framework development process demonstrates how simulated data informs framework parameters using criterion weights from surveys, performance metrics measured from simulation protocols, and decision thresholds. The simulated results indicate that the ISC system reduces ergonomic risks by up to 40% as measured by the Rapid Entire Body Assessment (REBA) mean scores of 4.57 for bolted connection and 2.57 for ISC. The assembly duration of ISC also decreased by approximately 29% and achieved cost savings of up to 10% across geographic locations. This study provides a replicable conceptual methodology for developing decision-support systems for a systematic evaluation of innovative systems. By applying simulated findings to validated decision-support systems, it illustrates how digital technologies such as BIM and computer vision can improve objective technology assessment in construction. The proposed framework offers a basis for future empirical data-based validation studies to guide decision making in steel connection systems adoption.

Keywords –

BIM, Computer vision, Construction, Decision support framework, Simulation, Steel connection, TOPSIS

1 Introduction

The construction industry faces persistent reluctance in adopting innovative technologies even where there is potential to improve safety, efficiency, and cost effectiveness [1]. Construction practitioners often require systematic frameworks to evaluate emerging construction methods and materials against established practices [2]. This oftentimes leads to conservative decision-making and slow technology diffusion [3]. For structural steel construction, where connection technologies have been evolving over time from riveting to welding and high-strength bolting, each transition still required decades of industry acceptance despite empirical performance advantages available at the time [4, 5]. The unavailability of structured decision-support systems integrating multiple performance dimensions, safety, efficiency, and economics, creates a major challenge for innovation adoption in a risk-prone industry such as the steel construction industry.

Decision-making in construction technology adoption is more complex, sometimes requiring a concession among the competing performance objectives. These objectives may include cost, quality, productivity, worker safety, and sustainability [6]. Traditionally, evaluation methods would focus on a single criterion, mostly cost, and avoid a comprehensive performance assessment. This overlooks the interconnectedness of construction performance metrics, where a change in one dimension can result in cascading benefits in the others [7]. A connection system that can reduce ergonomic strain on workers may also reduce assembly time, reduce injury-related costs on projects, and improve work quality and worker efficiency due to reduced fatigue. Yet these quantitative synergies are vastly unquantified in the traditional decision processes [8,9]. Multi-criteria-decision-making (MCDM) methods such as Analytical Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) have been used as tools to address this complexity. Although interest in MCDM frameworks for innovative construction technology assessments is growing, gaps exist in the literature on conceptual frameworks that systematically integrate digital construction technologies with multi-criteria decision analysis [10]. Most existing studies focus on theoretical MCDM applications while evading data collection limitations in evaluating new innovative technologies [11]. Some studies present case-specific analyses that lack generalizability across various construction contexts, such as steel construction [12, 13]. Conceptual frameworks offer the distinctive advantage of enabling systematic identification of relevant evaluation criteria, establishing relationships between performances, providing a foundation for future empirical validation, and steering the development of measurement protocols ahead of committing major resources to the experimental validation [10].

Integrating digital construction technologies introduces unprecedented opportunities for conceptual framework development. This can be improved by objective, automated performance assessment capabilities. Building information modeling (BIM) is now more than design coordination; it details project constructability analysis, clash detection, 4D scheduling, and assembly sequence optimization [14, 15]. Computer-vision technologies for pose estimation provide a system for objectively assessing worker safety and ergonomics through biomechanical posture analysis. [16, 17]. BIM-based construction sequencing allows for a time-motion analysis used for estimating task duration and productivity rates for comparative assessment [18]. The integration of these tools, alongside expert validation, creates an opportunity to develop a decision framework that bridges theoretical MCDM principles with the practicality of the construction industry.

Steel connection technology is critical to structural integrity, schedule performance, and worker hazard exposure, making it an ideal domain for developing a conceptual decision-support framework. Up to 40% of steel erection labor hours are spent on connection works, ranking the task as high-risk, exposing workers to hazardous risks such as fall from heights and struck-by hazards [6]. An intermeshed steel connection (ISC) is an innovative alternative to bolted steel connections and provides a perfect example for the performance criteria evaluation challenges facing the steel construction industry [19]. ISC uses the interlocking theory to secure steel elements using simple fastening mechanisms that significantly minimize the need for bolts. It potentially reduces assembly duration, minimizing ergonomic hazard exposure, repetitive overhead, and bolt installation work, and decreases material and labor costs [19]. An absence of a standardized evaluation framework, limited performance data, and a level of unfamiliarity among construction professionals pose a challenge, limiting contractors, structural engineers, and project owners in assessing whether the ISC technology is safe for adoption on their specific projects. This uncertainty is aggravated by the interconnectedness of the connection system performance criteria [20].

This study addresses this gap by presenting a comprehensive conceptual decision-support framework for evaluating steel connection systems using ISC and traditional bolted connections on a comparative basis. The conceptual framework will integrate (1) BIM-based constructability analysis, (2) computer-vision-based ergonomic assessment, (3) simulation-based performance evaluation for performance criteria, and (4) TOPSIS-based multi-criteria decision analysis. This study develops a repeatable conceptual methodology for structured decision-support frameworks for both simulation-based estimates and future empirical data. It illustrates the theoretical integration of computer-vision-based ergonomic assessment and BIM constructability, thereby advancing digital tools application beyond design coordination to advance construction method selection. The study also presents an expert validation approach centered on practical applicability, criterion relevance, and implementation of feasibility through professional feedback.

2 Literature Review

2.1 Construction technology adoption and innovation diffusion

The construction sector has a conservative approach to technology adoption. This stems from the industry being driven by project-based production systems, fragmented supply chains, low profit margins that discourage innovative experimentation, regulatory constraints, and liability from unproven methods [21, 22]. Client demand for innovation, a short-term returns focus, and insufficient collaboration between research institutions and construction practitioners further widen the innovation gap [23, 24]. The study of [25] posited diffusion of innovation theory as a foundational framework for technology adoption patterns. Mitropoulos [26] noted that new technologies must prove compatibility with existing work processes, need minimal learning curves, and provide evidence of advantages with pilot implementations. Where proof of field-tested employment cannot be avoided, it becomes inherently difficult to demonstrate the potential benefits that will justify adoption [27].

Steel connection technology evolution is an example of long adoption curves from riveting to welding and high-strength bolted steel connections. This was despite the clear advantages in connection strength and speed presented at each of these stages [19]. This confirms that the industry requires technical validation and a comprehensive decision-support tool that enables professionals and practitioners to evaluate innovations within their specific context [25, 21]. Intermeshed steel connections are currently facing these same adoption challenges, as they lack an extensive field of performance data and structured evaluation frameworks to provide informed decision-making.

2.2 Multi-criteria decision making in construction management

MCDM enables systematic multi-dimensional evaluation that accommodates diverse stakeholder preferences [10]. It applies across diverse situations, including contractor selection [20], construction method selection [27], sustainable building design [28], safety management strategy evaluation [1], and equipment selection decisions [12]. TOPSIS, an MCDM technique, is particularly suitable for construction applications due to its computational simplicity, large criterion handling, and intuitive logic [29]. The study of [30] successfully applied TOPSIS for green building project delivery methods, [31] utilized TOPSIS for subcontractor selection model, [32] applied TOPSIS for construction optimization decision scheme of urban subway tunnels. However, MCDM applications majorly rely on historical project data, and where innovative technology lacks such data, researchers must rely on expert judgement or develop alternative data generation approaches [1, 24]. These data limitations become even more acute where innovations are evaluated against established alternatives [13]. Recent research in MCDM has proposed framework validation as a means of establishing confidence in decision-support outputs [33].

2.3 Digital technologies in construction assessment

BIM-based constructability analysis evaluates assembly feasibility, detects spatial conflicts, and stimulates installation sequences, providing a significant influence on safety and productivity planning for steel connections [14, 15]. Computer vision pose estimation eliminates subjectivity in ergonomic data collection and enables continuous dynamic monitoring [10]. Its application has been extended to productivity measurement through activity recognition [18] and to simulated ergonomic assessment via virtual reality environments [34]. Despite these advances, systematic integration of computer vision ergonomic assessment into multi-criteria decision-support frameworks for technology evaluation remains unexplored.

Simulation-based research enables controlled investigations of construction processes without full-scale resource requirements, safety, economic concerns, and hidden variables in field experimentation [10, 35]. The extent to which simulation output correctly represents real-world scenarios requires careful consideration of model assumptions, input parameter estimates, and the need for validation against empirical data as soon as it is available [36]. For steel connections, construction process simulation for connection systems remains underdeveloped, with limited research examining the assembly sequences, worker movements, or comparative productivity analysis. Integrating a BIM-based spatial simulation with computer-vision-based ergonomic assessment for connection technology evaluation represents a novel approach to be documented.

Conceptual framework validation organizes challenging dynamics, identifying relationships between variables, and provides step-by-step guides for future empirical designs. The approach varies based on the intent and development stage. Expert panels assess the framework for comprehensiveness, clarity, intended use, and application feasibility [27]. Limited literature guides the development of conceptual decision-making frameworks, especially for incorporating simulation outputs and conducting expert validation in early research stages. This study adopts a simulation-based framework to illustrate how performance data would inform decision processes while awaiting actual empirical data confirmation to address this gap.

3 Framework Development Methodology

This section presents an overview of the process for developing the conceptual decision-support framework. The process follows 4 sequential phases, with each one building on the output of the prior phase. Phase one builds the evaluation criteria by identifying factors that matter when choosing between steel connection technologies. The factors were identified through a qualitative literature review from academic database searches (Web of Science, Engineering Village, Scopus). Three major performance dimensions of worker safety, assembly efficiency, and construction cost were identified, with a further split into 12 sub-criteria for expert review and feedback. These criteria were confirmed through prior ISC studies [19, 37], which established that up to 40% of steel erection labor hours are devoted to connection work, making ergonomic risks, assembly duration, and cost the most consequential performance dimensions for comparative technology evaluation.

Phase 2 designed the simulation process protocol. The model components (beams, columns, and connection details) were defined (14 ft × 14 ft × 20 ft steel frame comprising four W14×90 columns, four W18×50 beams, and eight connections, modeled in Autodesk Revit and exported to Navisworks for 4D simulation), tools, and equipment set-up positioning. Simulation assembly steps were defined from a work breakdown structure (WBS), and durations for task performance were recorded for analysis. A visualization software, Navisworks, analyzed the 4D timeline, clash detection, worker viewpoints, and time tracking. Next, a computer-vision-based algorithm measured how physically demanding each connection type is for workers. This was achieved through a REBA scoring system that identified worker postures during various stages of steel connections (Openpose algorithm helped to analyze and extract body key points and joint angles), risk levels, and guided required resolution actions. Cost analysis informed by historical cost data of RS Means identified each steel member by line-item description and broke down the assembly costs into material, labor, equipment, and life-cycle costs. A sensitivity analysis across various geographical locations also measured the cost impact expectations.

Phase 3 executed the simulation and data collection process in 3 scenarios: typical assembly process, constrained site conditions, and a detailed production phase. The typical assembly process relied on the ISC dataset from the study of [19] compared against the bolted connection dataset from site recordings. Results were aggregated into a performance data matrix. Weights for each performance criterion and sub-categories were also calculated for a final TOPSIS analysis. A point allocation expert survey was distributed to 8 steel construction professionals, spanning safety managers, general contractors, structural engineers, steel erectors, and project owners. Performance dimensions to be weighed were worker safety, assembly efficiency, and construction costs. Sub-criterion weights within worker safety placed the highest importance on ergonomic risk and fall protection requirements. For assembly efficiency, installation time, and labor requirements were noted as most important, while for construction costs, labor and material costs were both weighted as the highest consideration factors.

Phase 4 is the TOPSIS analysis stage; the two connection technologies are compared mathematically (vector normalization), and the best choice is closest to the ideal solution as much as possible and farthest from the worst solution. This is summarized as presented in Figure 1 above. The TOPSIS model measures the weightings from expert feedback on performance dimensions and sub-criterion factors, and plots against standard ideal ranges of performance. The technology with consistent weighting, closest to the ideal, is selected as a preferred technology.

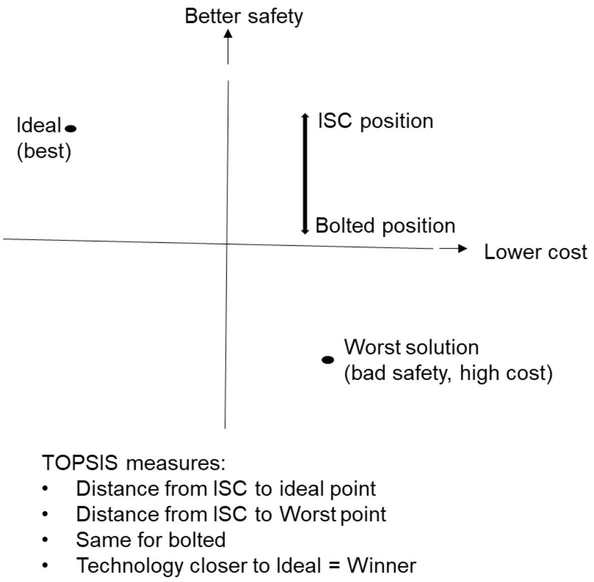

Figure 1. TOPSIS decision support analysis chart

The typical framework outputs and applications can be seen as presented in Table 1 below. The outputs translate analytical evaluation into practical decision support for multiple stakeholders. Overall closeness coefficients provide a single performance score that helps project managers and contractors decide whether the ISC system should be adopted. Criterion-level scores break this result down by technical, cost, or safety dimensions, allowing engineers and safety managers to identify specific strengths and weaknesses. Weight sensitivity results show how stable the recommendation is when priorities change, supporting confidence among risk-averse decision-makers. Cost breakdowns offer location-specific financial insight for owners and estimators, while safety metrics quantify hazard exposure to help safety directors and regulators assess whether the ISC system provides a safer alternative.

Table 1. Proposed Framework Output and Application Process

Output	What it shows	Who uses it	Decisions supported
Closeness coefficients	Overall technology performance score	Project managers, contractors	Should the ISC system be adopted?
Criterion-Level scores	Performance weight on specific dimensions or criteria	Engineers, Safety managers	Where does ISC perform better or worse?
Weight Sensitivity	How robust is the recommendation?	Risk-averse stakeholders	Can this decision be trusted?
Cost Breakdowns	Detailed cost comparison by location	Estimators, Owners	Market cost impact
Safety Metrics	Hazard exposure quantification	Safety directors, OSHA	Is the ISC system safer?

4 Results

The proposed conceptual decision-support framework incorporates three primary performance dimensions: worker safety, assembly efficiency, and construction cost. Each dimension was further split into 12 secondary evaluation criteria (four per dimension), and specific performance indicators were weighed from expert reviews. The framework integrates outputs from BIM-based constructability simulation, computer-vision-based ergonomic assessment, cost database analysis across geographical locations, and TOPSIS multi-criteria decision analysis for systematic technology comparison.

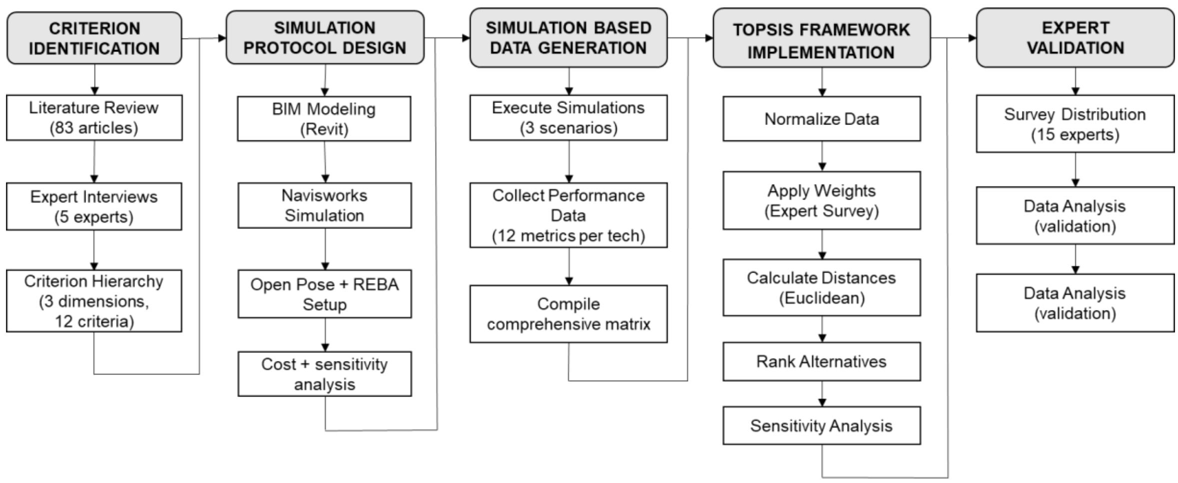

Figure 2. Conceptual Decision-Support Framework for Evaluating Steel Connection Systems

The proposed framework in Figure 2 addresses a critical gap in construction management by providing a structured, repeatable process for evaluating innovative steel connection systems, such as the intermeshed steel connection, against established traditional connection systems. The 3 dimensions of performance review offer practitioners a comprehensive overview of the technology when field performance data remains limited. The framework contributes to a systematic framework for integrating digital construction technologies with a thorough MCDM methodology, providing objective evaluation approaches. The proposed expert feedback weights from the survey and sensitivity analysis protocols enable the framework to accommodate several stakeholder priorities while maintaining robust decision recommendations. While this conceptual framework architecture establishes protocols and analytical procedures, further empirical data-based validation will be essential to confirm the framework's effectiveness and refine measurement approaches. Robust empirical data would also aid in verifying the criterion of relevance through expert review surveys and illustrating practical application through a pilot study.

Applying the survey-derived weights to the normalized performance matrix, the TOPSIS analysis yielded closeness coefficients of 0.664 for ISC and 0.344 for the bolted connection, ranking ISC as the preferred technology across all 12 evaluation criteria. ISC outperformed the bolted connection on 11 of the 12 criteria, with the bolted system retaining an advantage only on the learning curve due to established industry familiarity. Sensitivity analysis under three alternative weight scenarios (equal weights, safety-focused, and cost-focused) confirmed ISC as the ranked-first technology in every scenario, demonstrating ranking robustness regardless of stakeholder priority orientation. Panelists evaluated the framework on comprehensiveness, criterion relevance, measurement feasibility, TOPSIS appropriateness, and practical applicability using a 5-point Likert scale, with an acceptance threshold of $\geq$ 4.0 on each dimension and $\geq$ 60% likelihood of adoption.

5 Conclusion

The study presents a conceptual decision-support framework for evaluating steel connection systems. This framework was tested through simulated performance data drawn from prior ISC research. Although the framework is conceptual in design, its development was informed by empirical and simulation-based evidence. A computer vision REBA assessment using OpenPose on steelworker image datasets quantified a 40% ergonomic risk deduction for ISC over bolted connections. 4D assembly simulations also documented a 29% reduction in installation time with a reduction in fall hazard exposure. RS means cost data analysis across five geographic locations confirmed a consistent 10% life-cycle cost advantage for ISC. These data-informed inputs strengthen the credibility of the TOPSIS ranking outputs and demonstrate how digital construction technologies can objectively support technology adoption decisions before full-scale empirical validation is available. The framework offers construction researchers and practitioners a replicable, evidence-based methodology for evaluating innovative steel connection systems. Future research should operationalize the framework through controlled laboratory or field-based pilot tests using live assembly data to validate the simulated performance metrics. A formal expert validation survey spanning professionals, academia, and industry practitioners will provide additional criterion-weighting feedback. The framework is also extensible to connection technologies beyond ISC and bolted systems, and automation through user-friendly TOPSIS-based decision tools would further support industry adoption.

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