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A BIM-Based Multi-Criteria Bridge Design Evaluation Framework Integrating Design for Manufacture and Assembly (DfMA) for Prefabricated Bridge Construction

Mubashir Islam[1];

[1]. *Master of Engineering in Civil Engineering, College of Engineering, Lamar University, TX, USA; Email: muby.im454@gmail.com*

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Abstract

This study has examined how the integration of Design for Manufacture and Assembly (DfMA) principles into a Building Information Modelling (BIM) based multi-criteria evaluation process affects the quality of design decisions in prefabricated bridge construction, and it has developed and tested a framework for evaluating competing bridge design alternatives at the concept and preliminary stages. The central problem has been that bridge design alternatives are conventionally selected on cost and structural adequacy alone, at a point when manufacturing, transport, lifting, and erection knowledge has not yet entered the process, so that buildability problems are discovered during shop-drawing production or on site, when the design is frozen, the moulds are cut, and correction is possible only through rework, variation, or site improvisation. Guided by five research questions, concerning how BIM-based DfMA integration affects design evaluation performance, which DfMA attributes most influence assembly outcomes, which multi-criteria decision-making methods are most robust for bridge design evaluation, what risks conventional cost-dominated evaluation carries, and how manufacturability, logistics, and lifecycle criteria improve evaluation reliability, the study has proposed a framework comprising five contributing constructs: BIM design representation and parametric maturity; DfMA principle embedment in bridge design; multi-criteria evaluation rigour and weighting robustness; manufacturability and logistics constraint integration; and lifecycle sustainability and cost criteria integration, with design evaluation effectiveness as the outcome. A quantitative, cross-sectional design supplemented by a prototype evaluation of a precast bridge design set has been used, and data have been collected from bridge design engineers, BIM and digital engineering leads, precast production engineers, construction and erection managers, and client advisers. Out of 268 distributed questionnaires, 231 valid responses have been retained, producing an 86.2% valid response rate. The analysis has included descriptive statistics, reliability testing, correlation analysis, multiple regression, hypothesis testing, and a prototype evaluation of buildability-issue resolution timing, DfMA attribute influence, and the rank stability of competing decision methods under weight perturbation. The findings have shown that all five constructs were significantly and positively associated with design evaluation effectiveness, that the regression model was significant, $F(5, 225) = 57.74$, $p < .001$, explaining 56.2% of the variance, and that DfMA principle embedment and manufacturability and logistics constraint integration were the strongest predictors.

KEYWORDS

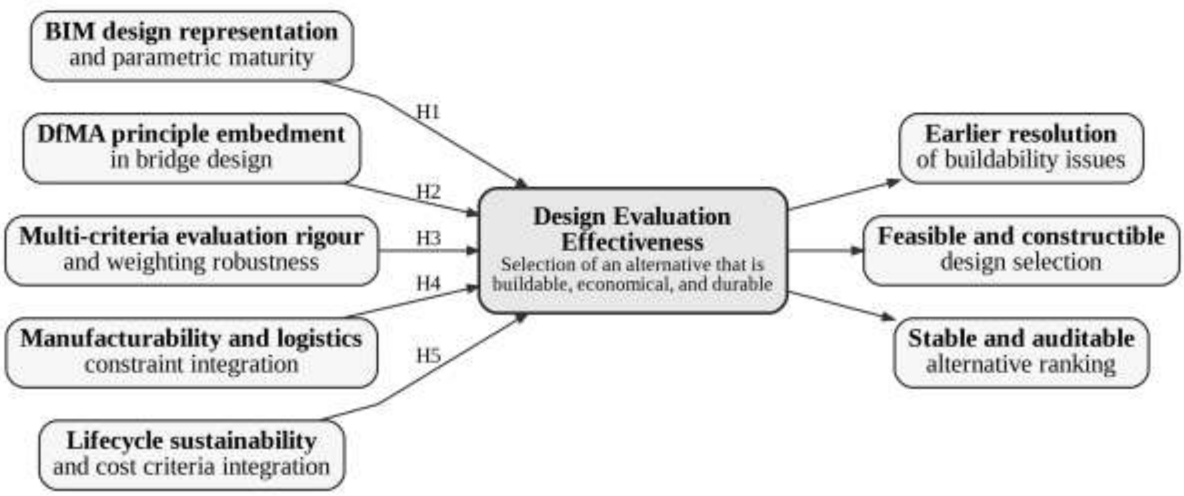
Design for Manufacture and Assembly; Building Information Modelling; Multi-Criteria Decision Making; Prefabricated Bridges; Buildability; AHP–TOPSIS; Design Evaluation.

INTRODUCTION

Bridge design evaluation is one of the most consequential and least structured decisions in transportation infrastructure delivery, because the alternative selected at concept or preliminary design commits the project to a fabrication method, a component inventory, a transport and lifting regime, and an erection sequence, all of which are extremely costly to revise once detailed design begins. Building Information Modelling has become the medium in which those alternatives are represented, and its application to bridges and transportation assets has advanced considerably (Costin et al., 2018; Bradley et al., 2016). Yet a structural feature of the design process undermines the value of that representation: the criteria on which alternatives are actually compared at the concept stage are almost invariably capital cost and structural adequacy, while the manufacturing, logistics, and assembly knowledge that determines whether a design can be built economically resides downstream, with precasters and erection contractors who are not yet appointed. This asymmetry between when a design is committed and when its buildability is understood is the central challenge this study addresses.

The consequence is that buildability problems are discovered late. A connection detail that cannot be formed in the mould, a segment that exceeds the permissible transport envelope on the only available haul route, a lifting weight that requires a larger crane than the site can accommodate, or a proliferation of bespoke component types that destroys the economics of prefabrication are all discoverable at concept stage in principle, but in practice surface during shop-drawing production or on site (Johnsson & Meiling, 2009; Jin et al., 2018). This latency is particularly damaging in prefabricated bridge construction because the promise of prefabrication is precisely repetition, factory quality, and short site occupation, and each of these is forfeited when the design must be adapted after the fact (Jiang et al., 2018). The premise of this study is that better prefabricated bridge outcomes cannot be obtained by refining a chosen design, but require that manufacturing and assembly knowledge be brought upstream into the evaluation of alternatives, and that the evaluation itself be conducted with methodological rigour rather than by cost comparison.

Figure 1: Theoretical Framework for BIM-Based DfMA Multi-Criteria Bridge Design Evaluation



The stakes are substantial and growing. Prefabricated and modular methods are increasingly mandated or incentivised as a response to construction productivity stagnation, skilled-labour scarcity, and the need to minimise disruption on operating networks, and bridge replacement in particular is a domain where site occupation is the dominant cost to the travelling public (Kamali & Hewage, 2016; Jin et al., 2018). At the same time the intellectual means to close the gap have matured in parallel. DfMA, long established in manufacturing, has been adapted into construction-oriented guidelines that make manufacturability and assemblability assessable at design stage (Lu et al., 2021; Tan et al., 2020); multi-criteria decision-making methods have been applied extensively to sustainable bridge design and are now well characterised in their relative strengths (Penadés-Plà et al., 2016; Navarro et al., 2019); and BIM provides the parametric substrate on which alternatives can be generated and quantified at low marginal cost (Vignali et al., 2021; Li et al., 2024). What has not been established is how these three combine into a single evaluation process for prefabricated bridges, and whether that combination in fact improves design decisions rather than merely formalising them. That is the gap this study seeks to close.

Research on the individual components is substantial but disconnected. The DfMA literature has produced construction-oriented principles and guidelines, but has concentrated on buildings and modular volumetric systems rather than on the linear, heavy, tolerance-critical components characteristic of bridges (Lu et al., 2021; Tan et al., 2020). The bridge MCDM literature has developed sophisticated weighting and ranking procedures, but has applied them predominantly to sustainability assessment of already-defined structural typologies rather than to manufacturability and assembly (Penadés-Plà et al., 2016; Navarro et al., 2020a). The BIM literature has established model-based quality assessment for precast elements, but downstream of design rather than as an input to design selection (Kim et al., 2015; Wang et al., 2018). Their integration into a single evaluation framework for prefabricated bridges remains incomplete (Md Mostafizur, 2025; Muhammad Zahidul, 2024; Mukut Kanti, 2025). This study addresses that gap by developing a framework that couples BIM-based parametric generation, DfMA scoring, and constraint screening to a weight-robust multi-criteria evaluation, and by testing it against practitioner data and a prototype design set (Debasish, 2021; Md Mesbaul, 2025).

This study is organised around five research questions. The first asks how BIM-based DfMA integration affects design evaluation performance for prefabricated bridges, and it is addressed by characterising the mechanism and magnitude of the improvement in the timing of buildability resolution. The second asks which DfMA design attributes most influence prefabricated bridge buildability and assembly performance, and it is addressed by distinguishing attributes and evaluating their differential influence. The third asks which multi-criteria decision-making methods are most effective and most robust for bridge design evaluation, and it is addressed by comparing the principal methods on multiple criteria and by testing the stability of their rankings under weight perturbation. The fourth asks what risks conventional, cost-dominated, single-criterion design evaluation carries, and it is addressed by identifying and rating those risks. The fifth asks how manufacturability, logistics, and lifecycle criteria integration improves evaluation reliability, and it is addressed by testing whether these capabilities strengthen the evaluation's capacity to identify designs that prove buildable in execution. The purpose of the study is therefore both explanatory, to characterise the effect of upstream integration and the risks of cost-led selection, and prescriptive, to identify the attributes and methods that make evaluation effective.

The study contributes in three ways. Theoretically, it integrates the DfMA, bridge multi-criteria decision-making, and BIM literatures into a single framework of design evaluation effectiveness, treating bridge design selection as a manufacturability-constrained multi-criteria problem rather than a cost comparison among structurally adequate options. Empirically, it tests this framework against data from practitioners spanning design, manufacture, erection, and ownership, and evaluates a prototype design set measuring resolution timing, attribute influence, and rank stability. Practically, it offers designers and owners a structured account of why cost-led selection fails, which DfMA attributes and decision methods matter most, and how constraint screening converts a design comparison into a buildability judgement. The remainder of the article reviews the relevant literature and develops the framework and hypotheses, formalises the DfMA index and the ranking procedures, describes the method, presents the findings organised around the research questions, and concludes with recommendations, limitations, and directions for future work.

LITERATURE REVIEW AND FRAMEWORK DEVELOPMENT

The literature review develops the theoretical foundation for the evaluation framework by drawing on five research streams, each corresponding to one construct. It begins with BIM-based design representation for bridges, then examines DfMA in construction, multi-criteria decision-making for bridge design, manufacturability and logistics constraints in prefabrication, and lifecycle sustainability and cost assessment, and it concludes by synthesising them into the framework and hypotheses. Throughout, the review maintains that design evaluation effectiveness, the capacity of an evaluation process to select at concept or preliminary stage an alternative that proves buildable, economical, and durable in execution, is jointly determined by the maturity of the model in which alternatives are represented, the depth to which DfMA principles are embedded in them, the rigour of the multi-criteria procedure applied, the integration of manufacturing and logistics constraints, and the inclusion of lifecycle criteria.

BIM-based design representation and parametric alternative generation

Building Information Modelling has been applied extensively to bridges and transportation structures, with object-oriented models supporting coordination, quantity extraction, and construction sequencing (Costin et al., 2018; Vignali et al., 2021). The literature has established the characteristic difficulties of the bridge case, including alignment-driven geometry that resists the orthogonal object hierarchies of building models, and the comparative immaturity of standardised classification and property definitions for bridge components (Čuš-Babič et al., 2022; Li et al., 2024). It has also established that the value of BIM at concept stage lies less in visualisation than in parametrisation: where the model is authored parametrically, a family of design alternatives can be generated and quantified at low marginal cost, which is the precondition for comparing more than the two or three options that manual production permits (Succar, 2009; Cerovsek, 2011; Bryde et al., 2013). A parallel body of work has demonstrated that a formally structured model can be tested automatically against codified requirements through rule-based and semantic checking (Eastman et al., 2009; Solihin & Eastman, 2015), and that the same model can subsequently serve as the reference against which the constructed object is verified geometrically (Bosché, 2010; Yang et al., 2022), which establishes the model rather than the drawing as the locus of design evidence.

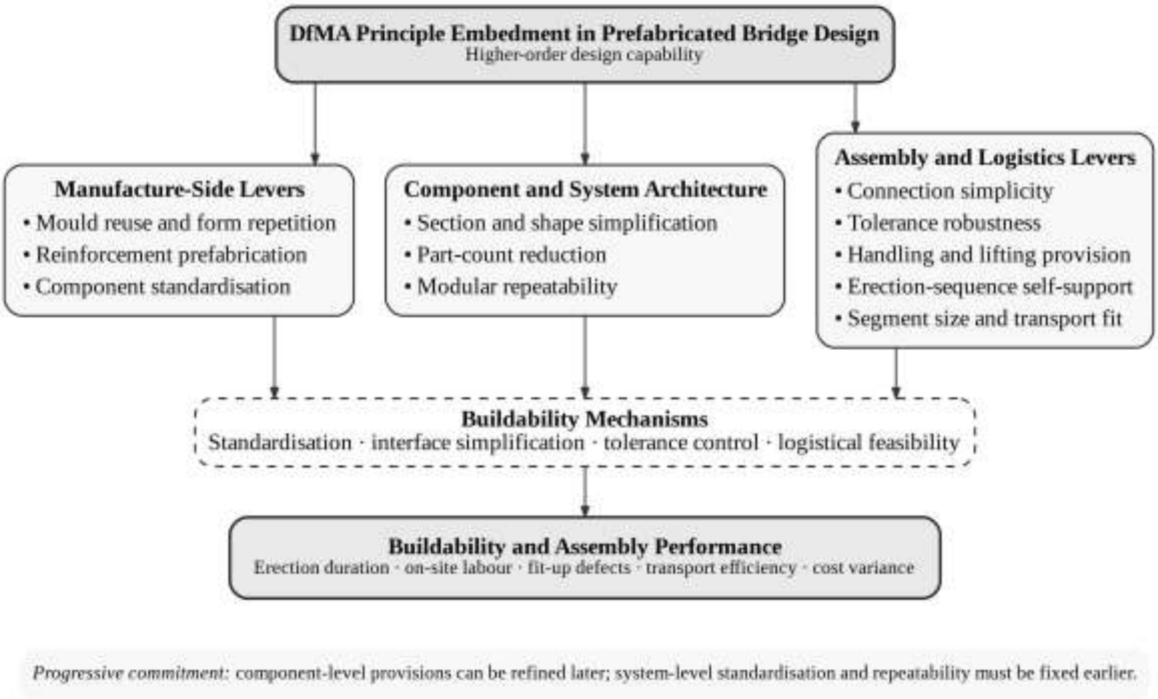
This literature grounds the BIM design representation and parametric maturity construct. It establishes that automated evaluation can only test what the model formally carries, so that object classification, property completeness, and parametric flexibility determine the range and depth of the comparison that is possible at all (Volk et al., 2014; Deng et al., 2021). The framework builds on this by treating the model as the generator and the evidence base of the alternative set, and by requiring that it be structured for evaluation rather than for documentation alone (Md Arif Uz et al., 2025; Md Mesbaul, 2023).

Design for Manufacture and Assembly in construction

The second stream concerns DfMA, which supplies the design principles whose embedment the framework measures (Debasish, 2021; Mukut Kanti, 2020). Originating in manufacturing, DfMA provides methodological procedures for evaluating and improving a design simultaneously for factory production and for assembly, principally through part-count reduction, standardisation, simplification of connections, and provision for handling and tolerance (Lu et al., 2021). Its translation into construction has been rapid but contested, with some arguing that it restates buildability and lean construction and others that it constitutes a distinct direction (Abdur & Iftekhar, 2021; Mohammad Abir Chowdhury & Tonay, 2022; Hossan, 2021); the resulting construction-oriented guidelines make manufacturability and assemblability assessable at design stage rather than merely exhortatory (Tan et al., 2020). The offsite construction literature has documented the performance differences between prefabricated and conventional methods and the conditions under which the former delivers its promised advantages (Jin et al., 2018; Kamali & Hewage, 2016; Jiang et al., 2018), and has shown that defects in offsite work concentrate at interfaces and connections rather than within components (Johnsson & Meiling, 2009).

This literature grounds the DfMA principle embedment construct and frames the study's account of buildability (Md Mesbaul, 2023; Mst Shurovi, 2024; Zahidul & Begum, 2022). It establishes that DfMA is not a single property but a family of design attributes with different levers and different points of effect, and that the attributes differ substantially in how early they must be fixed (Muhammad Zahidul, 2024; Kanti, 2024; Shima Ali et al., 2024): a decision about component standardisation constrains the entire scheme and must be taken at concept stage, whereas a lifting-point provision can be added later at modest cost (Md Arif Uz et al., 2025; Md Mesbaul, 2025; Tonay et al., 2024). The framework treats DfMA embedment as a distinct construct because an organisation may profess DfMA while embedding it only superficially, and because the comparative influence of the attributes is what the second research question asks the study to establish (Muhammad Zahidul & Amena Begum, 2022; Mst Shurovi, 2024).

Figure 2: Theoretical Taxonomy of DfMA Design Attributes for Prefabricated Bridges



Multi-criteria decision-making for bridge design evaluation

A substantial literature has applied multi-criteria decision-making to bridge design, which the third research question concerns. Reviews of this literature have classified the methods used, their frequency of application across the bridge lifecycle, and the criteria to which they have been applied (Penadés-Plà et al., 2016; Navarro et al., 2019; Navarro et al., 2020a). The methods fall into several families. Weight-elicitation procedures, principally the analytic hierarchy process, derive criteria weights from structured pairwise comparison and provide a consistency check on the judgements supplied (Saaty, 1990). Distance-based ranking procedures, notably TOPSIS and VIKOR, rank alternatives by proximity to an ideal solution and, in VIKOR's case, by a compromise between group utility and individual regret, and the two have been compared directly (Opricovic & Tzeng, 2004). Simple additive weighting remains widely used for its transparency despite its known sensitivity to weight specification. Applications to bridges have addressed deck design in aggressive environments and post-tensioned box-girder alternatives, and have increasingly incorporated fuzzy and neutrosophic treatments of judgement uncertainty (Navarro et al., 2020b; Penadés-Plà et al., 2017).

This literature grounds the multi-criteria evaluation rigour and weighting robustness construct. It establishes that the choice of method is not a formality, because different procedures applied to the same decision matrix can produce different rankings, and because the sensitivity of a ranking to the weights it rests on is itself a property of the method rather than of the data (Opricovic & Tzeng, 2004; Saaty, 1990). The framework treats evaluation rigour as a distinct construct, encompassing criteria completeness, weight elicitation quality, consistency checking, and sensitivity analysis, because an evaluation that is formally multi-criteria but rests on unexamined weights offers the appearance of rigour without its substance (Md Syeedur & Sharmin, 2025; Tonay et al., 2024).

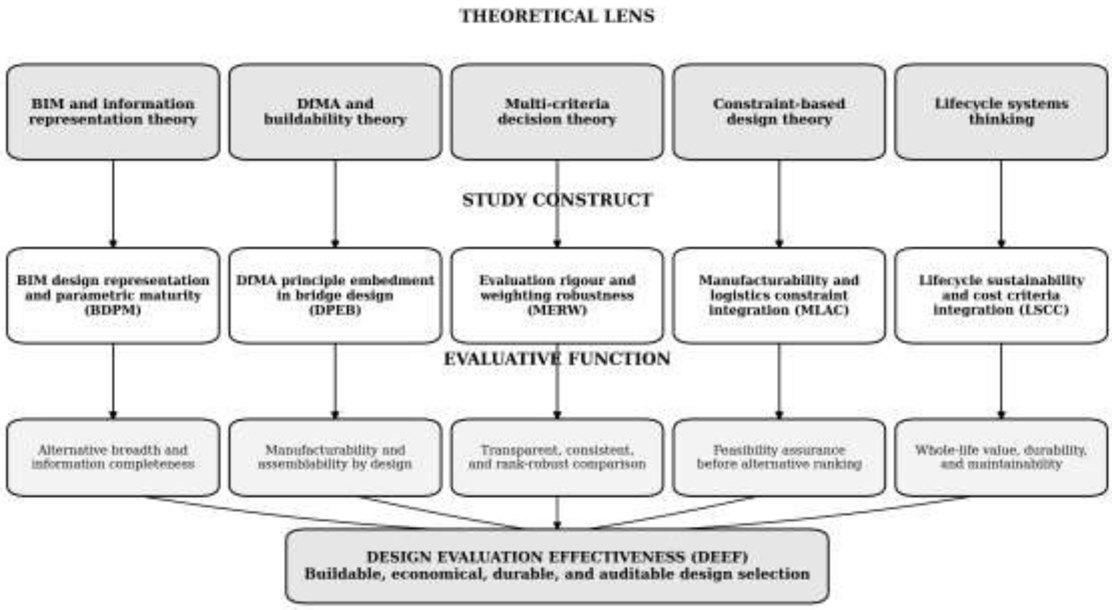
Manufacturability, logistics, and assembly constraints in prefabrication

The fourth stream concerns the hard constraints that separate a design that scores well from one that can actually be produced and erected (Md Mostafizur, 2025; Md Mostafizur et al., 2025; Md Syeedur & Sharmin, 2025). Factory capacity, mould availability and reuse, curing and storage, transport envelope and route restrictions, crane capacity, and the permissible site occupation window each impose feasibility limits that are binary rather than graded, and a design violating any of them is not a lower-ranked alternative but an infeasible one (Jin et al., 2018; Kamali & Hewage, 2016). The literature on precast quality has developed model-based methods for verifying that manufactured components conform to their design geometry, using laser scanning compared against the model to assess dimensional and surface quality (Kim et al., 2014; Kim et al., 2015; Kim et al., 2016), and has extended this to as-built model creation for precast bridge deck panels specifically (Wang et al., 2018). Related work has integrated defect and condition information into bridge models and demonstrated the coupling of models to lifecycle digital representations (Hüthwohl et al., 2018; Honghong et al., 2023). This literature grounds the manufacturability and logistics constraint integration construct. It establishes that constraint screening is logically prior to ranking, because a multi-criteria comparison across an alternative set containing infeasible members produces a ranking whose leader may be unbuildable, and it establishes that tolerance is the mechanism through which manufacturing capability and assembly feasibility are linked, since a connection that assumes tighter tolerances than the plant can hold will fail at fit-up regardless of how the design was scored (Johnsson & Meiling, 2009; Kim et al., 2016). The framework treats constraint integration as a distinct construct because it is the dimension on which design offices most often lack information, and because its absence converts an evaluation into a hypothesis (Mohammad Shoriful Hossan, 2021; Md. Abdur & Iftekhar, 2021).

Lifecycle sustainability and cost criteria

The fifth stream concerns the criteria that extend evaluation beyond capital cost. Life-cycle assessment and life-cycle costing have been applied to bridge alternatives to quantify environmental burden and whole-life expenditure, and reviews have documented their incorporation into multi-criteria frameworks, together with the persistent difficulty of the end-of-life stage and of the social dimension (Navarro et al., 2020a; Penadés-Plà et al., 2017; Navarro et al., 2020b). The literature has also established that durability and maintainability criteria interact directly with DfMA choices, since standardisation and connection accessibility govern the cost of future intervention as much as the cost of initial assembly (Kaewunruen & Xu, 2018; Callcut et al., 2021), and that model-based methods increasingly support the transfer of design assumptions into operational assessment (Torzoni et al., 2024; Wang et al., 2022). The digital twin literature has extended this trajectory, framing the design model as the origin of a representation that is maintained and enriched across the asset lifecycle rather than superseded at handover (Sacks et al., 2020; Boje et al., 2020; Jiang et al., 2021; Honghong et al., 2023), and artificial-intelligence applications in construction engineering have begun to automate parts of the design appraisal itself (Pan & Zhang, 2021; Zhang et al., 2022).

Figure 3: Theoretical Lineages, Construct Derivation, and Evaluative Functions

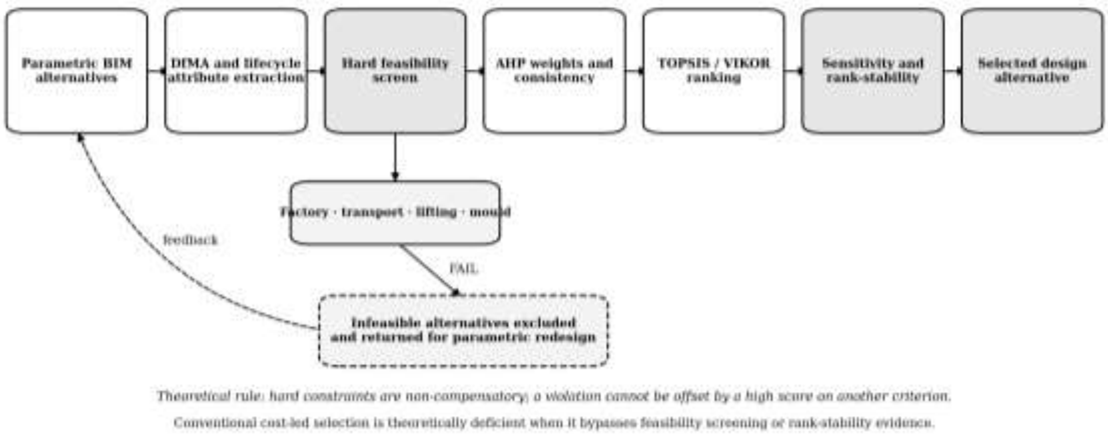


This literature grounds the lifecycle sustainability and cost criteria construct. It establishes that an evaluation confined to capital cost systematically favours alternatives whose burdens fall outside the appraisal boundary, and that the criteria most often omitted, maintenance access, component replaceability, and embodied carbon, are precisely those most strongly determined by the DfMA decisions taken at concept stage (Penadés-Plà et al., 2016; Navarro et al., 2019). The framework treats lifecycle criteria as a distinct construct because their inclusion changes not only the ranking but the design attributes that the evaluation rewards (Md Mostafizur et al., 2025; Sharif Md Yousuf et al., 2025; Shima Ali et al., 2025). Figure 3 consolidates these five theoretical lineages by tracing each literature stream to its corresponding construct, evaluative function, and common outcome.

Synthesis: the evaluation framework and hypotheses

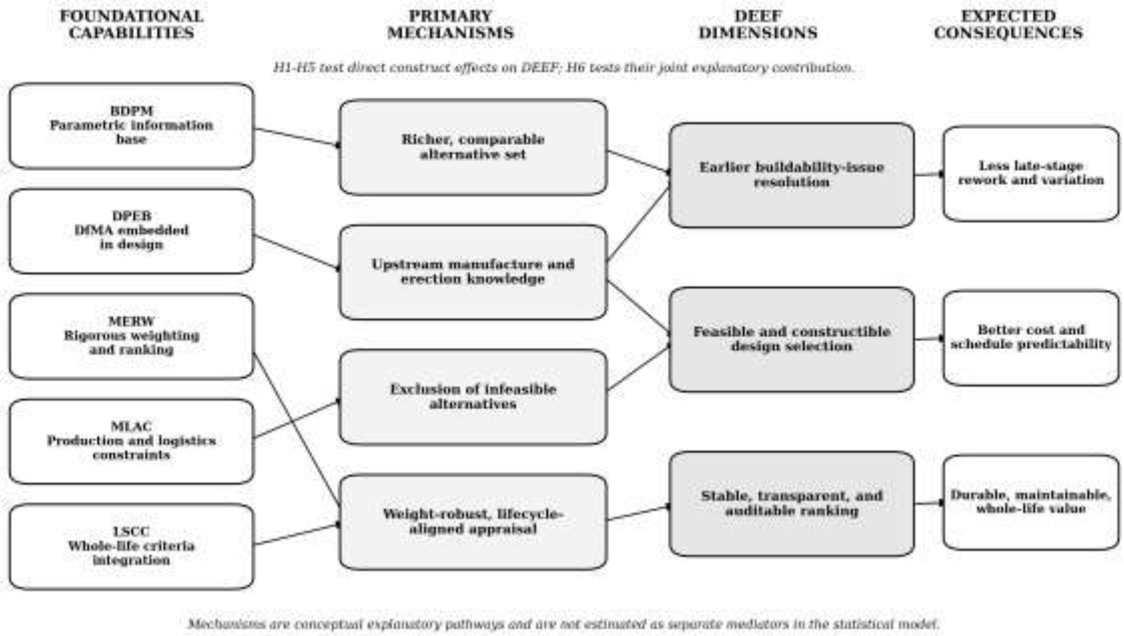
Synthesising the five streams yields the design evaluation effectiveness framework that this study tests. The framework holds that the effectiveness of a bridge design evaluation, its capacity to select an alternative that proves buildable, economical, and durable, is jointly determined by five constructs: BIM design representation and parametric maturity (Muhammad Zahidul, 2025; Mukut Kanti, 2025; Sharif Md Yousuf et al., 2025); DfMA principle embedment in bridge design; multi-criteria evaluation rigour and weighting robustness; manufacturability and logistics constraint integration; and lifecycle sustainability and cost criteria integration. A deficiency in any one can undermine effectiveness: without a parametric model the alternative set is too narrow to contain a good option, without DfMA embedment the alternatives differ only structurally, without evaluation rigour the comparison rests on unexamined weights, without constraint integration the winner may be infeasible, and without lifecycle criteria the evaluation optimises the wrong horizon (Shima Ali et al., 2025). This framework answers the first and fourth research questions, on how integration affects evaluation and what risks cost-led selection carries, and it structures the empirical investigation of the second, third, and fifth. Figure 4 translates this synthesis into a constraint-first decision logic in which feasibility screening precedes compensatory ranking and failed alternatives return to parametric redesign.

Figure 4: Constraint-First Theoretical Logic for BIM-Based DfMA Multi-Criteria Evaluation



From the framework, five hypotheses are derived, each proposing that stronger performance on a construct is associated with higher design evaluation effectiveness. H1: BIM design representation and parametric maturity is positively associated with design evaluation effectiveness. H2: DfMA principle embedment in bridge design is positively associated with design evaluation effectiveness. H3: Multi-criteria evaluation rigour and weighting robustness is positively associated with design evaluation effectiveness. H4: Manufacturability and logistics constraint integration is positively associated with design evaluation effectiveness. H5: Lifecycle sustainability and cost criteria integration is positively associated with design evaluation effectiveness. A sixth, integrative hypothesis addresses the framework as a whole. H6: The five constructs jointly explain a significant proportion of the variance in design evaluation effectiveness. These hypotheses are tested in the analysis, alongside a prototype evaluation of attribute influence and method rank stability, to address the five research questions. Figure 5 then specifies the multi-level explanatory mechanisms through which the five capabilities are expected to shape evaluation effectiveness and downstream project consequences; these mechanisms are conceptual and are not estimated as separate mediators.

Figure 5: Multi-Level Theoretical Mechanism Framework Linking Capabilities, Evaluation Effectiveness, and Project Consequences



METHODS

This study adopted a quantitative, cross-sectional research design supplemented by a prototype evaluation of a prefabricated bridge design set. The quantitative design was selected because the study measured relationships among the five contributing constructs and design evaluation effectiveness through numerical survey responses, and the cross-sectional design was used because data were collected at a single point in time, capturing practitioners' assessments of model maturity, DfMA embedment, evaluation rigour, constraint integration, and lifecycle criteria within their design processes. The prototype evaluation complemented the survey by applying the framework to a set of competing precast bridge alternatives and measuring buildability-issue resolution timing, DfMA attribute influence, and the rank stability of competing decision methods, providing a technical counterpart to the perceptual measures. The unit of analysis was the individual respondent, understood as an informed practitioner engaged in the design, manufacture, erection, or procurement of prefabricated bridges.

The population comprised bridge design engineers, BIM and digital engineering leads, precast production and manufacturing engineers, construction and erection managers, and client or asset-owner advisers across design consultancies, contractors, precast manufacturers, and public transport agencies. A purposive sampling strategy was used because respondents were selected for their direct relevance to prefabricated bridge design decisions. Primary data were collected through a structured questionnaire using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree), distributed through online forms and professional networks. The instrument included multi-item measures for each of the five constructs and for design evaluation effectiveness, demographic items, and rating items on DfMA attribute influence, decision-method performance, and cost-led evaluation risk that fed the analyses addressing the research questions. A pilot test was conducted with bridge designers and precast engineers to check clarity and technical precision, and feedback was used to refine wording and to align terminology with published construction-oriented DfMA guidelines (Tan et al., 2020) and with the information-requirement vocabulary of the ISO 19650 series (ISO, 2018a). Validity was ensured through literature-based item development, expert review, and alignment among the framework, hypotheses, and items, with convergent validity assessed against the average-variance-extracted criterion (Fornell & Larcker, 1981), and reliability was tested through Cronbach's alpha with a .70 threshold. Procedural remedies against common-method variance were applied, including item separation, response anonymity, and reverse-worded items (Podsakoff et al., 2003). Analysis was conducted in SPSS and Python, the latter using the pandas, NumPy, SciPy, and scikit-learn libraries for data preparation, ranking computation, and sensitivity simulation (Harris et al., 2020; Virtanen et al., 2020). Ethical considerations were observed: participation was voluntary, informed consent was obtained, responses were anonymised, and no proprietary design data, plant capability information, or client-identifying records were collected.

Formalising the DfMA index and the evaluation procedure

The evaluation problem is defined over a finite set of design alternatives assessed against a finite set of criteria. Writing the alternatives as A and the criteria as C, the decision matrix is given in Equation (1), where x_{ij} is the performance of alternative i on criterion j:

$$A = \{ a_1, \dots, a_m \},\ \ C = \{ c_1, \dots, c_n \},\ \ X = [x_{ij}]_{mxn} \tag{1}$$

Because the criteria are measured in incommensurable units, the matrix is normalised by the vector norm before weighting, as in Equation (2):

$$r_{ij} = x_{ij} / \sqrt{\left(\Sigma(k=1 \text{ to } m)\ x_{kj}^2 \right)} \tag{2}$$

Criteria weights are elicited by pairwise comparison. The weight vector is the normalised principal eigenvector of the comparison matrix, as in Equation (3), and the internal consistency of the judgements is tested through the consistency index and ratio in Equation (4), with the conventional acceptance bound of 0.10 (Saaty, 1990):

$$P \cdot w = \lambda[max] \cdot w,\ \ \Sigma(j=1 \text{ to } n)\ w_j = 1,\ \ w_j > 0 \tag{3}$$

$$CI = (\lambda[max] - n) / (n - 1),\ \ CR = CI / RI \leq 0.10 \tag{4}$$

The weighted normalised matrix follows in Equation (5), and the ideal and anti-ideal reference points are defined in Equation (6), where J^+ denotes benefit criteria and J^- cost criteria:

$$v_{ij} = w_j \cdot r_{ij} \tag{5}$$

$$v_j^+ = max_i\ v_{ij}\ (j \in J^+) \text{ or } min_i\ v_{ij}\ (j \in J^-);\ \ v_j^- \text{ correspondingly reversed} \tag{6}$$

Separation from the reference points and the resulting closeness coefficient, on which the TOPSIS ranking rests, are given in Equations (7) and (8):

$$d_i^+ = \sqrt{\left(\Sigma(j)\ (v_{ij} - v_j^+)^2 \right)},\ \ d_i^- = \sqrt{\left(\Sigma(j)\ (v_{ij} - v_j^-)^2 \right)} \tag{7}$$

$$CC_i = d_i^- / (d_i^+ + d_i^-),\ \ 0 \leq CC_i \leq 1 \tag{8}$$

The VIKOR compromise measure, which balances group utility against individual regret through the weight v, is given in Equation (9), where S and R denote the utility and regret measures (Opricovic & Tzeng, 2004):

$$Q_i = \nu \cdot (S_i - S*) / (S^- - S*) + (1 - \nu) \cdot (R_i - R*) / (R^- - R*) \tag{9}$$

The DfMA performance of an alternative is expressed as a composite index over four attribute scores, each normalised to the unit interval, as defined in Equation (10), where N[p] is the part count, N[std] the number of standardised components, κ the aggregate connection-complexity score, and δ the required assembly tolerance:

$$DI(a) = \omega_1(1 - N[p] / N[p,max]) + \omega_2(N[std] / N[p]) + \omega_3(1 - \kappa / \kappa[max]) + \omega_4(\delta / \delta[plant]) \tag{10}$$

Manufacturing and logistics feasibility is treated as a binary screen applied before ranking, so that an alternative violating any hard limit is excluded rather than penalised, as expressed in Equation (11), where L, W, H, and M are the segment length, width, height, and mass:

$$g(a) = 1 \Leftrightarrow (L \leq L[route]) \wedge (W \leq W[route]) \wedge (H \leq H[route]) \wedge (M \leq M[crane]) \wedge (n[mould] \leq n[plant]) \tag{11}$$

Erection performance, the criterion most directly affected by DfMA choices, is estimated from the component inventory and the lifting cycle, as in Equation (12):

$$T[erect] = \Sigma(i)\ n_i \cdot t[cycle,i] + T[setup] + T[closure] \tag{12}$$

Because a ranking is only as trustworthy as the weights supporting it, rank robustness is measured by perturbing the weight vector and recording the rank correlation with the baseline ordering, as defined in Equation (13), where ρ is the Spearman coefficient and the expectation is taken over random perturbations of magnitude ε:

$$RRI(\varepsilon) = E[\,\rho(\,rank(\,w\,)\,,\,rank(\,w + \Delta w\,)\,)\,]\,,\ \ \|\Delta w\|[\infty] \le \varepsilon\ \cdot w \quad (13)$$

Design evaluation effectiveness, the outcome construct, is operationalised both perceptually, through survey items, and, in the prototype, as a weighted composite of the share of buildability issues resolved before design freeze, the realised feasibility of the selected alternative a∗, and the rank robustness of the evaluation that selected it, defined in Equation (14):

$$DEE = \gamma 1\ \cdot \Phi[pre\text{-}freeze] + \gamma 2\ \cdot g(\,a*\,) + \gamma 3\ \cdot RRI(\,\varepsilon_0\,) \quad (14)$$

Statistical model and prototype evaluation

The principal hypothesis test used ordinary least squares multiple regression of design evaluation effectiveness on the five constructs, with BDPM denoting BIM design representation and parametric maturity, DPEB DfMA principle embedment in bridge design, MERW multi-criteria evaluation rigour and weighting robustness, MLAC manufacturability and logistics constraint integration, and LSCC lifecycle sustainability and cost criteria integration, as specified in Equation (15):

$$DEEF_i = \beta_0 + \beta_1\, BDPM_i + \beta_2\, DPEB_i + \beta_3\, MERW_i + \beta_4\, MLAC_i + \beta_5\, LSCC_i + \varepsilon_i \quad (15)$$

Model significance was assessed through the F-statistic, explanatory power through R-squared and adjusted R-squared, residual independence through the Durbin–Watson statistic, and multicollinearity through the variance inflation factor, all confirmed within conventional bounds. The prototype evaluation applied the framework to a set of competing precast bridge alternatives spanning beam-and-slab, segmental box-girder, and modular composite configurations, recording where in the design timeline each buildability issue was resolved, the influence of each DfMA attribute on assembly outcomes, and the rank stability of each decision method under weight perturbation. Attribute influence was reported with feature-attribution explanations so that the contribution of each DfMA lever to the composite score could be inspected and contested by designers rather than accepted as a single figure of merit (Rudin, 2019; Guidotti et al., 2018).

RESULTS

Sample and descriptive statistics

Table 1: Respondent profile and response rate

Variable	Category	Frequency	Percentage
Questionnaires	Distributed	268	100.0%
Questionnaires	Returned	246	91.8%
Questionnaires	Valid and retained	231	86.2%
Role	Bridge design engineer	64	27.7%
Role	BIM / digital engineering lead	52	22.5%
Role	Precast production / manufacturing engineer	45	19.5%
Role	Construction & erection manager	40	17.3%
Role	Client / asset owner adviser	30	13.0%
Organisation	Design consultancy	79	34.2%
Organisation	Contractor / erection specialist	61	26.4%
Organisation	Precast manufacturer	48	20.8%
Organisation	Public owner / transport agency	43	18.6%
Bridge type focus	Precast beam and slab	98	42.4%
Bridge type focus	Segmental box girder	71	30.7%
Bridge type focus	Modular composite and other	62	26.9%
Experience	More than 12 years	79	34.2%
Experience	6–12 years	97	42.0%
Experience	Under 6 years	55	23.8%

Table 1 shows an 86.2% valid response rate, with 231 usable responses. The sample spanned the parties whose knowledge the framework seeks to bring together, from the bridge designers who generate alternatives (27.7%) and the digital engineering leads who model them (22.5%), through the production engineers who must cast them (19.5%) and the erection managers who must assemble them (17.3%), to the client advisers who authorise the selection (13.0%). The organisational distribution across consultancies (34.2%), contractors (26.4%), precast manufacturers (20.8%), and public owners (18.6%) covers the parties between whom design risk is contractually allocated, and 76.2% of respondents had six or more years of experience. This composition matters because the framework's central claim is that manufacturing and assembly knowledge should enter design evaluation upstream, and a sample drawn only from designers or only from manufacturers would answer that question from one side of the gap.

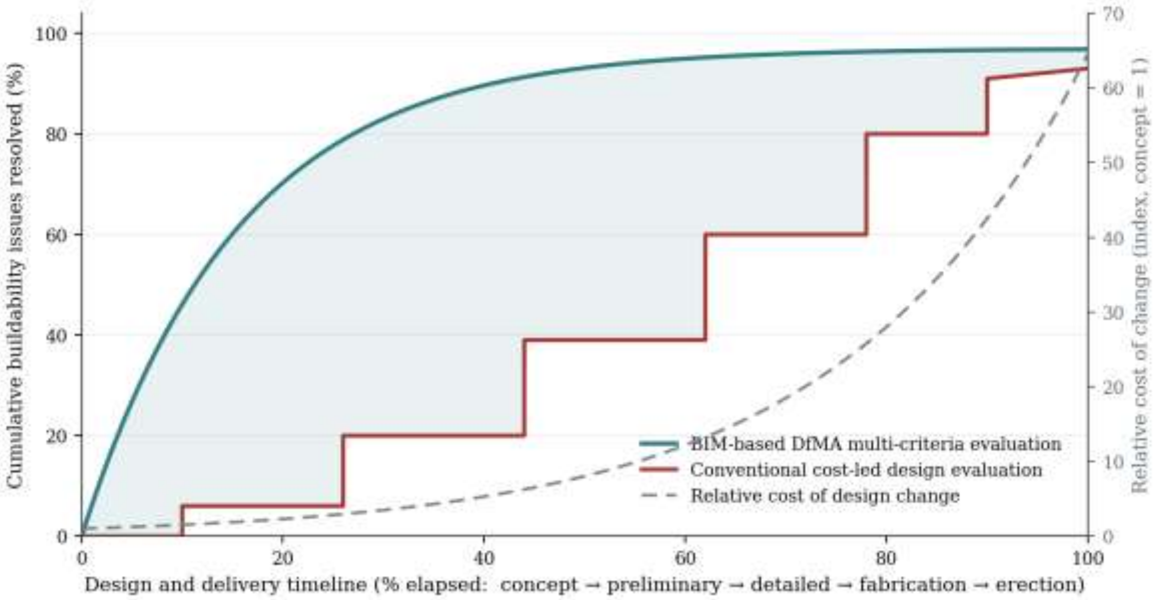
Table 2: Descriptive statistics and reliability of study constructs (N = 231)

Construct	Mean	SD	Cronbach's α
DfMA principle embedment in design (DPEB)	4.28	0.57	.90
Manufacturability & logistics constraint integration (MLAC)	4.21	0.60	.88
BIM design representation & parametric maturity (BDPM)	4.17	0.62	.89
Multi-criteria evaluation rigour & weighting robustness (MERW)	4.02	0.68	.85
Lifecycle sustainability & cost criteria integration (LSCC)	3.94	0.71	.84
Design evaluation effectiveness (outcome, DEEF)	3.82	0.77	.92
Overall instrument	—	—	.94

Table 2 presents the descriptive statistics and reliability. All constructs exceeded the neutral midpoint and all Cronbach's alpha values exceeded .70, ranging from .84 to .92 with overall reliability of .94. The ordering is diagnostically informative.

RQ1: How BIM-based DfMA integration affects design evaluation performance

Figure 6: Buildability Issue Resolution Across the Design Timeline, with Relative Cost of Change



DfMA principle embedment (4.28) and manufacturability and logistics constraint integration (4.21) recorded the highest means, indicating that practitioners regard the upstream movement of production knowledge as the foundation of effective evaluation. Design evaluation effectiveness itself, the outcome, recorded the lowest mean (3.82) and the widest dispersion (SD = 0.77), a revealing pattern: practitioners rate the realised quality of their design decisions lower than any of the contributing capabilities, and the wide spread indicates that realised effectiveness is highly uneven across organisations. This gap between capability and realised outcome foreshadows the study's central finding, that professing DfMA is not the same as embedding it in the evaluation that actually selects the design. Figure 6 presents the prototype evidence for the first research question and shows the mechanism of the improvement directly. Under conventional cost-led evaluation, cumulative resolution of buildability issues rises slowly and in discrete steps corresponding to design reviews and to the eventual appointment of the precaster and erector, with the majority of issues resolved only after detailed design has begun. Under BIM-based DfMA evaluation, resolution rises steeply from the earliest concept cycles, because each parametric alternative is scored and screened against manufacturing and logistics constraints as it is generated rather than after it is selected. The superimposed cost-of-change curve explains why this matters: the two resolution curves diverge most sharply in the region where the cost of change is still near unity, so that the same issues that cost a redesign iteration under the DfMA regime cost a variation, a mould modification, or a site improvisation under the conventional one.

Figure 7: Shift in Buildability Issue Resolution Stage Under BIM-Based DfMA Evaluation

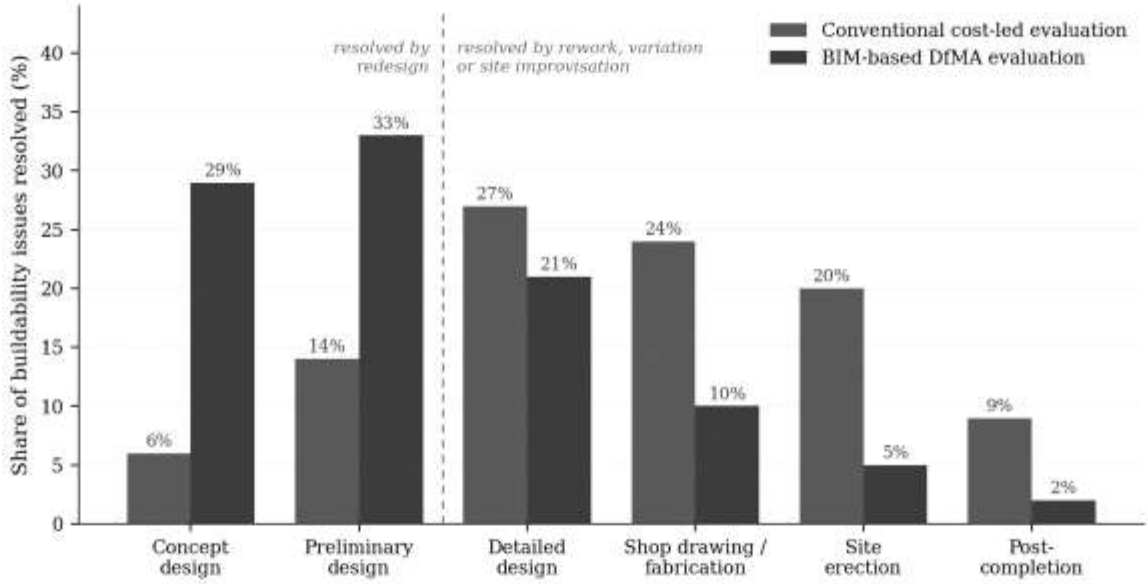
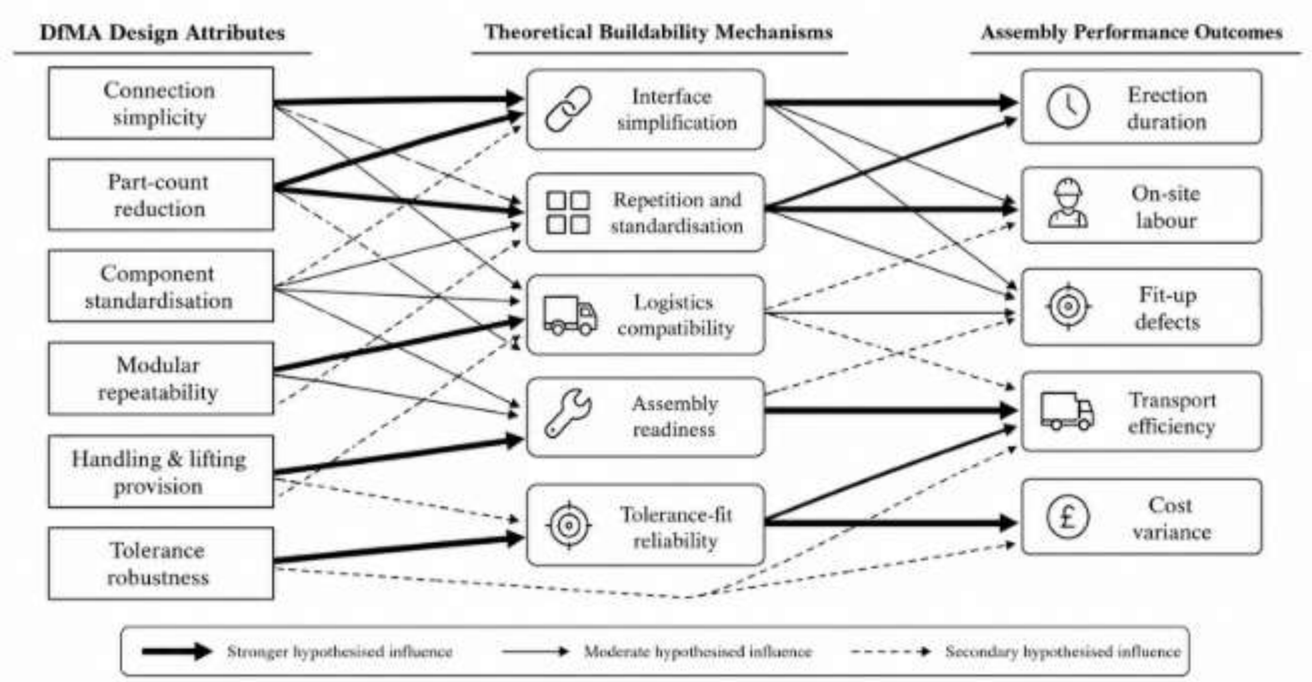


Figure 7 makes the operational consequence concrete by decomposing where in the design timeline issues are resolved under each regime. Under the conventional regime the distribution is weighted toward detailed design and beyond, with substantial mass at shop-drawing production and site erection; under the DfMA regime the distribution shifts markedly toward concept and preliminary design, and the tail beyond detailed design contracts sharply. This redistribution is the practical face of the curve separation in Figure 6, and it clarifies why the improvement matters: the organisation does not merely resolve more issues in the abstract but resolves them while the response is still a change of design rather than a change to a design that has already been priced, detailed, and committed to a fabrication programme.

RQ2: Which DfMA attributes most influence buildability and assembly performance

Figure 8 addresses the second research question by mapping the influence of each DfMA attribute across the principal assembly performance metrics. Reading down the columns, connection simplicity and part-count reduction exert the strongest overall influence, component standardisation and modular repeatability follow, and handling provision and tolerance robustness are more narrowly concentrated; reading across the rows reveals which metrics each attribute most affects. The pattern is theoretically coherent and operationally important. Connection simplicity dominates erection duration and on-site labour because every connection is a discrete site operation performed at height, in weather, and often at night under traffic possession, so that removing a connection removes a whole activity rather than shortening one (Johnsson & Meiling, 2009).

Figure 8: Influence of DfMA Attributes Across Assembly Performance Metrics



Part-count reduction operates similarly but extends further upstream, since fewer distinct components also means fewer moulds, fewer deliveries, and fewer interfaces to detail. Tolerance robustness shows the most concentrated profile of all, exerting decisive influence on fit-up defects while contributing little to transport efficiency, which reflects its nature as an interface property rather than a component property (Kim et al., 2016). Modular repeatability is the strongest single influence on transport efficiency, because a repeated segment can be optimised once against the haul route rather than assessed case by case. The heatmap thus answers the second research question with more resolution than a single buildability score: the attributes are not interchangeable levers on a common outcome but act on distinct performance dimensions, which is why a design scoring well on an aggregate DfMA index may still fail on the specific dimension that governs its project.

RQ3: Which multi-criteria methods are most effective and most robust

Figure 9: Multi-Criteria Decision Methods Compared Across Five Evaluation Criteria

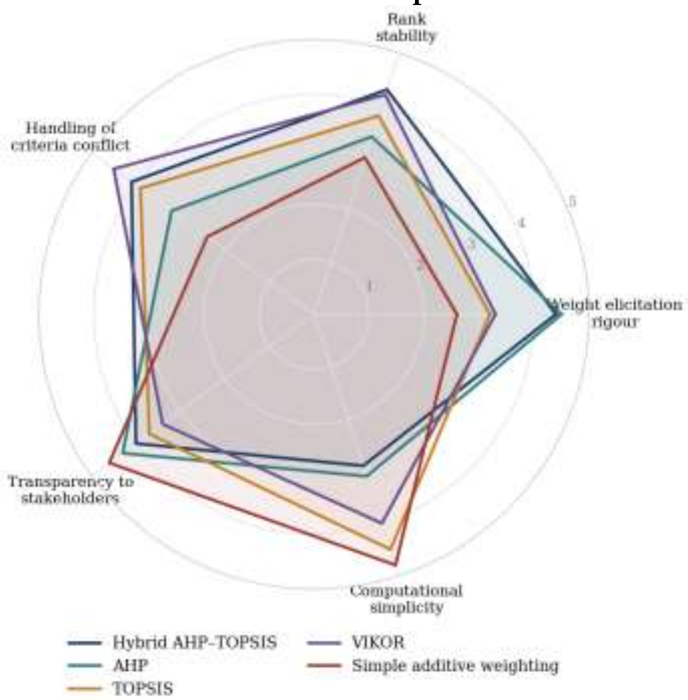


Figure 9 addresses the third research question by profiling the decision methods across five criteria rather than on a single effectiveness score, which reveals the trade-offs that a single ranking conceals. Hybrid AHP–TOPSIS traces the largest and most balanced profile, combining the structured weight elicitation and consistency checking of the analytic hierarchy process with the distance-based ranking of TOPSIS, at a cost in computational simplicity that practitioners rated lowest in the set. AHP alone scores highest on weight elicitation rigour and stakeholder transparency, since pairwise comparison is intelligible to non-specialist decision-makers and yields an auditable consistency ratio, but scores poorly on rank stability and on the handling of conflicting criteria (Saaty, 1990). VIKOR traces the strongest profile on criteria conflict, which follows directly from its construction as a compromise between group utility and individual regret, making it the natural choice where a single alternative must satisfy parties with opposed priorities (Opricovic & Tzeng, 2004). Simple additive weighting scores highest on transparency and simplicity and lowest on everything else, which is the profile of a method that is used because it is understood rather than because it is sound. The comparative geometry answers the first half of the third research question: no method dominates, but the hybrid procedure offers the broadest performance, and the widely used additive procedure is the weakest on precisely the properties that determine whether a ranking can be relied upon.

Figure 10: Rank Stability of Decision Methods Under Criteria Weight Perturbation

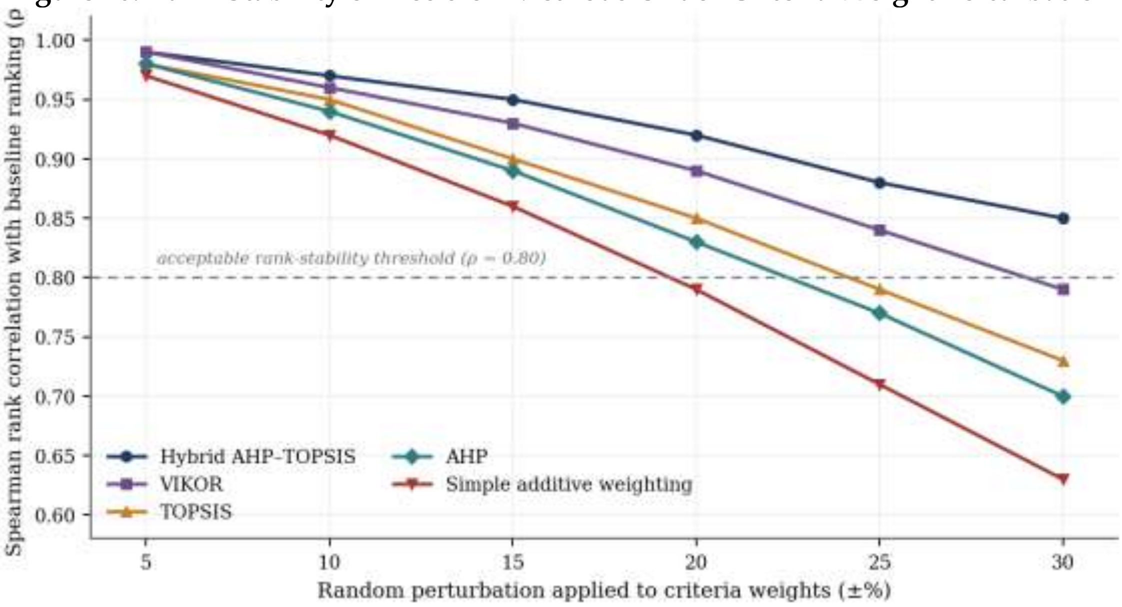
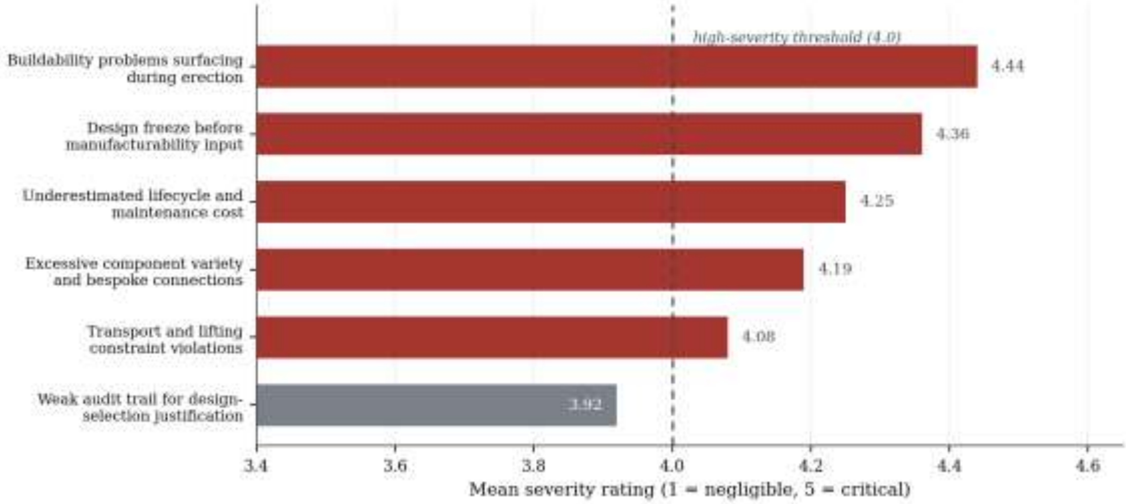


Figure 10 addresses the second and more consequential half of the third research question by testing what happens to each method's ranking when the weights it rests on are perturbed. The result is stark. All methods agree closely at small perturbations, which is why sensitivity analysis is so often omitted, but they diverge rapidly as the perturbation grows. Simple additive weighting falls below the rank-stability threshold at approximately a nineteen per cent perturbation, AHP and TOPSIS at around twenty-two and twenty-four per cent respectively, VIKOR at around twenty-seven per cent, while hybrid AHP–TOPSIS remains above the threshold across the entire tested range. This matters because a twenty per cent uncertainty in elicited criteria weights is not an extreme assumption but a routine one, given that the weights encode contested organisational priorities gathered from a handful of judgements. The practical implication is that a ranking reported without a stability test carries an unquantified risk of reversal, and that the appropriate response is not to elicit weights more confidently but to select a method whose ordering survives the uncertainty that will inevitably remain.

RQ4: Risks of conventional cost-dominated design evaluation

Figure 11: Risks of Cost-Dominated Single-Criterion Design Evaluation



Note. N = 231. Risks are ranked by mean severity rating; the dashed line marks the high-severity threshold (4.0).

Figure 11 addresses the fourth research question by ranking the risks of cost-dominated single-criterion evaluation by severity. The highest-rated risks were buildability problems surfacing during erection (4.44), design freeze occurring before manufacturability input is available (4.36), and underestimated lifecycle and maintenance cost (4.25), followed by excessive component variety and bespoke connections (4.19), transport and lifting constraint violations (4.08), and a weak audit trail for design-selection justification (3.92). The ranking is instructive: the two highest risks are not independent but sequential, since design freeze before manufacturability input is precisely the mechanism by which buildability problems reach the erection stage, which suggests that practitioners locate the failure in the timing of the decision rather than in the competence of the designer. The five highest risks all clear the high-severity threshold, underscoring that cost-led selection is not a defensible simplification but a first-order hazard. The prominence of excessive component variety connects the commercial failure to the DfMA one, because a cost comparison conducted on structural quantities alone is blind to the mould, handling, and interface costs that component proliferation generates, so that the alternative that appears cheapest on the decision matrix may be the most expensive to build (Lu et al., 2021; Kamali & Hewage, 2016). This ranking is the study's direct answer to the fourth research question.

Correlation and regression across the evaluation framework

Figure 12: Descriptive Means of Study Constructs with Standard Deviations

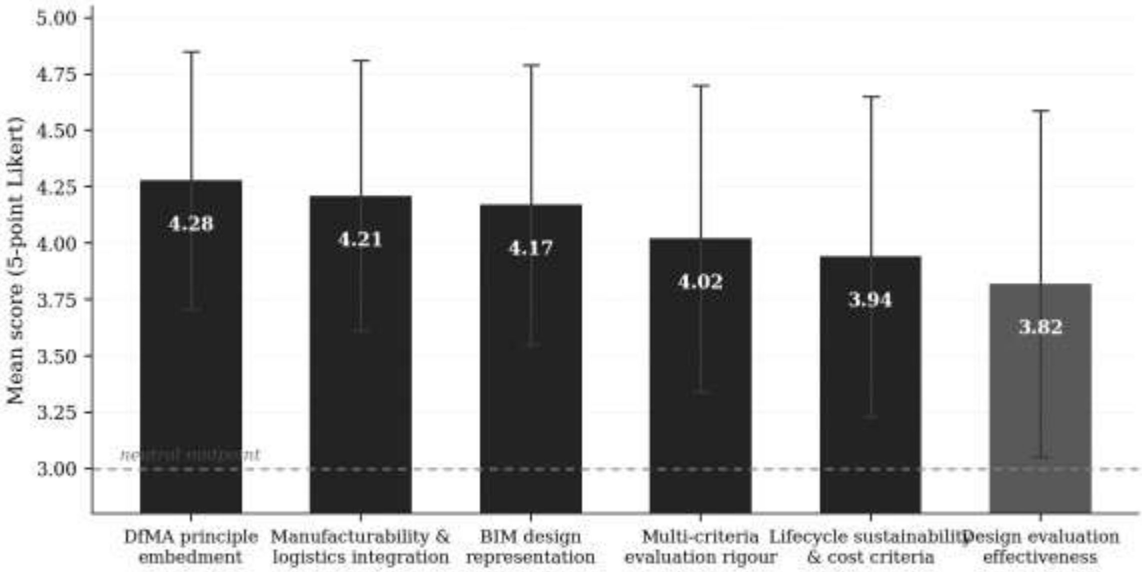
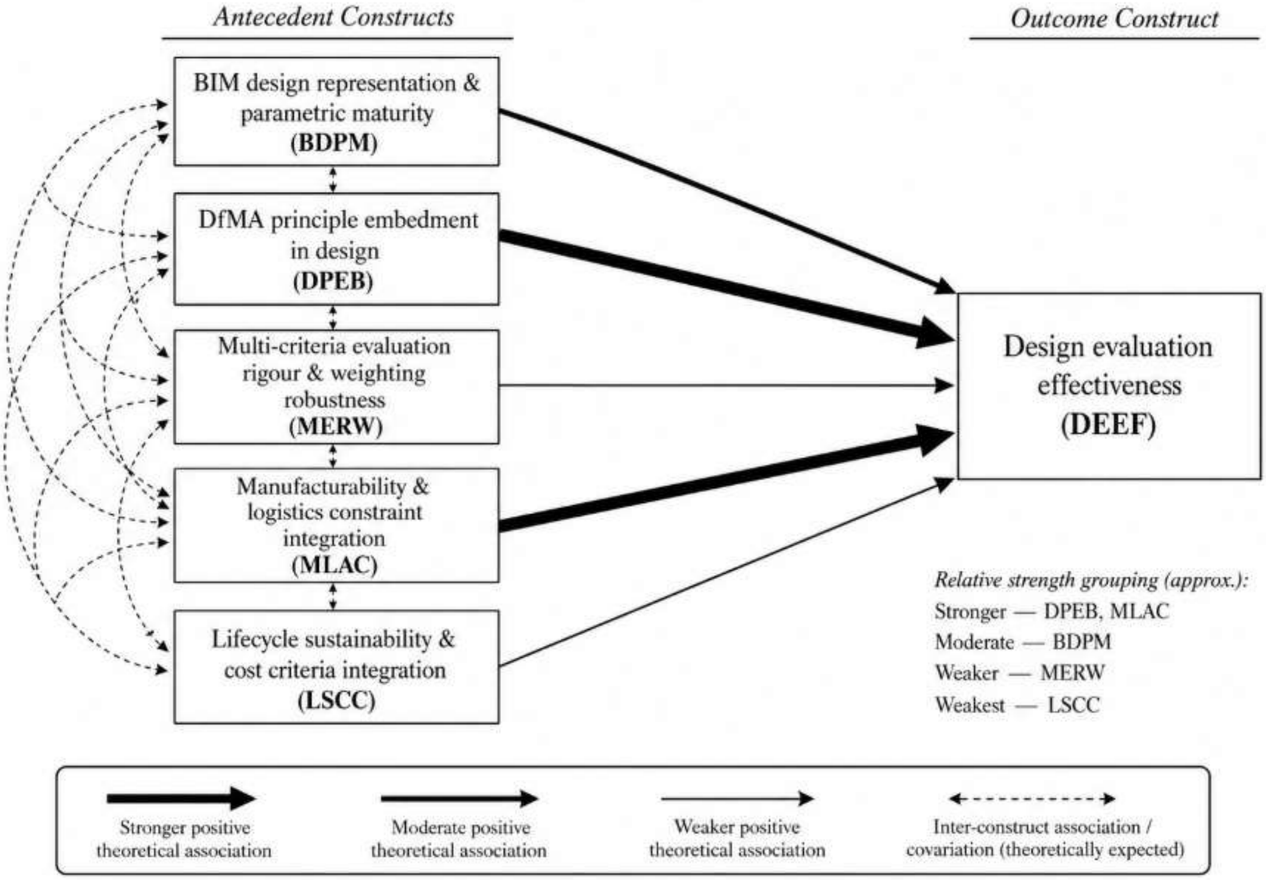


Figure 12 displays the construct means. The DfMA and constraint-integration capabilities stand highest, while design evaluation effectiveness, the outcome, stands lowest and most variable, its long error bar giving graphical evidence that realised decision quality lags the capabilities that contribute to it and is unevenly distributed across organisations, consistent with the descriptive pattern in Table 2.

Figure 13: Pearson Correlation Matrix Among Study Variables



Note. N = 231. All reported correlations significant at p < .001 (two-tailed). Darker cells indicate stronger positive association.

Figure 13 presents the correlation structure. Every construct is significantly and positively associated with design evaluation effectiveness, with the strongest associations for DfMA principle embedment (r = .71) and manufacturability and logistics constraint integration (r = .68), followed by BIM design representation and parametric maturity (r = .66), multi-criteria evaluation rigour (r = .61), and lifecycle criteria integration (r = .58). The uniformly positive associations support the framework's multi-construct account of evaluation effectiveness, and the moderate inter-construct correlations, ranging from .51 to .63, indicate related but distinct facets of a coherent design-evaluation capability rather than a single undifferentiated maturity factor.

Table 3: Multiple regression predicting design evaluation effectiveness (N = 231)

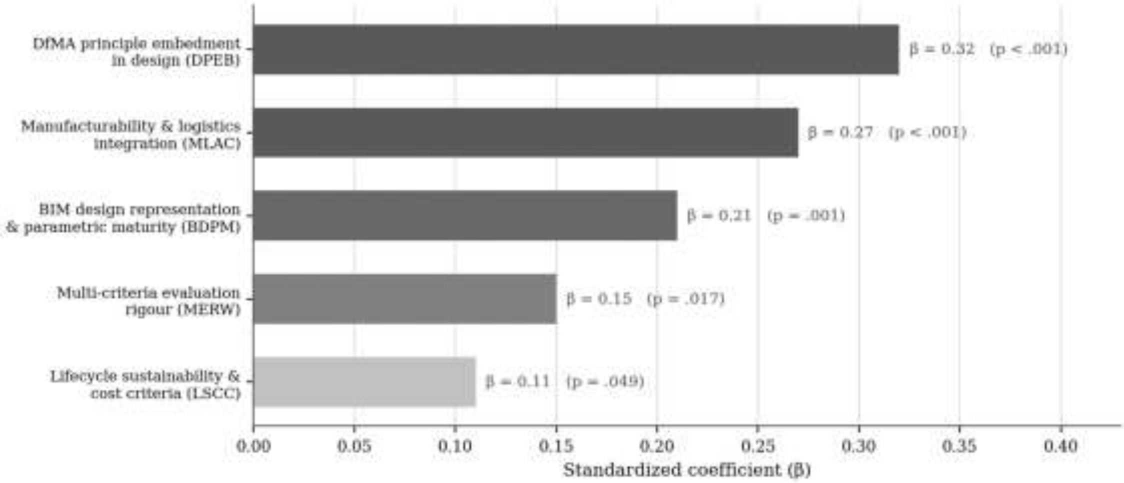
Predictor	B	SE	β	t	p
(Constant)	0.371	0.178	–	2.084	.038
DfMA principle embedment in design (DPEB)	0.291	0.057	0.32	5.105	<.001
Manufacturability & logistics integration (MLAC)	0.248	0.058	0.27	4.276	<.001
BIM design representation & parametric maturity (BDPM)	0.192	0.058	0.21	3.310	.001
Multi-criteria evaluation rigour (MERW)	0.137	0.057	0.15	2.404	.017
Lifecycle sustainability & cost criteria (LSCC)	0.109	0.055	0.11	1.982	.049

Note. Dependent variable = design evaluation effectiveness. R^2 = .562; Adjusted R^2 = .552; F(5, 225) = 57.74, p < .001; Durbin–Watson = 1.96; all VIF < 2.5.

Table 3 presents the regression. The overall model was significant, F(5, 225) = 57.74, p < .001, with R^2 =

.562, indicating that the five constructs jointly explain 56.2% of the variance in design evaluation effectiveness and confirming H6. All five constructs made significant positive contributions, supporting H1 through H5. DfMA principle embedment (β = .32) and manufacturability and logistics constraint integration (β = .27) were the strongest predictors, followed by BIM design representation and parametric maturity (β = .21), multi-criteria evaluation rigour (β = .15), and lifecycle criteria integration (β = .11). The dominance of the DfMA and constraint constructs confirms that evaluation effectiveness is driven primarily by what enters the comparison rather than by how the comparison is computed, while the significance of the evaluation-rigour construct confirms that the computation is not therefore immaterial.

Figure 14: Standardized Beta Coefficients Predicting Design Evaluation Effectiveness



Note. N = 231. Dependent variable = design evaluation effectiveness. All five constructs significant at p < .05.

Figure 14 ranks the constructs by standardised coefficient, confirming that the DfMA and constraint capabilities lead, with parametric modelling, evaluation rigour, and lifecycle criteria contributing significantly but more modestly. Read alongside the research-question findings, the regression establishes that the capabilities that move buildability resolution upstream in the prototype are those most strongly associated with practitioners' perceived evaluation effectiveness, providing convergent evidence across the perceptual and technical strands of the study.

This study examines how evaluation effectiveness is distributed across organisation types, which qualifies the aggregate findings with an important observation about variance. Precast manufacturers and erection contractors report somewhat higher median effectiveness than consultancies and public owners, which is consistent with the framework, since these are the parties whose constraint knowledge the evaluation most needs and who are therefore best placed to judge whether a design reflected it. The more striking feature, however, is the wide and overlapping spread within every organisation type: each group contains both highly effective and markedly ineffective evaluation practice, and the within-group variation exceeds the differences between groups. This reinforces the study's central theme that evaluation effectiveness is not conferred by organisational position but by the deliberate integration of the capabilities the framework identifies. The comparatively lower median among public owners is nonetheless notable, because owners set the procurement route and the evaluation criteria under which designers work, so a deficit at that point propagates through every subsequent decision (Nielsen et al., 2024).

DISCUSSION

The findings support the evaluation framework and, taken together, answer the five research questions. This section synthesises the evidence, focusing on the fifth research question, which the preceding results set up but did not directly resolve, and drawing out the implications of the whole.

RQ5: How constraint integration and lifecycle criteria improve evaluation reliability

The fifth research question asked how manufacturability, logistics, and lifecycle criteria integration improves evaluation reliability, and the study's evidence answers it at two levels. Statistically, both constructs contributed significantly to evaluation effectiveness over and above DfMA embedment and parametric modelling, confirming that they add something the design attributes alone do not supply.

Mechanistically, they operate through two different and complementary pathways. Constraint integration operates as a screen rather than a criterion: because transport envelopes, crane capacities, and mould inventories impose limits that are binary rather than graded, their proper role is to remove infeasible alternatives before ranking rather than to penalise them within it, and an evaluation that treats them as weighted criteria can and does return an infeasible leader whose violation has been offset by strong performance elsewhere. This is why constraint integration was the second strongest predictor while being, formally, the least sophisticated element of the framework. Lifecycle criteria operate in the opposite direction, not by narrowing the alternative set but by widening the appraisal boundary, and their significance confirms that an evaluation confined to capital cost systematically rewards the wrong design attributes: connection accessibility, component replaceability, and standardisation all impose modest first cost and return their value over decades, so they are invisible to a capital-cost comparison and salient in a lifecycle one (Penadés-Plà et al., 2016; Navarro et al., 2020a). Together the two constructs bound the evaluation from below and from ahead, one determining what may be built and the other what will prove worth having built.

Synthesis across the research questions

The five research questions resolve into a single coherent account. BIM-based DfMA integration improves design evaluation principally by moving buildability resolution upstream, into the region of the timeline where the cost of change is still low, rather than by producing a different final design through the same late process (RQ1). Connection simplicity and part-count reduction exert the strongest influence on assembly outcomes, because each acts by eliminating site operations rather than shortening them, while tolerance robustness governs fit-up specifically and modular repeatability governs transport (RQ2). Hybrid AHP–TOPSIS offers the broadest methodological performance and, decisively, the only ranking that remained stable across the full range of weight perturbation, while the widely used additive procedure failed the stability test at perturbations well within the range of ordinary weight uncertainty (RQ3). The risks of cost-dominated evaluation are led by a sequential pair, design freeze before manufacturability input and buildability problems at erection, which locates the failure in the timing of the decision rather than in the analysis (RQ4). And constraint integration and lifecycle criteria improve reliability by screening the infeasible and by widening the horizon over which value is counted (RQ5). The unifying insight is that the quality of a prefabricated bridge is largely determined before the design that will be built has been chosen, and that improving outcomes therefore requires intervening in the selection rather than in the design.

Theoretical and practical implications

Theoretically, the study integrates the DfMA, bridge multi-criteria decision-making, and BIM literatures, demonstrating that evaluation effectiveness is jointly determined by model maturity, DfMA embedment, methodological rigour, constraint integration, and lifecycle criteria, and that the heavy, tolerance-critical, transport-constrained nature of bridge components makes this integration necessary rather than optional (Lu et al., 2021; Costin et al., 2018). It reframes bridge design selection from a cost comparison among structurally adequate alternatives into a manufacturability-constrained multi-criteria problem, in which the relevant measure of a design is not its computed score but the robustness of the ranking that produced it. Practically, the study offers designers and owners a clear account of which DfMA attributes to prioritise, which decision method to adopt, and why a sensitivity test is not an optional refinement but the difference between a defensible selection and an arbitrary one. For practitioners, it cautions that a formally multi-criteria evaluation resting on unexamined weights offers the appearance of rigour without its substance. For owners and regulators, it implies that procurement should require manufacturability input before design freeze and should require rank-stability evidence alongside any reported design ranking, because those two requirements address the two failure modes the study identifies.

CONCLUSION

This study set out to characterise how the integration of DfMA principles into a BIM-based multi-criteria evaluation affects design decisions in prefabricated bridge construction, and to identify the attributes and methods that make such evaluation effective. It proposed that design evaluation effectiveness, the capacity to select an alternative that proves buildable, economical, and durable, is jointly determined by five constructs, BIM design representation and parametric maturity, DfMA principle embedment, multi-criteria evaluation rigour and weighting robustness, manufacturability and logistics constraint integration, and lifecycle sustainability and cost criteria integration, and it tested this framework against 231 practitioners and a prototype design set.

The empirical results supported the framework. All five constructs were significantly and positively associated with design evaluation effectiveness, the regression model explained 56.2% of the variance, and all six hypotheses were supported, with DfMA embedment and constraint integration the strongest predictors. The prototype evaluation showed that conventional cost-led evaluation resolves most buildability issues only after design freeze, that connection simplicity and part-count reduction exert the strongest influence on assembly outcomes while tolerance robustness governs fit-up and modular repeatability governs transport, and that hybrid AHP–TOPSIS was the only method to retain rank stability across the full range of weight perturbation tested. The risks of cost-dominated selection were led by a sequential pair locating the failure in the timing of the decision.

The central conclusion is that better prefabricated bridge outcomes cannot be obtained by refining the chosen design, because the decisions that govern manufacturability and assembly are foreclosed by the choice itself. They require instead that manufacturing and erection knowledge be brought forward into the evaluation of alternatives, that infeasible options be screened rather than penalised, and that the resulting ranking be reported with evidence of its stability under the weight uncertainty that will always remain. In prefabricated bridge construction, the robustness of the selection, not the elegance of the selected design, is the property that determines whether the promised advantages of prefabrication are realised.

RECOMMENDATIONS

Several recommendations follow from the findings. First, owners and designers should require manufacturability and erection input before concept design freeze, through early contractor and precaster involvement or through a documented plant and logistics capability statement, because the risk evidence locates the principal failure precisely at that point rather than in the subsequent analysis. Second, design teams should prioritise connection simplicity and part-count reduction above the other DfMA attributes when the alternatives must be narrowed quickly, because these exerted the strongest and broadest influence on assembly outcomes, each acting by eliminating site operations rather than by shortening them.

Third, evaluations should apply manufacturing and logistics limits as a feasibility screen prior to ranking rather than as weighted criteria within it, so that an alternative violating a transport envelope or a crane capacity is excluded rather than offset by strong performance elsewhere.

Fourth, organisations should adopt a hybrid weight-elicitation and distance-based ranking procedure, and should report the consistency ratio of the elicited weights alongside the ranking, because structured elicitation with an auditable consistency check is what distinguishes a defensible weight vector from an asserted one.

Fifth, no design ranking should be reported without an accompanying rank-stability test, since the perturbation evidence shows that commonly used procedures reverse their ordering within the range of ordinary weight uncertainty, and a ranking whose stability is unknown is not a decision basis.

For owners and regulators, the recommendation is to write design-selection requirements in terms of criteria completeness, manufacturability screening, and rank-stability evidence rather than in terms of cost comparison, and to treat the documented evaluation as part of the design record. For researchers, the recommendation is to extend the framework through longitudinal studies that follow selected alternatives into fabrication and erection to test whether predicted buildability is realised, through work on the elicitation of criteria weights under genuine stakeholder conflict, and through the integration of automated DfMA scoring directly into parametric bridge modelling environments.

LIMITATIONS OF THE STUDY

Several limitations should be acknowledged. First, the cross-sectional survey identifies associations but not causation, and the perceptual measures of the constructs and of evaluation effectiveness may diverge from realised project outcomes and are subject to common-method variance, although procedural remedies were applied (Podsakoff et al., 2003). Second, the prototype evaluation used a constructed set of precast bridge alternatives with representative parameters rather than live project data, so the reported resolution timings, attribute influences, and stability thresholds reflect a controlled evaluation rather than realised project outcomes; the magnitudes should be read as indicative rather than exact. Third, the purposive sample, though drawn across organisation types and bridge typologies, limits generalisability and may over-represent organisations already committed to prefabrication and digital delivery. Fourth, the DfMA index in Equation (10) aggregates four attributes with weights that are themselves a matter of judgement, so the index inherits the weighting problem that the study identifies in the ranking procedure, and the study does not resolve that recursion. Fifth, the framework treats manufacturing and logistics limits as fixed, whereas plant capacity, mould inventories, and permissible loads are partly negotiable and partly a function of the commercial arrangement, so the binary screen is a simplification of a boundary that is in practice movable at a price. Sixth, the findings derive predominantly from short and medium-span precast beam and box-girder bridges, and the relative influence of the DfMA attributes is likely to differ for long-span, cable-supported, or steel-composite structures where erection engineering dominates. Future research using live project data, negotiated rather than fixed constraints, and a wider span and typology range would address these limitations.

REFERENCES

[1]. Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. Automation in Construction, 114, 103179. https://doi.org/10.1016/j.autcon.2020.103179

[2]. Bosché, F. (2010). Automated recognition of 3D CAD model objects in laser scans and calculation of as-built dimensions for dimensional compliance control in construction. Advanced Engineering Informatics, 24(1), 107-118. https://doi.org/10.1016/j.aei.2009.08.006

[3]. Bradley, A., Li, H., Lark, R., & Dunn, S. (2016). BIM for infrastructure: An overall review and constructor perspective. Automation in Construction, 71, 139-152. https://doi.org/10.1016/j.autcon.2016.08.019

[4]. Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of Building Information Modelling (BIM). International Journal of Project Management, 31(7), 971-980. https://doi.org/10.1016/j.ijproman.2012.12.001

[5]. Callcut, M., Cerceau Agliozzo, J.-P., Varga, L., & McMillan, L. (2021). Digital twins in civil infrastructure systems. Sustainability, 13(20), 11549. https://doi.org/10.3390/su132011549

[6]. Cerovsek, T. (2011). A review and outlook for a 'Building Information Model' (BIM): A multi-standpoint framework for technological development. Advanced Engineering Informatics, 25(2), 224-244. https://doi.org/10.1016/j.aei.2010.06.003

[7]. Costin, A., Adibfar, A., Hu, H., & Chen, S. S. (2018). Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations. Automation in Construction, 94, 257-281. https://doi.org/10.1016/j.autcon.2018.07.001

[8]. Čuš-Babič, N., Guerra De Oliveira, S., & Tibaut, A. (2022). Interoperability of infrastructure and transportation information models: A public transport case study. Applied Sciences, 12(12), 6234. https://doi.org/10.3390/app12126234

[9]. Debasish, A. (2021). Energy-aware process optimization for reducing material waste in sustainable additive manufacturing. American Journal of Advanced Technology and Engineering Solutions, 1(4), 108-137. https://doi.org/10.63125/j0wk7j48

[10]. Deng, M., Menassa, C. C., & Kamat, V. R. (2021). From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. Journal of Information Technology in Construction, 26, 58-83. https://doi.org/10.36680/j.itcon.2021.005

[11]. Eastman, C., Lee, J.-M., Jeong, Y.-S., & Lee, J.-K. (2009). Automatic rule-based checking of building designs. Automation in Construction, 18(8), 1011-1033. https://doi.org/10.1016/j.autcon.2009.07.002

[12]. Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. Journal of Marketing Research, 18(1), 39-50. https://doi.org/10.1177/002224378101800104

[13]. Guidotti, R., Monreale, A., Ruggieri, S., Turini, F., Giannotti, F., & Pedreschi, D. (2018). A survey of methods for explaining black box models. ACM Computing Surveys, 51(5), 1-42. https://doi.org/10.1145/3236009

[14]. Harris, C. R., Millman, K. J., van der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., … Oliphant, T. E. (2020). Array programming with NumPy. Nature, 585(7825), 357-362. https://doi.org/10.1038/s41586-020-2649-2

[15]. Honghong, S., Gang, Y., Haijiang, L., Tian, Z., & Annan, J. (2023). Digital twin enhanced BIM to shape full life cycle digital transformation for bridge engineering. Automation in Construction, 147, 104736. https://doi.org/10.1016/j.autcon.2022.104736

[16]. Hüthwohl, P., Brilakis, I., Borrmann, A., & Sacks, R. (2018). Integrating RC bridge defect information into BIM models. Journal of Computing in Civil Engineering, 32(3), 04018013. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000744

[17]. International Organization for Standardization. (2018). ISO 19650-1:2018. Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) —

Information management using building information modelling — Part 1: Concepts and principles. ISO. https://www.iso.org/standard/68078.html
[18]. Jiang, F., Ma, L., Broyd, T., & Chen, K. (2021). Digital twin and its implementations in the civil engineering sector. Automation in Construction, 130, 103838. https://doi.org/10.1016/j.autcon.2021.103838
[19]. Jiang, R., Mao, C., Hou, L., Wu, C., & Tan, J. (2018). A SWOT analysis for promoting off-site construction under the backdrop of China's new urbanisation. Journal of Cleaner Production, 173, 225-234. https://doi.org/10.1016/j.jclepro.2017.06.147
[20]. Jin, R., Gao, S., Cheshmehzangi, A., & Aboagye-Nimo, E. (2018). A holistic review of off-site construction literature published between 2008 and 2018. Journal of Cleaner Production, 202, 1202-1219. https://doi.org/10.1016/j.jclepro.2018.08.195
[21]. Johnsson, H., & Meiling, J. H. (2009). Defects in offsite construction: Timber module prefabrication. Construction Management and Economics, 27(7), 667-681. https://doi.org/10.1080/01446190903002797
[22]. Kaewunruen, S., & Xu, N. (2018). Digital twin for sustainability evaluation of railway station buildings. Frontiers in Built Environment, 4, 77. https://doi.org/10.3389/fbuil.2018.00077
[23]. Kamali, M., & Hewage, K. (2016). Life cycle performance of modular buildings: A critical review. Renewable and Sustainable Energy Reviews, 62, 1171-1183. https://doi.org/10.1016/j.rser.2016.05.031
[24]. Kim, M.-K., Cheng, J. C. P., Sohn, H., & Chang, C.-C. (2015). A framework for dimensional and surface quality assessment of precast concrete elements using BIM and 3D laser scanning. Automation in Construction, 49, 225-238. https://doi.org/10.1016/j.autcon.2014.07.010
[25]. Kim, M.-K., Sohn, H., & Chang, C.-C. (2014). Automated dimensional quality assessment of precast concrete panels using terrestrial laser scanning. Automation in Construction, 45, 163-177. https://doi.org/10.1016/j.autcon.2014.05.015
[26]. Kim, M.-K., Wang, Q., Park, J.-W., Cheng, J. C. P., Sohn, H., & Chang, C.-C. (2016). Automated dimensional quality assurance of full-scale precast concrete elements using laser scanning and BIM. Automation in Construction, 72, 102-114. https://doi.org/10.1016/j.autcon.2016.08.035
[27]. Li, Y., Li, Y., & Ding, Z. (2024). Building Information Modeling applications in civil infrastructure: A bibliometric analysis from 2020 to 2024. Buildings, 14(11), 3431. https://doi.org/10.3390/buildings14113431
[28]. Lu, W., Tan, T., Xu, J., Wang, J., Chen, K., Gao, S., & Xue, F. (2021). Design for manufacture and assembly (DfMA) in construction: The old and the new. Architectural Engineering and Design Management, 17(1-2), 77-91. https://doi.org/10.1080/17452007.2020.1768505
[29]. Md Arif Uz, Z., Sharmin, S., & Md Abdur, R. (2025). Factors influencing behavioural intention to use the innovative open and distance learning systems with the role of continuance intention. American Journal of Scholarly Research and Innovation, 4(01), 202-220. https://doi.org/10.63125/pbjxp014
[30]. Md Mesbaul, H. (2023). A Meta-Analysis of Lean Merchandising Strategies In Fashion Retail: Global Insights From The Post-Pandemic Era. Review of Applied Science and Technology, 2(04), 94-123. https://doi.org/10.63125/y8x4k683
[31]. Md Mesbaul, H. (2025). A framework-based meta-analysis of artificial intelligence-driven ERP solutions for circular and sustainable supply chains. International Journal of Scientific Interdisciplinary Research, 6(1), 327-367. https://doi.org/10.63125/n6k7r711
[32]. Md Mostafizur, R. (2025). Data-driven graph neural network models for detecting fraudulent insurance claims in healthcare systems. American Journal of Interdisciplinary Studies, 6(1), 263-294. https://doi.org/10.63125/pmqa1e33
[33]. Md Mostafizur, R., Omar Muhammad, F., & Sheratun Noor, J. (2025). Data privacy in business intelligence systems: Ensuring compliance in HRIS and enterprise platforms. International Journal of Scientific Interdisciplinary Research, 6(1), 97-136. https://doi.org/10.63125/527rnx08
[34]. Md Syeedur, R., & Sharmin, R. (2025). A data-driven study on the use of small language models and large language models for interpreting complex industrial data and deriving actionable outcome. American Journal of Data Science and Analytics, 6(11), 01-19. https://doi.org/10.63125/5vyhgs98
[35]. Md. Abdur, R., & Iftekhar, A. (2021). Customer retention forecasting in mobile wallet services using neural networks: A comparative quantitative study. International Journal of Business and Economics Insights, 1(4), 70-102. https://doi.org/10.63125/dyrpc387
[36]. Mohammad Abir Chowdhury, S., & Tonay, P. (2022). An Empirical Analysis of the Impact of Robotic Process Automation and Continuous Auditing on the Timeliness And Accuracy Of Financial Reporting Assurance. International Journal of Business and Economics Insights, 2(4), 73-126. https://doi.org/10.63125/7p8dcr47
[37]. Mohammad Shoriful Hossan, S. (2021). Reducing worker exposure and electrical failure risk in brownfield manufacturing facilities after COVID-era maintenance delays. Review of Applied Science and Technology, 6(1), 263-279. https://doi.org/10.63125/cm1c2c20
[38]. Mst Shurovi, A. (2024). Machine learning models for bank reconciliation anomaly detection in high-volume financial transactions. American Journal of Data Science and Analytics, 5(12), 314-354. https://doi.org/10.63125/mmwb6467

[39]. Muhammad Zahidul, I. (2024). Assessment of data integrity gaps and preventive strategies in QC laboratories in compliance with FDA and cGMP expectations. American Journal of Scholarly Research and Innovation, 3(01), 243-291. https://doi.org/10.63125/a3xjb608

[40]. Muhammad Zahidul, I. (2025). Development of a Dashboarding and Visualization Framework For Pharmaceutical Brand Performance Analytics Using Tableau and Python. American Journal of Interdisciplinary Studies, 6(3), 351-393. https://doi.org/10.63125/e6djq308

[41]. Muhammad Zahidul, I., & Amena Begum, S. (2022). Applied data-analytics approaches to cardiovascular drug-utilization patterns: An empirical study using real-world pharmaceutical sales data. American Journal of Data Science and Analytics, 3(12), 89-129. https://doi.org/10.63125/7xgryf71

[42]. Mukut Kanti, B. (2020). Integrated Framework for Fire Safety and Electrical Hazard Assessment in Large-Scale Industrial and Commercial Facilities: A Mixed-Method Analysis. American Journal of Advanced Technology and Engineering Solutions, 1(01), 40-86. https://doi.org/10.63125/zxsbdr47

[43]. Mukut Kanti, B. (2024). AI-Enabled Predictive Asset Integrity Monitoring for Industrial Equipment in Oil & Gas and Energy Sector Facilities. International Journal of Scientific Interdisciplinary Research, 5(2), 746–791. https://doi.org/10.63125/3mjcah04

[44]. Mukut Kanti, B. (2025). Lifecycle carbon reduction and net zero pathway modeling using LEED, EDGE, and SBTi frameworks in developing economy industrial buildings. American Journal of Interdisciplinary Studies, 6(3), 306-350. https://doi.org/10.63125/tnneth75

[45]. Navarro, I. J., Pena dés-Plà, V., Martínez-Muñoz, D., Rempling, R., & Yepes, V. (2020a). Life cycle sustainability assessment for multi-criteria decision making in bridge design: A review. Journal of Civil Engineering and Management, 26(7), 690-704. https://doi.org/10.3846/jcem.2020.13599

[46]. Navarro, I. J., Yepes, V., & Martí, J. V. (2019). A review of multicriteria assessment techniques applied to sustainable infrastructure design. Advances in Civil Engineering, 2019, 6134803. https://doi.org/10.1155/2019/6134803

[47]. Navarro, I. J., Yepes, V., & Martí, J. V. (2020b). Sustainability assessment of concrete bridge deck designs in coastal environments using neutrosophic criteria weights. Structure and Infrastructure Engineering, 16(7), 949-967. https://doi.org/10.1080/15732479.2019.1676791

[48]. Nielsen, O. A., Miceli, G., Ferreira Filho, A. dos S., & Pellanda, P. C. (2024). A review of global efforts in BIM adoption for road infrastructure. Infrastructures, 9(8), 126. https://doi.org/10.3390/infrastructures9080126

[49]. Opricovic, S., & Tzeng, G.-H. (2004). Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. European Journal of Operational Research, 156(2), 445-455. https://doi.org/10.1016/S0377-2217(03)00020-1

[50]. Pan, Y., & Zhang, L. (2021). Roles of artificial intelligence in construction engineering and management: A critical review and future trends. Automation in Construction, 122, 103517. https://doi.org/10.1016/j.autcon.2020.103517

[51]. Penadés-Plà, V., García-Segura, T., Martí, J. V., & Yepes, V. (2016). A review of multi-criteria decision-making methods applied to the sustainable bridge design. Sustainability, 8(12), 1295. https://doi.org/10.3390/su8121295

[52]. Penadés-Plà, V., Martí, J. V., García-Segura, T., & Yepes, V. (2017). Life-cycle assessment: A comparison between two optimal post-tensioned concrete box-girder road bridges. Sustainability, 9(10), 1864. https://doi.org/10.3390/su9101864

[53]. Podsakoff, P. M., MacKenzie, S. B., Lee, J.-Y., & Podsakoff, N. P. (2003). Common method biases in behavioral research: A critical review of the literature and recommended remedies. Journal of Applied Psychology, 88(5), 879-903. https://doi.org/10.1037/0021-9010.88.5.879

[54]. Rudin, C. (2019). Stop explaining black box machine learning models for high stakes decisions and use interpretable models instead. Nature Machine Intelligence, 1(5), 206-215. https://doi.org/10.1038/s42256-019-0048-x

[55]. Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. European Journal of Operational Research, 48(1), 9-26. https://doi.org/10.1016/0377-2217(90)90057-I

[56]. Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems. Data-Centric Engineering, 1, e14. https://doi.org/10.1017/dce.2020.16

[57]. Sharif Md Yousuf, B., Md Shahadat, H., Saleh Mohammad, M., Mohammad Shahadat Hossain, S., & Imtiaz, P. (2025). The green hydrogen blueprint: Optimizing America's clean energy future. American Journal of Data Science and Analytics, 6(10), 43-69. https://doi.org/10.63125/y9b1k470

[58]. Shima Ali, S., Musomi, K., & Sonya, G. (2024). Integrated Infectious Disease Preparedness: Multilingual Health Communication Strategies for Public Health Risk Mitigation, Disease Intervention and Prevention for Culturally Diverse Population in United States. American Journal of Data Science and Analytics, 5(10), 01-47. https://doi.org/10.63125/ehk4mt02

[59]. Shima Ali, S., Sonya, G., & Mahbubul, I. (2025). Telemedicine and remote patient monitoring for preventing risk and chronic disease management in underserved communities. American Journal of Health and Medical Sciences, 6(04), 01-42. https://doi.org/10.63125/y0e9dc38

[60]. Solihin, W., & Eastman, C. (2015). Classification of rules for automated BIM rule checking development. Automation in Construction, 53, 69-82. https://doi.org/10.1016/j.autcon.2015.03.003

[61]. Succar, B. (2009). Building information modelling framework: A research and delivery foundation for industry stakeholders. Automation in Construction, 18(3), 357-375. https://doi.org/10.1016/j.autcon.2008.10.003

[62]. Tan, T., Lu, W., Tan, G., Xue, F., Chen, K., Xu, J., Wang, J., & Gao, S. (2020). Construction-oriented design for manufacture and assembly guidelines. Journal of Construction Engineering and Management, 146(8), 04020085. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001877

[63]. Tonay, P., Md Maruf, I., & Al, A. (2024). Artificial intelligence-based decision support systems and managerial performance. American Journal of Advanced Technology and Engineering Solutions, 4(04), 154-184. https://doi.org/10.63125/wmz8dc67

[64]. Torzoni, M., Tezzele, M., Mariani, S., Manzoni, A., & Willcox, K. E. (2024). A digital twin framework for civil engineering structures. Computer Methods in Applied Mechanics and Engineering, 418, 116584. https://doi.org/10.1016/j.cma.2023.116584

[65]. Vignali, V., Acerra, E. M., Lantieri, C., Di Vincenzo, F., Piacentini, G., & Pancaldi, S. (2021). Building information Modelling (BIM) application for an existing road infrastructure. Automation in Construction, 128, 103752. https://doi.org/10.1016/j.autcon.2021.103752

[66]. Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., … van Mulbregt, P. (2020). SciPy 1.0: Fundamental algorithms for scientific computing in Python. Nature Methods, 17(3), 261-272. https://doi.org/10.1038/s41592-019-0686-2

[67]. Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. Automation in Construction, 38, 109-127. https://doi.org/10.1016/j.autcon.2013.10.023

[68]. Wang, Q., Sohn, H., & Cheng, J. C. P. (2018). Automatic as-built BIM creation of precast concrete bridge deck panels using laser scan data. Journal of Computing in Civil Engineering, 32(3), 04018011. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000754

[69]. Wang, T., Gan, V. J. L., Hu, D., & Liu, H. (2022). Digital twin-enabled built environment sensing and monitoring through semantic enrichment of BIM with SensorML. Automation in Construction, 144, 104625. https://doi.org/10.1016/j.autcon.2022.104625

[70]. Yang, X., Del Rey Castillo, E., Zou, Y., Wotherspoon, L., & Tan, Y. (2022). Automated semantic segmentation of bridge components from large-scale point clouds using a weighted superpoint graph. Automation in Construction, 142, 104519. https://doi.org/10.1016/j.autcon.2022.104519

[71]. Zhang, F., Chan, A. P. C., Darko, A., Chen, Z., & Li, D. (2022). Integrated applications of building information modeling and artificial intelligence techniques in the AEC/FM industry. Automation in Construction, 139, 104289. https://doi.org/10.1016/j.autcon.2022.104289