

Review

Review of Decision-Making Tools for Accelerated Bridge Construction in the United States

Sylvain St-Pierre  and Munzer Hassan * 

Department of Construction Engineering, École de Technologies Supérieures, University of Quebec, Montreal, QC H3C 1K3, Canada; sylvain.st-pierre.3@ens.etsmtl.ca

* Correspondence: munzer.hassan@etsmtl.ca

Abstract

Accelerated Bridge Construction (ABC) projects in the United States (U.S.) have consistently demonstrated the significant advantages of prefabrication over conventional construction methods. Since the early 2010s, the adoption of ABC has expanded steadily, with projects achieving substantial reductions in construction duration while concurrently mitigating traffic disruptions. Screening-level evaluation and decision-making tools for selecting between ABC and conventional construction methods emerged in the U.S. in the mid-2000s. These tools, together with cost-estimation tools developed to support them, have continued to evolve. This paper presents a comprehensive literature review examining the evolution of screening-level evaluation, decision-making, and cost-estimation tools for ABC projects in the U.S. The review indicates that existing qualitative and quantitative evaluation and decision-making approaches remain practically useful for the selection of ABC methods but exhibit limited methodological robustness when applied to support decisions across a broad range of influencing factors. However, hybrid approaches based on the Analytic Hierarchy Process (AHP) represent an important advancement toward more structured Multi-Criteria Decision-Making (MCDM). In particular, AHP hybrid models constitute a significant progression beyond traditional AHP by mitigating several of its inherent limitations. The review also highlights that early cost-estimation approaches incorporated within evaluation and decision-making frameworks primarily focused on short-term construction costs and road user costs associated with the construction phase. However, with sustainability becoming a principal objective of modern infrastructure management, Life-Cycle Cost (LCC) estimation should comprehensively incorporate long-term Maintenance and Rehabilitation (M&R) expenditures throughout the entire service life of bridge infrastructure. Furthermore, the review highlights the need for improved screening-level MCDM tools capable of strengthening the identification and selection of preferred ABC alternatives during the earliest stages of project development while enhancing their long-term sustainability.



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1. Introduction

During the 1990s and 2000s, the initial implementation of Accelerated Bridge Construction (ABC) projects in the United States fostered a growing recognition of the advantages of prefabrication over conventional construction methods. The adoption of prefabrication in ABC projects has contributed to substantial reductions in construction duration and

improvements in structural quality while concurrently mitigating the adverse impacts of on-site construction activities on traffic, the environment, local economic conditions, and surrounding communities. Since the early 2010s, the implementation of ABC has expanded steadily. Building on the early successes of ABC, the mid-2000s witnessed the emergence of tools designed to support the evaluation and selection of ABC methods relative to conventional approaches for bridge construction, rehabilitation, and replacement. Initial efforts relied on qualitative approaches, notably logic-driven flowcharts supplemented by question-based matrices, which facilitated high-level decision-making regarding the applicability of ABC methods, including those involving Prefabricated Bridge Elements and Systems (PBES).

Subsequently, various combinations of qualitative flowcharts and criteria-based matrices were developed across multiple states in the United States (U.S.). Tailored to reflect state-specific priorities and preferences, these tools progressively expanded in scope to encompass a broader range of ABC techniques. This evolution ultimately led to the development of quantitative decision-making matrices. More advanced tools further extended their analytical scope by integrating qualitative and quantitative approaches within hybrid frameworks, including Multi-Criteria Decision-Making (MCDM) techniques. These hybrid approaches enabled the systematic evaluation of complex project environments characterized by competing—and often qualitative—trade-offs. Additional features incorporated into these evaluation and decision-making tools include flowcharts that guide the identification of feasible ABC techniques, facilitate the selection of the most appropriate ABC alternative for a given project, and incorporate considerations related to project delivery models.

In parallel with these methodological developments, cost-estimation approaches for ABC projects have also evolved. During the early stage of framework development, cost considerations were typically incorporated as a single aggregated parameter within evaluation and decision-making models. Cost was treated either qualitatively or quantitatively, with the latter often represented as a pre-estimated input to the analytical process. In comparative assessments of ABC and conventional construction methods, early cost-estimation efforts focused primarily on direct construction costs and on the economic consequences of traffic disruptions for road users during the construction period. As the portfolio of completed ABC projects has expanded, construction cost-estimation methodologies have advanced, particularly through the parametrization of ABC project construction costs. Concurrently, significant progress has been made in the estimation of road user costs, supported by comprehensive analyses of traffic impacts and the development of the concept of “work zone road user costs”, which reflects the additional economic burden imposed on road users and the broader community as a result of work-zone activities.

Over time, the importance of integrating Life-Cycle Cost considerations into the evaluation of ABC projects has become increasingly recognized. Beyond short-term construction and road user costs, Life-Cycle Costing encompasses maintenance and rehabilitation expenditures incurred throughout the bridge’s service life—typically extending to at least 75 years—as well as end-of-life disposal costs or residual value. Despite this growing recognition, the systematic estimation of Life-Cycle Costs, whether incorporated as an input parameter or directly integrated as a component of evaluation and decision-making frameworks, remains relatively recent and continues to present unresolved methodological challenges.

Evaluation and decision-making frameworks, together with cost-estimation tools for both ABC and conventional bridge projects, have continued to evolve throughout the 2010s and into the present decade in the United States (U.S.). This progress has been supported by the U.S. Federal Highway Administration (FHWA), numerous state

Departments of Transportation (DOTs), and the Accelerated Bridge Construction University Transportation Center (ABC-UTC) at Florida International University. In particular, the ABC-UTC has played a key role in advancing ABC research, technology transfer, and nationwide implementation.

This paper presents a comprehensive literature review examining the evolution of evaluation and decision-making tools developed in the U.S. since the mid-2000s to support the selection of ABC methods in comparison with conventional approaches for bridge construction, rehabilitation, and replacement. The review also examines the development of cost-estimation tools designed to inform ABC-related decision-making. The two categories of tools are primarily intended for screening-level analyses conducted during the early stages of project development (e.g., pre-feasibility and feasibility studies), where they facilitate the evaluation of preliminary alternatives before selecting a preferred ABC solution and proceeding to detailed engineering design and optimization.

The primary objective of this review paper is to examine the principal methodologies and concepts underpinning the development of these tools, which collectively encompass (i) the evaluation and selection of ABC alternatives and (ii) the associated cost-estimation methodologies. By examining these two categories separately, this review provides a clearer understanding of their respective roles and facilitates the identification of the methodological and conceptual limitations that continue to affect the selection of ABC methods during the project screening stage. Accordingly, the review identifies the principal challenges that remain to be addressed and highlights opportunities for methodological and conceptual advancement.

Beyond enhancing understanding of the applications and limitations of existing tools, this review provides insights into their historical development, the current state of practice, and promising avenues for future advancement. The review also identifies priority areas for methodological improvement and future research aimed at advancing the evaluation and selection of ABC alternatives.

From a broader sustainability perspective, Life-Cycle Analysis (LCA) provides a holistic framework for evaluating infrastructure projects by considering resource consumption, environmental impacts, energy use, economic performance, and social dimensions throughout the asset life cycle. However, given the objectives and scope of the present review, sustainability is examined primarily from the perspective of Life-Cycle Cost Analysis (LCCA).

The structured search methodology underpinning this comprehensive literature review was conducted from September 2025 to April 2026. The review drew upon the principal bibliographic databases in the field, including Scopus, Compendex, and other databases. The search strategy was further complemented by automated alerts to identify newly published studies relevant to the research objectives throughout the review period. In addition to the database search, the reference lists of all eligible publications—including journal articles, conference papers, and technical reports—were systematically screened using backward citation tracking. This process enabled the identification of additional relevant publications that were not retrieved through the initial database search. Collectively, this systematic search methodology provides confidence that the present review captures the current state of knowledge on evaluation and decision-making methods for the selection of ABC alternatives, as well as the cost-estimation methods that support their planning and implementation in the United States.

2. Synthesis of Evaluation and Decision-Making Tools

2.1. Main Methodologies and Concepts

2.1.1. Qualitative Approaches

Ralls (2006) developed a decision-making framework for Prefabricated Bridge Elements and Systems (PBES), providing a structured tool for evaluating the applicability of prefabrication within ABC methods and determining whether a prefabricated bridge solution is both feasible and beneficial for a given project [1]. The qualitative framework comprises (i) a logic-driven flowchart to support high-level decision-making; (ii) a matrix of 21 questions enabling the assessment of multiple factors; and (iii) detailed guidance elaborating on these factors. Collectively, these components provide progressively refined decision support for selecting prefabricated bridge solutions as the construction method. This framework addresses a broad range of considerations, including (i) factors associated with rapid on-site construction, (ii) additional considerations such as safety, environmental impacts, standardization, site constraints, and (iii) cost-related factors. When responses within the matrix are predominantly positive, the framework indicates that prefabrication is likely to be beneficial and warrants further detailed analysis. Ralls also notes that users may assign weights to individual criteria to reflect project-specific priorities. This approach—often referred to as the 2006 FHWA framework for PBES decision-making (FHWA 2006)—is illustrated in Figure 1 [1].

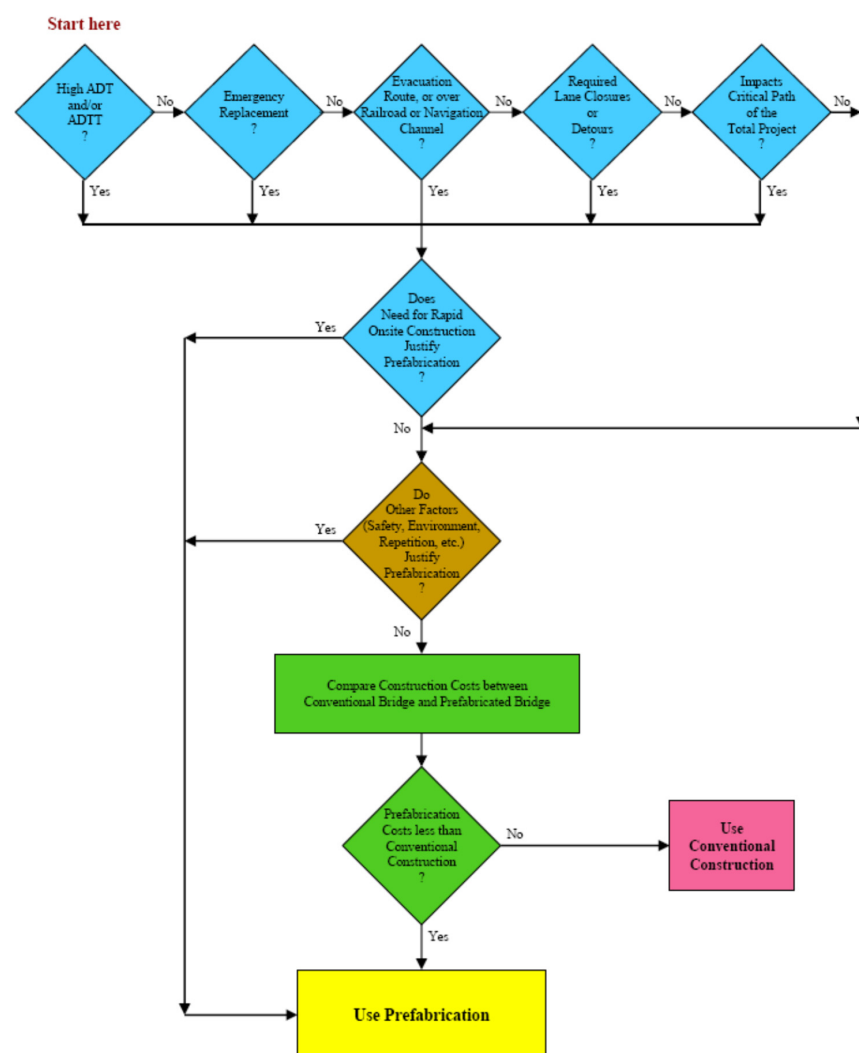


Figure 1. Logic-driven flowchart for high-level decision on prefabricated bridge project, reprinted with permission from [1], 2006, FHWA.

Subsequently, various combinations of qualitative flowcharts and matrices were adopted across different U.S. states. Some agencies relied solely on the FHWA flowchart, others used it in conjunction with its accompanying matrix, while others developed customized qualitative approaches integrating state-specific flowcharts and matrices. In 2016, Orabi et al. provided an overview of the qualitative approaches used by the FHWA and five U.S. state Departments of Transportation (DOTs)—Colorado, Idaho, Utah, Washington, and Wisconsin (Orabi et al. 2016) [2]. Their analysis identified factors considered across all reviewed tools, including daily traffic volume, traffic impacts, and safety, as well as commonly applied factors such as cost, environmental impacts, and economies of scale. In addition, the authors noted the inclusion of other factors in selected tools, including quality, economic and social impacts, and traffic-control costs. Readers are referred to Orabi et al. (2016) for a summary table illustrating the extent to which qualitative decision-making tools developed by U.S. organizations (e.g., FHWA and state DOTs) address a range of decision criteria [2].

2.1.2. Quantitative Approaches

Another category of tools for the evaluation and selection of ABC methods involves quantitative matrices that require numerical scoring for each question or criterion, with predefined weights assigned to reflect their relative importance. The resulting weighted scores are aggregated, and the cumulative score is evaluated against a pre-defined threshold indicating the relative suitability of a given ABC alternative, including PBES and/or other ABC techniques. This multi-criteria, weighting-based approach enables the comparative evaluation of ABC alternatives through a structured set of decision criteria. Initially, the quantitative matrices used by various U.S. states were derived from the question-based matrix incorporated into the 2006 FHWA framework for PBES decision-making (FHWA, 2006) [1]. Subsequently, several U.S. states developed customized quantitative approaches, incorporating different combinations and configurations of criteria tailored to their specific contexts and priorities.

According to Mohamadiazar and Ebrahimian (2025, 2024), such quantitative, matrix-based approaches have been implemented across multiple U.S. states, including Arizona, Connecticut, Iowa, Utah, and Wisconsin [3,4]. Readers are also referred to Orabi et al. (2016) for a summary table illustrating the extent to which selected quantitative decision-making tools developed in the U.S. address a range of decision criteria [2]. As an illustrative example, the authors present the quantitative decision matrix developed by the Connecticut DOT (CTDOT, 2019), which comprises ten criteria, each scored on a scale ranging from 0 to 5 (See Figure 2) [5]. The associated weighting factors across all criteria sum to 108, resulting in a maximum attainable score of 465. Within this matrix-based rating system, a cumulative score equal to or greater than 60% is interpreted as indicative of a favourable disposition toward ABC, thereby supporting the selection of ABC methods. The authors further demonstrated the application of the CTDOT ABC decision matrix through two bridge case studies in Connecticut. These case studies, which are partially documented in their study, were further analyzed by Fields and Culmo (2021) [6].

Mohamadiazar and Ebrahimian (2025, 2024) presented a multi-criteria decision support tool (DST) that extends the CTDOT ABC decision matrix, originally comprising ten primary criteria, by incorporating additional considerations related to safety, social equity, and environmental justice [3,4]. Within this enhanced tool, the safety criterion captures crash-related costs and associated safety benefits, which are quantified based on crash severity and frequency. Social Equity and Environmental Justice (SE EJ) are addressed through a unified formulation based on a weighted average of key social, economic, and environmental factors. The authors applied this expanded CTDOT-based tool to the two previously referenced case studies,

demonstrating that the inclusion of safety and SEEJ considerations can significantly influence decision outcomes, particularly for projects positioned near ABC-related decision thresholds. The resulting CTDOT tool, which comprises a base-case evaluation component consisting of ten criteria and an additional evaluation component incorporating safety and SEEJ benefits, is referred to as the “FIU ABC DST” tool and is made available through the ABC-UTC website (see Mohamadzadeh and Ebrahimian, 2025) [3].

Connecticut Department of Transportation
2800 Berlin Turnpike, PO Box 317546
Newington, CT 06131-7846

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Newington, CT 06131-7846

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CTDOT ABC Decision Making Process

ABC Rating procedure
Enter values for each aspect of the project. Attach back-up data if applicable

Average Daily Traffic: 0 No traffic impacts
1 Less than 10000
2 10000 to 40000
3 40000 to 70000
4 70000 to 100000
5 More than 100000

User Impact Reduction: #DIV/0!
Calculated by spreadsheet
0 Zero
1 1% to 20%
2 21% to 40%
3 41% to 60%
4 61% to 80%
5 81% to 100%

Bridge Location: 0 Rural Bridge away from town center
1 Rural bridge near town center
2 Suburban bridge away from town center
3 Suburban bridge near major traffic generators
4 Urban Bridge near major traffic generators
5 Urban Bridge near emergency services

Use of Typical Details: 1 Complex and unfavorable geometry
2 Curved and skewed bridges
3 Curved bridges
4 Skewed Bridges
5 Simple geometry well suited for typical details

Work Zone Geometry: 1 Short duration project with good geometry & flow
2 Short duration project with moderate geometry & flow
3 Average project duration with average geometry & flow
4 Long duration project with moderate geometry & flow
5 Long duration project with complex geometry & flow

Site Conditions: 0 significant limitations on work
1 moderate construction limitations for portions of the work
2 minor construction limitations
3 No Restrictions
4
5

Railroad Impacts: 0 No Railroad (entry of 0 = not considered in score)
1 Freight Siding (Less than 1 train per week)
2 Light Freight (1 Train per week to 1 Train per day)
3 Heavy Freight (More than 1 Train per day)
4 Commuter rail
5 Electrified Commuter Rail

Cost Analysis: 0 >30%
1 20% < Factor < 30%
2 10% < Factor < 20%
3 5% < Factor < 10%
4 0% < Factor < 5%
5 Factor < 0%

Envir./Water Handling: 0 No Restrictions (entry of 0 = not considered in score)
1 minor construction limitations
2
3 moderate construction limitations for portions of the work
4
5 significant limitations on work

Waterway Limitations: 0 No impact (entry of 0 = not considered in score)
1 Minor impacts
2
3 Seasonal recreational impacts
4 Significant recreational impacts
5 Significant commercial impacts

ABC Rating

	Score	Weight	Adjusted Score	Maximum Score	Adjusted Score
Average Daily Traffic	0	10	0	5	50
User Impact Reduction	#DIV/0!	30	#DIV/0!	5	150
Bridge Location	0	5	0	5	25
Use of Typical Details	0	5	0	5	25
Work Zone Geometry	0	8	0	5	40
Site Conditions	0	5	0	5	25
Railroad Impacts	0	5	0	0	0
Cost Analysis	0	30	0	5	150
Envir./Water Handling	0	5	0	0	0
Waterway Limitations	0	5	0	0	0
Total Score		#DIV/0!		Max. Score	465

ABC Rating: #DIV/0!

ABC Rating Scale

60-100	Use ABC
50-60	Consider ABC
0-50	Do not use ABC

Note: Weight factors determined by CTDOT. Do not adjust factors without prior consultation.

Figure 2. Connecticut DOT ABC decision-making tool (quantitative matrix), reprinted with permission from [5], 2019.

2.1.3. Hybrid Approaches

Analytic Hierarchy Process (AHP) Approaches

Salem and Miller (2006) [7] and Arurkar (2005) [8] emphasize that selecting the optimal bridge construction strategy—between ABC and conventional construction methods—requires the evaluation of a wide range of factors. These factors include construction costs, road user costs, future rehabilitation costs, traffic maintenance, safety for road users, construction workers, and pedestrians, as well as impacts on surrounding communities, businesses, and the environment [7,8]. The authors highlighted that effective decision-making requires balancing competing priorities among these factors while also highlighting the complexity of assigning weights, particularly when converting qualitative judgments into quantitative inputs within a structured decision-making framework.

Salem and Miller (2006) [7] further noted that the Analytic Hierarchy Process (AHP), developed by Saaty (1980, 1977) [9,10], provides a structured approach for converting qualitative trade-offs into quantitative weights representing the relative importance of criteria. AHP enables decision-makers to decompose complex problems into a hierarchical structure linking the overall goal to criteria, sub-criteria, and alternative solutions. As a hybrid Multi-Criteria Decision-Making (MCDM) methodology, AHP integrates qualitative judgments and quantitative analysis to support complex decision processes [7,9,10]. Following Saaty (1980) [9], the AHP methodology relies on pairwise comparisons among criteria and sub-criteria, which are numerically evaluated on a ratio scale of relative importance ranging from 1 (equal importance) to 9 (extreme importance). The resulting judgments are

organized into pairwise comparison matrices. The weights of sub-criteria relative to a given criterion are derived from the principal eigenvector of the corresponding matrix. Eigenvector values are estimated using Saaty's recommended approximation method, which involves calculating the average of the normalized columns of the comparison matrix. This approach provides a reliable approximation of the principal eigenvector, provided that the consistency of pairwise comparisons remains within acceptable limits. A consistency validation procedure is applied throughout the decision hierarchy to assess the reliability of pairwise comparisons and matrix calculations. According to Saaty's consistency criterion, a calculated consistency ratio (CR) of 10% or less indicates an acceptable level of consistency in pairwise comparisons. Conversely, when the CR exceeds 10%, pairwise comparison judgements should be reviewed until an acceptable consistency level is achieved. In addition to evaluating the matrix consistency, sensitivity analyses are conducted to assess the robustness of alternative rankings with respect to individual criteria and to determine the variations in preference ratings. This additional assessment strengthens confidence in the reliability of the resulting decision hierarchy and evaluation outcomes [5,8,10,11].

Using AHP, Salem and Miller (2006) developed a decision-making system for ABC, encompassing PBES as well as other ABC techniques [7]. The authors argue that traditional cost-centric decision-making approaches are insufficient for capturing broader qualitative considerations, such as maintaining traffic flow and minimizing disruptions to business and communities. They demonstrated that their AHP-based system facilitates the justification of accelerated construction strategies, particularly in situations where qualitative benefits outweigh the higher initial construction costs associated with ABC methods. Based on the analysis of survey data from DOTs, the authors identified six main decision-making factors influencing construction strategy selection: cost (initial construction costs, road user costs and maintenance costs); traffic flow; safety (for all stakeholders); economy (impacts on local economy); social factors (impacts on surrounding communities); and environment (impacts on ecosystems and environmental conditions). The main factors of safety, economy, society, and environment were further supported by additional sub-factors. Analysis of the survey results led to generalized mean weight guidelines for these factors. The study also demonstrated a six-step application procedure through two bridge construction case studies.

Doolen et al. (2011) developed an AHP-based software tool to support early-stage project design decisions regarding the adoption of ABC techniques [11]. The tool was developed using data from completed and ongoing bridge projects in Oregon, collected through expert interviews and validated surveys based on AHP pairwise comparisons among criteria and sub-criteria across multiple levels of the decision hierarchy. The development process involved collaboration with eight U.S. state DOTs.

The finalized decision criteria hierarchy presented in the authors' study consists of three levels of criteria and sub-criteria, supported by accompanying documentation and the AHP-based software implementation [11]. The hierarchy comprises five high-level criteria—schedule constraint, indirect costs, direct costs, site constraints, and customer service—each further decomposed into between two and nine sub-criteria, resulting in a total of 25 sub-factors (see Figure 3). The Oregon-developed AHP tool generates comparative evaluations of ABC alternatives relative to conventional construction methods. Through collaboration with several U.S. states, the tool was further refined and subsequently released as the "ABC-AHP" tool, available on the FHWA website (see FHWA, 2012) [12].

According to Doolen et al. (2011), additional data were collected on completed and ongoing bridge projects through responses provided by DOT experts to a final AHP-based survey [11]. The compiled responses were used to generate project-specific AHP evaluation reports comparing ABC and conventional construction methods. An illustrative example is

presented in Figure 4 for the Oregon DOT's Elk Creek Project. The results indicate that the ABC alternative (score of 62) is preferred over the conventional alternative (score of 38), with the difference primarily attributable to schedule-related considerations.

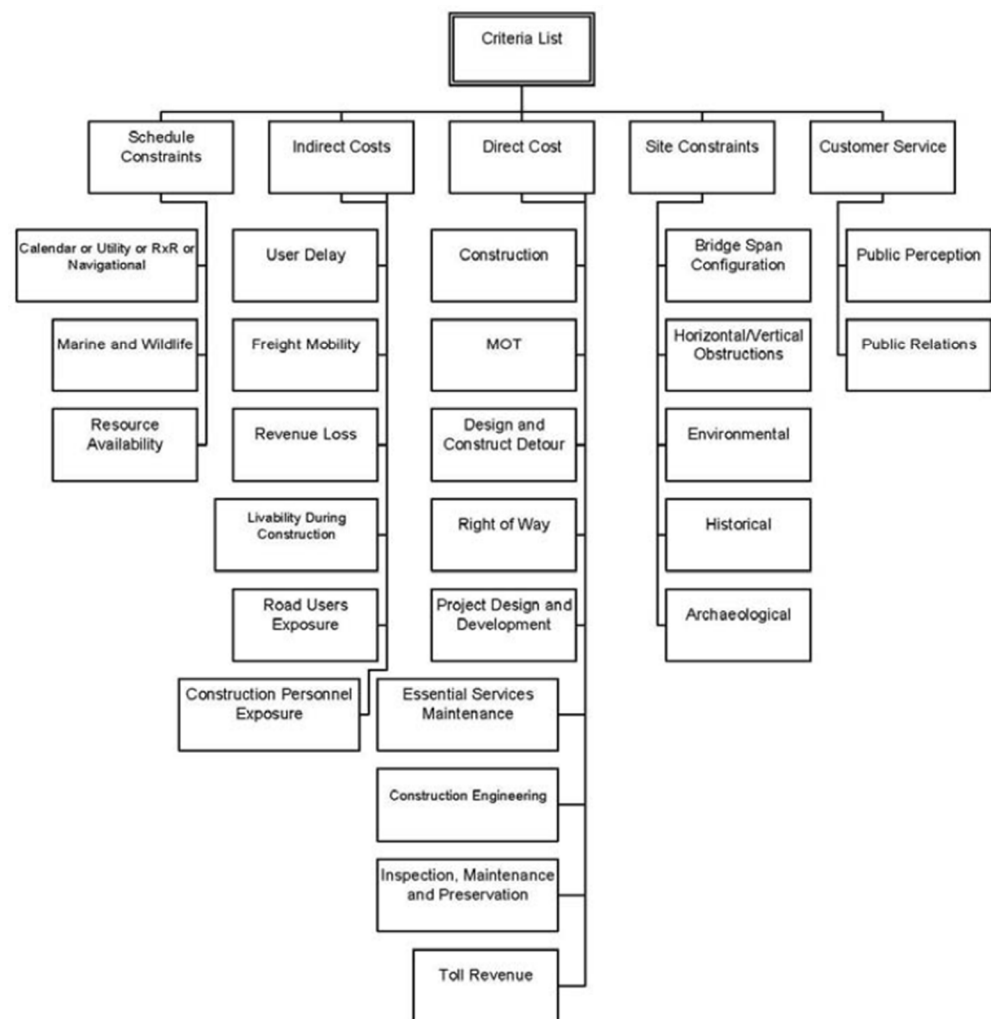


Figure 3. Final decision criteria hierarchy, MCDM tool, reprinted with permission from [11], 2011.

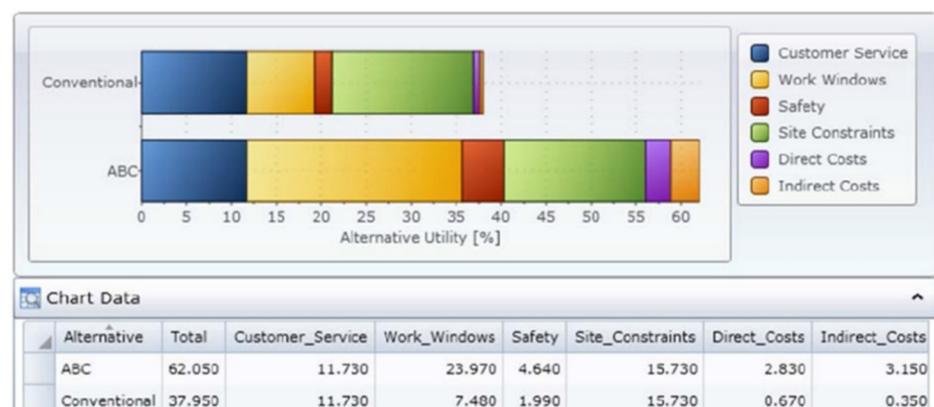


Figure 4. AHP analysis results for the Elk Creek Project, Oregon, reprinted with permission from [11], 2011.

Salem (2013) conducted a comprehensive review of ABC components, techniques, project delivery methods, and existing decision-making models [13]. Based on the analysis of data collected through a national survey of DOTs, prevailing practices related to ABC

projects, associated techniques, project delivery methods, and the factors influencing decision-making processes were characterized. Supplementary surveys and interviews further elucidated these influencing factors. Among the findings, the relative importance of cost categories in the selection of ABC alternatives for both emergency and planned projects was highlighted. In decreasing order of importance, these categories were identified as initial costs, road user costs, and Life-Cycle Costs.

Building on this review and survey, Salem (2013) proposed a conceptual two-phase decision-support platform to assess and compare the relative significance of factors influencing ABC strategy selection for a given project [13]. In the first phase, ABC criteria and alternatives are evaluated using an AHP-based model comprising 19 factors identified through the survey as exerting the greatest influence on decision-making. Within this model, pairwise comparisons are conducted at the factor level. Notably, the model does not explicitly incorporate direct cost-related factors; however, it retains “budget constraints” and “finance availability” among the 19 decision factors. Model validation was conducted through interviews with representatives from the New York State DOT and other transportation experts, followed by application to six completed ABC bridge projects. When ABC is determined to be appropriate, the second phase of the decision-support platform provides conceptual guidance—through two decision-making flowcharts—for identifying the most suitable ABC components and construction techniques, as well as for selecting the most suitable project delivery method.

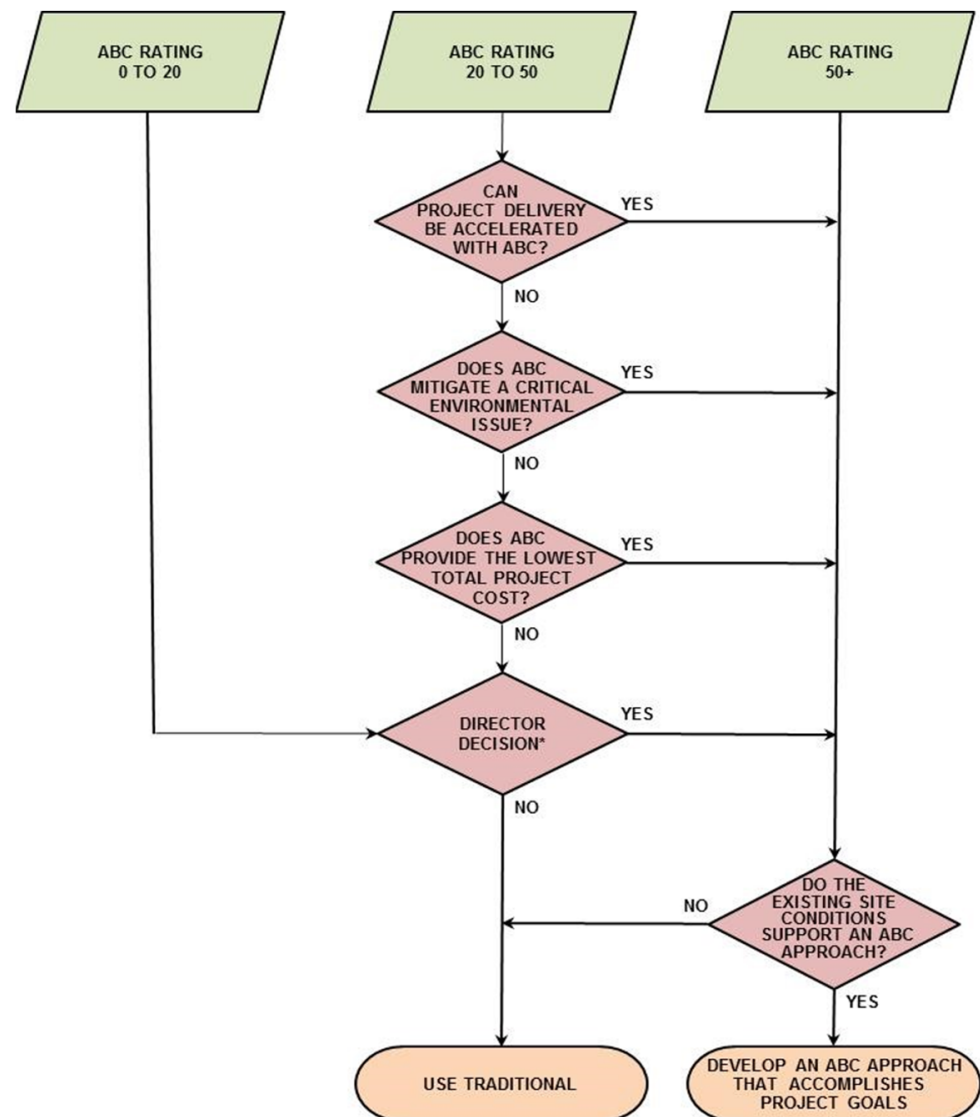
Quantitative Matrices with Subsequent Flowcharts

Mohamadiazar and Ebrahimian (2025, 2024) presented a hybrid variant of the quantitative matrix-based evaluation approach for ABC alternatives, based on a tool developed by the Utah DOT (2026), in which the total score from a quantitative evaluation serves as the entry point to a subsequent qualitative decision-making flowchart [3,4,14]. This flowchart incorporates broader considerations—including ABC techniques, cost factors, and project delivery methods—to support a more comprehensive assessment and further guide the selection of ABC alternatives. Figure 5 illustrates this hybrid approach as implemented by UDOT (2026) [14]. In some cases, an AHP-based evaluation constitutes an optional step within these subsequent qualitative decision flowcharts. It should also be noted that the FIU ABC DST, discussed in Section 2.1.2, can perform both quantitative matrix-based evaluations and hybrid evaluations integrating quantitative and qualitative AHP-based analyses. Mohamadiazar and Ebrahimian (2025, 2024) also applied the AHP-based approach to the case studies presented in that section [4,5].

With respect to the California DOT (Caltrans), the authors indicate that Caltrans similarly employs both a quantitative, questionnaire-based matrix and a subsequent qualitative decision flowchart as part of its ABC Manual (Caltrans, 2021) [15]. The manual established a managerial framework intended to assist planners and engineers in understanding the range of available ABC methods, supporting the project-specific selection of appropriate ABC solutions, and promoting the broader adoption of ABC practices.

According to Mohamadiazar and Ebrahimian (2025, 2024), decision-making within the Caltrans framework is conceptualized as a structured, multi-stage process that integrates coordinated input from multiple stakeholders throughout the project development phases [3,4]. During the technical and feasibility study phase, potentially viable ABC solutions are initially screened and assessed. This is followed by a structural cost-estimation phase, as well as the further refinement of feasible ABC alternatives alongside their associated cost implications. The process then advances to an evaluation stage aimed at determining whether the adoption of ABC methods is justified. A central component of the framework is a comparative assessment of the overall value of ABC relative to conventional

construction alternatives, integrating both cost and benefit considerations. Throughout this process, project-specific objectives and constraints exert a decisive influence, guiding the selection of appropriate construction methods and influencing decisions regarding the potential implementation of ABC.



* Region Director or Project Development Director to evaluate possible indirect benefits.

Figure 5. Utah DOT ABC decision flowchart, reprinted with permission from [14], UDOT 2026.

Analytical Hierarchy Process (AHP) Hybrid Approaches

Aktan and Attanayake (2013) [16] developed an AHP hybrid decision-making model for ABC, together with a corresponding supporting platform. The model integrates both quantitative and qualitative parameters identified through an extensive synthesis of the literature, including evidence from post-construction evaluations and lessons-learned documentation [16].

As summarized by Mohammed et al. (2014), the model computes preference indicators for quantitative parameters by incorporating general project information, site-specific data, traffic data, and Life-Cycle Cost (LCC) data [17]. Input data are derived from analytical

models, including those for the estimation of road user costs, LCC, and traffic-related levels of service, as well as from additional sources. Preference indicators for qualitative parameters are elicited through expert judgments captured using structured preference ratings. Furthermore, computed values for quantitative parameters—such as road user cost and LCC estimates—are presented to subject-matter experts to inform and support their evaluations. The platform implementing this AHP hybrid model is referred to as the Michigan ABC Decision-Making (MiABCD). The model adopts an AHP framework in which decision variables are organized into six main parameters: (i) site and structure considerations (S&ST), (ii) cost, (iii) work zone mobility (WZM), (iv) technical feasibility and risk (TF&R), (v) environmental considerations (EC), and (vi) seasonal constraints and project schedule (SC&PS). These parameters are further decomposed into 26 sub-parameters encompassing both quantitative and qualitative parameters. Quantitative parameters are defined by known or computable values during the early planning stages of a project, with certain inputs derived from analytical models. The associated information is provided by an “Advanced User”, typically the project manager, who assigns preference ratings to these quantitative parameters using a 1-to-9 Ordinal Scale Rating (OSR). In contrast, qualitative parameters rely on expert judgments provided by “Basic Users”, who similarly express their preferences using the OSRs.

According to Mohammed et al. (2014), the data-integration methodology developed for the MiABCD tool enables the automatic transformation of quantitative input data into OSRs for the sub-parameters, which are subsequently converted into AHP pairwise comparison matrices [17]. Similarly, qualitative judgments provided by experts through OSRs are translated into pairwise comparison matrices. These matrices are automatically generated from the assigned OSRs, processed through eigenvalue analysis, and used to compute normalized preference weights for competing alternatives—namely, ABC and conventional construction—in accordance with AHP principles. Consequently, the MiABCD method represents an AHP hybrid approach because it integrates OSRs-based assessments rather than relying on the direct elicitation of pairwise comparisons typically required in traditional AHP applications.

The authors illustrate the application of the MiABCD tool through a case study comparing ABC and conventional construction alternatives for the Stadium Drive Bridge project in Kalamazoo, Michigan. In this example, the project manager (User 1) enters the input data described above, together with preference ratings (i.e., OSRs) for decision-making parameters and accompanying comments (Figure 6). Subsequently, the subject-matter experts (User 2, User 3, etc.) provide their own preference ratings and comments while taking into account the information previously entered by User 1 [16,17].

The results of the MiABCD application to the Stadium Drive Bridge project are presented in Figure 7. In this case, both the upper- and lower-bound results favour the ABC alternative over conventional construction. The findings further indicate that Seasonal Constraints and Project Schedule (SC&PS), followed by Cost, exert the greatest influence on the decision outcome. Figure 7 also illustrates the sensitivity of the results to variations in user input, highlighting the influence of differing stakeholder perspectives on the final evaluation [16,17].

According to Attanayake and Aktan (2018), the MiABCD tool has continued to evolve over time, with its scope of application progressively expanded [18,19]. Beginning in 2017, software enhancements enabled the comparative assessment of four bridge construction and replacement methods: (i) Prefabricated Bridge Elements and Systems (PBES), (ii) Slide-In Bridge Construction (SIBC), (iii) Self-Propelled Modular Transporter (SPMT) moves, and (iv) Conventional Construction (CC). In addition to the six main parameters, the updated software allows for the inclusion of up to six supplementary sub-parameters

for each main parameter, resulting in a total of 36 sub-parameters. The study further describes improvements to the MiABCD tool in the computation of normalized preferences within the decision matrices, highlighting methodological advancements relative to traditional AHP approaches. These developments originated from a comprehensive report by Aktan and Attanayake (2017) [19]. Among other contributions, the report addressed: (i) the expansion of the Mi-ABCD tool to incorporate SIBC and SPMT; (ii) the development of a model for quantifying the economic impact of bridge construction projects on surrounding communities and businesses; and (iii) the standardization of SIBC design and operations based on the review of 28 SIBC project activities [18,19].

Preference Ratings for Decision-Making Parameters

Advanced User Menu View the preference ratings of respective user here:

Parameter		Rating Significance		Ordinal Scale Rating (1 to 9)	Comments Provided by (User-1):
		1	9		
Initial construction cost	Conventional Construction: \$6.00 M Accelerated Bridge Construction: \$7.50 M	More flexible	Highly constrained	8	Cost difference is quite large
User cost	Conventional Construction: \$5.88 M Accelerated Bridge Construction: \$2.32 M	Not significant	Extremely significant	5	ABC really helps reduce user cost
Life-cycle cost	Conventional Construction: \$15.65 M Accelerated Bridge Construction: \$8.61 M	Not significant	Extremely significant	9	ABC also reduces LCC
Economic impact on surrounding businesses		Insignificant impact	Extreme impact	9	University as well as Pfizer, Stryker, and hospital employees use this road
Work zone traffic risk		Not significant	Extremely significant	7	Quite high traffic, the accident risk is high
Construction risks (Involved with the proposed ABC technology)		Not significant	Extremely significant	5	Contractor has some experience
Existing structure type and foundations		Not complex	Extremely complex	5	Narrow shoulder width and near entrance and exit ramps
Terrain to traverse (e.g., Viaduct over rapids, deep water, a valley, or restricted access)		Not difficult	Extremely difficult	5	Narrow shoulder width and near entrance and exit ramps
Access and mobility of construction equipment		Not difficult	Extremely difficult	5	Narrow shoulder width and near entrance and exit ramps
Contractor experience (Required for the proposed ABC technology)		Limited experience	Experienced	6	Contractor has some experience
Manufacturer/Precast plant experience (Required for the proposed ABC technology)		Limited experience	Experienced	3	Limited experience
Seasonal limitations		Not significant	Extremely significant	7	Minimum impact to the University during late summer
Stakeholder(s) limitation		Not significant	Extremely significant	7	University and named businesses will be constrained
Environmental protection		Minimal	Extremely important	3	Not significant
Aesthetic requirements		Not a concern	Required	5	Urban area, aesthetics important

User1-OK User-1

Figure 6. Mi-ABCD: Example of preference ratings decision-making parameters, reprinted with permission from [16], 2013.

A key limitation of traditional AHP-based models concerns the consistency of pairwise comparisons, which can be compromised when comparisons involve unrelated parameters or a large number of parameters (Aktan and Attanayake, 2013; Mohammed et al., 2014; and Attanayake and Aktan, 2018) [16–18]. Furthermore, Aktan and Attanayake (2013) discussed additional limitations of traditional AHP-based models, particularly the challenges associated with maintaining acceptable consistency ratios when using approximate methods for computing local priorities—a limitation that may ultimately lead to unreliable or biased ratings [16]. Using the ABC-AHP tool (discussed in Section Analytic Hierarchy Process

(AHP) Approaches) and applying it to a prototype bridge project, the authors conducted a sensitivity analysis by introducing small variations in the preference ratings assigned to both the major parameters and their associated sub-parameters. When equal preference ratings were assigned to the major parameters and the sub-parameter ratings reflected site-specific conditions, most sub-parameters favoured conventional construction methods. Further analysis indicated that the competing alternatives received equal scores for each major parameter despite constant ratings for major parameters and varying ratings for the sub-parameters. Based on these findings, the authors concluded that failure to verify the consistency ratio may lead to inconsistent or unreliable ranking outcomes [16].

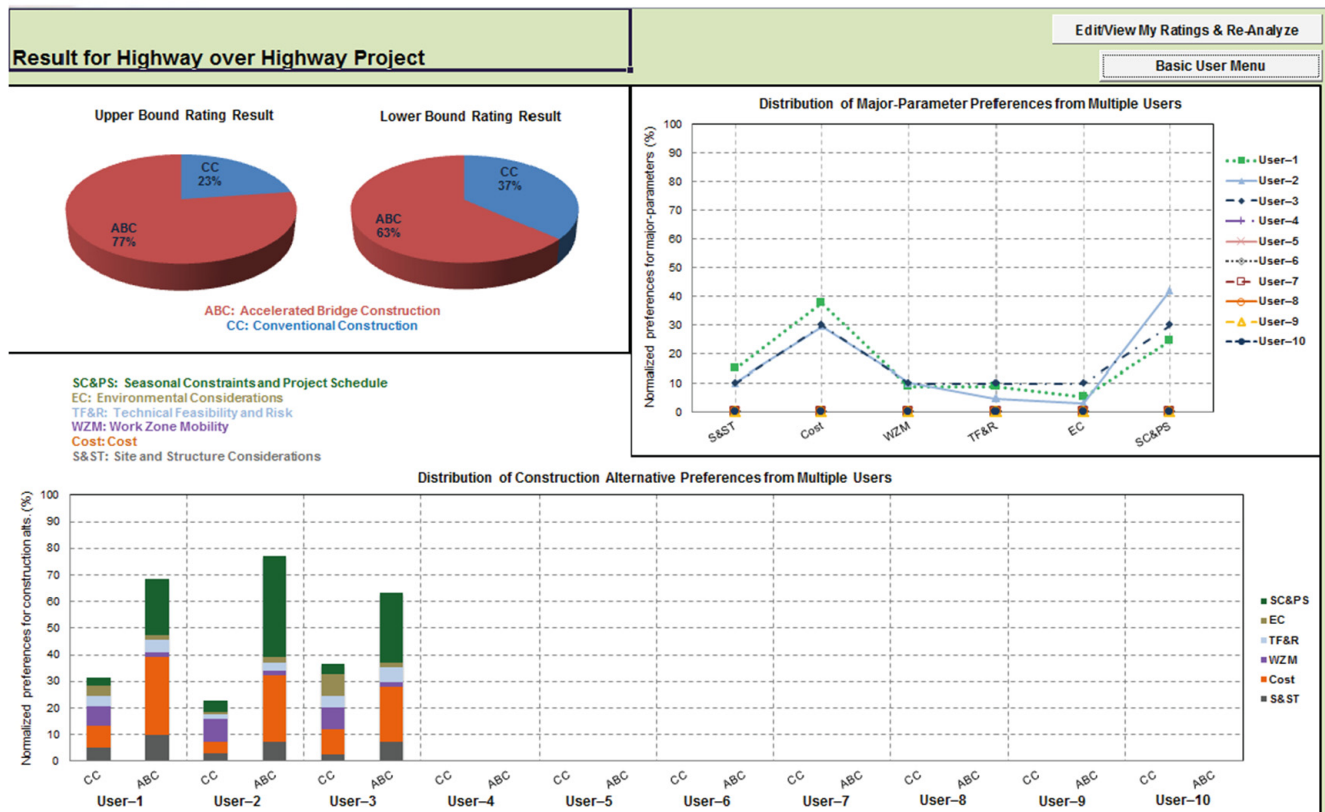


Figure 7. Mi-ABCD: Example of outputs: ABC versus conventional construction reprinted with permission from [16], 2013.

Consequently, Attanayake and Aktan (2018), together with the earlier work by Aktan and Attanayake (2013) and Mohammed et al. (2014), argued that the MiABCD AHP hybrid model represents a methodological advancement over traditional AHP-based decision models [16–18]. According to these authors, the distinctive features of the MiABCD approach address several limitations inherent to traditional AHP applications. In particular, the framework enables the integration of site-specific data, which are translated into Ordinal Scale Ratings (OSRs), while employing advanced computerized procedures to facilitate compliance with AHP consistency requirements. The use of OSRs, informed by site-specific inputs provided by the project manager, reduces the reliance on extensive expert elicitation through pairwise comparisons and mitigates challenges associated with comparing disparate parameters. Collectively, these hybrid features enhance the robustness of the decision-making process while addressing key shortcomings of traditional AHP methodologies.

Other Hybrid Approaches and Limitations

A comprehensive examination of the theoretical foundations of MCDM methodologies is beyond the scope of the present literature review. Nevertheless, in addition to the U.S. experience with MCDM applications to ABC projects discussed earlier, this section reviews selected international studies to provide broader perspectives on the application of these techniques in bridge infrastructure decision-making.

Wang et al. (2008) presented an integrated AHP and Data Envelopment Analysis (DEA) methodology for evaluating bridge risks across large bridge inventories—potentially comprising hundreds or even thousands of structures—and supporting maintenance prioritization [20]. Specifically, the methodology uses AHP to determine criterion weights, employs linguistic descriptors (e.g., high, medium, low, and none) to assess bridge risks under each criterion, applies DEA to quantify the corresponding linguistic assessments, and integrates the resulting values using the Simple Additive Weighting (SAW) method to produce an overall risk score for each bridge. The authors demonstrated the applicability of the methodology using a bridge maintenance prioritization framework developed in the United Kingdom in 2004 [20].

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is another widely used MCDM approach for ranking alternatives across multiple performance dimensions (Wang and Elhag, 2006) [21]. Within the TOPSIS framework, each alternative is evaluated against a comprehensive set of criteria, and two reference points are defined: a positive ideal solution (PIS), which maximizes benefit criteria and minimizes cost criteria, and a negative ideal solution (NIS), which represents the least desirable performance across all metrics. By integrating quantitative measures and qualitative judgments, TOPSIS enables comprehensive comparisons of alternatives in complex project contexts. Furthermore, TOPSIS can be extended through fuzzy logic to address uncertainty and imprecision in decision-making, particularly when criteria evaluations involve subjective judgments. Wang and Elhag (2006) applied this Fuzzy TOPSIS extension to a bridge maintenance prioritization framework in the United Kingdom [21]. An overview of the main trends in fuzzy and linguistic decision-making is provided by Herrera-Wiedma et al. (2021) [22]. Jia et al. (2018) and Hadi et al. (2017) reported the application of Fuzzy TOPSIS to the comparative evaluation of ABC and conventional construction methods through two case studies involving interstates I-4 and I-595 in Florida [23,24]. The decision outcomes derived from the Fuzzy TOPSIS approach—which integrates both qualitative and quantitative criteria—were compared with those obtained using the traditional present worth analysis (PWA) method, which evaluates alternatives primarily on the basis of monetary outcomes. For the I-4 case study, both approaches favoured ABC. In contrast, for the I-595 case study, the results diverged: Fuzzy TOPSIS favoured ABC, whereas PWA favoured conventional construction. Hadi et al. (2017) did not discuss the reasons underlying this discrepancy [24]. Jia et al. (2018) reported results only for the I-4 case study [23]. Because both case studies relied on site-specific data and analyses, and because the Fuzzy TOPSIS method depends on expert-assigned linguistic ratings across multiple evaluation dimensions—including mobility, reliability, safety, emissions, and construction—it remains whether the agreement between the Fuzzy TOPSIS and PWA decision outcomes for the I-4 case study, and their divergence for the I-595 case study can be attributed to the decision-making methodology itself or to differences in the underlying project-specific inputs.

Ors et al. (2023) presented a distinct yet related application of AHP and TOPSIS in bridge engineering construction [25]. The authors propose a Decision-Support System (DSS) for selecting the optimal construction technique for bridge piers through the combined application of AHP and TOPSIS. The framework evaluates seven criteria: lateral stiffness, ductility, risk, maintainability, constructability, cost, and time. The alternatives include

monolithic cast-in-place, precast post-tensioned, and anchored precast post-tensioned piers. AHP is used to derive the relative importance of the evaluation criteria, whereas TOPSIS is employed to rank the competing alternatives. The study also provides a detailed description of the consistency verification procedures associated with the AHP and TOPSIS methodologies. The results indicate that the post-tensioned alternative is the preferred option under prevailing market conditions in Egypt. Furthermore, the findings suggest that the influence of individual criteria depends not only on their assigned weights but also on the range of their performance values. The analysis further shows that risk, constructability, and cost exert a comparatively limited influence on the selection of the preferred alternative.

Additional limitations of MCDM methodologies were highlighted by Zhu et al. (2021), who presented a comprehensive review of MCDM applications in the construction domain [26]. Based on a dataset of 530 construction-related publications published between 2000 and 2019, the authors observed that most of the reviewed studies do not adequately address the practical applicability of the proposed models. In addition, issues related to the model robustness are often overlooked. Two key robustness concerns were identified: (i) the potential risk of rank reversal when decision alternatives are added or removed—an issue particularly relevant to AHP-based techniques—and (ii) the potential that different MCDM methodologies may produce divergent ranking outcomes when applied to the same decision problem.

2.2. ABC Techniques and Delivery Methods

2.2.1. Selection of Site-Specific ABC Techniques

Following the introduction of ABC, Culmo (2011) examined ABC techniques, accelerated project delivery approaches, and contracting provisions, and their applicability across different project contexts [27]. As part of project planning and scoping activities, and building on the 2006 FHWA framework for PBES decision-making, Culmo developed detailed decision-making flowcharts for four construction scenarios, assuming that the decision to adopt ABC methods had already been made.

Culmo's (2011) flowcharts are intended to guide the selection of appropriate ABC techniques, involving PBES and various associated moving methods, including Self-Propelled Modular Transporters (SPMT), lateral skidding or sliding, and longitudinal launching [27]. The four construction scenarios are (i) superstructure construction over roadway or land, (ii) superstructure construction over railroad or transit, (iii) superstructure construction over waterway or wetland, and (iv) construction of infrastructure elements. For a given project site, these flowcharts facilitate the identification of feasible ABC techniques by accounting for site-specific constraints and project characteristics, thereby supporting decision-makers in selecting the most appropriate construction solution. Culmo's decision flowchart for infrastructure construction is presented in Figure 8 [27].

El-Rayes et al. (2023) developed a Life-Cycle Cost (LCC)-driven Decision Support Tool (DST) to support the selection between ABC and conventional construction methods through comparative cost-based evaluations [28]. The qualitative component of the DST is structured into three sequential steps. The first step consists of a preliminary evaluation to assist Illinois DOT (IDOT) decision-makers in determining the suitability of ABC methods for a planned bridge project. This initial assessment builds upon the qualitative flowchart and question matrix of the 2006 FHWA framework for PBES decision-making discussed earlier. However, in this stage, the DST converts the original qualitative questions matrix into a quantitative scoring matrix, applied in a manner similar to the quantitative approaches described in Section 2.1.2 [28].

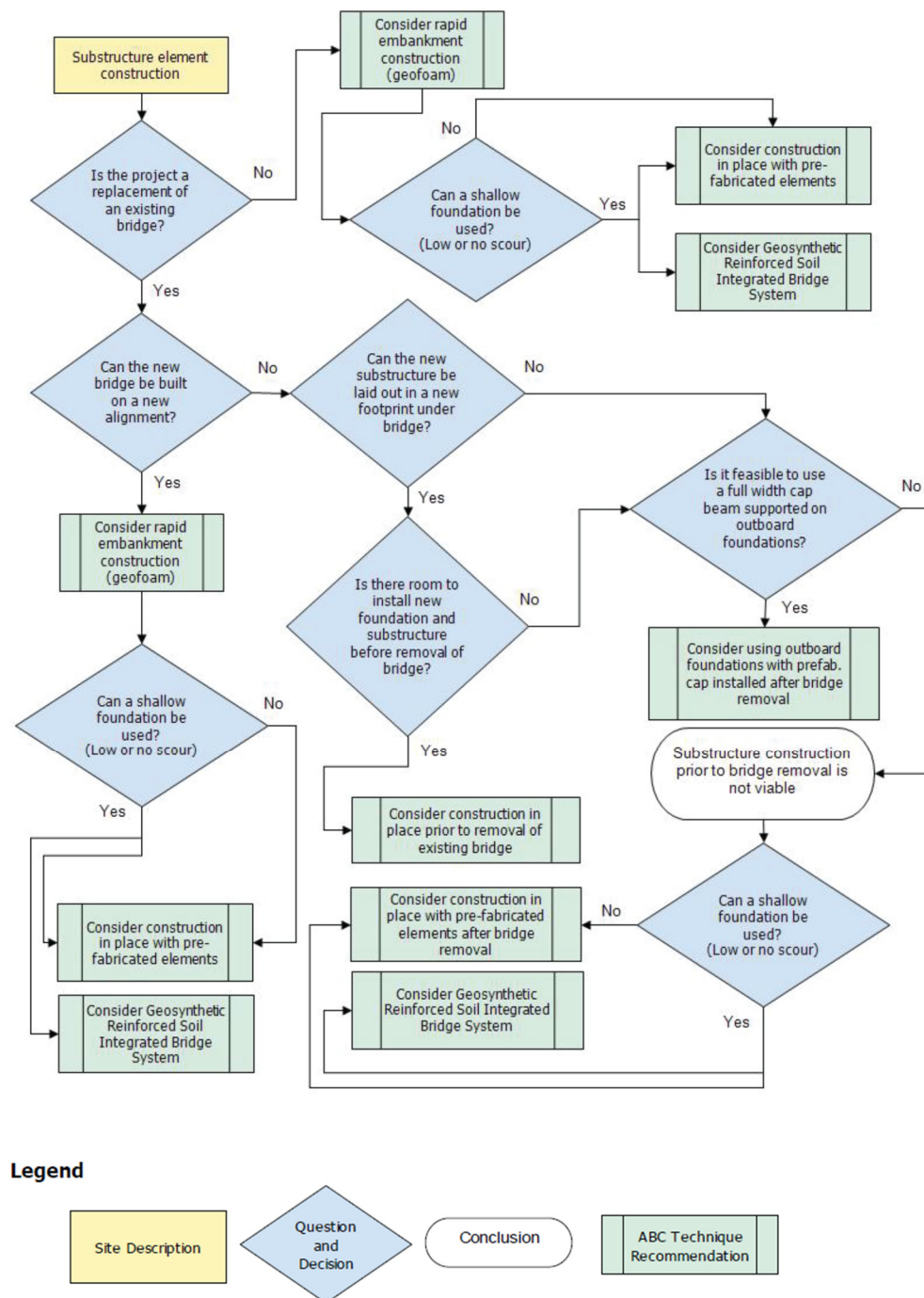


Figure 8. Decision flowchart for infrastructure, reprinted with permission from [27], 2011, FHWA.

In the second step, the DST enables decision-makers to systematically identify all ABC methods for projects determined to be suitable for ABC during the first stage [28]. This second step is based on a set of guidelines that integrates the decision-flow logic proposed by Culmo (2011) [27]. Through an additional evaluation matrix, planners first select one of the four construction scenarios introduced previously, based on project location and the nature of the proposed work. Responses to a predefined set of questions, derived from Culmo's framework for the selected scenario, are then used to generate a list of feasible ABC and conventional construction methods applicable to the project under consideration. This procedure may be repeated for each relevant construction scenario [28].

In the third step, the qualitative component of the DST automatically consolidates the outputs from the second step to produce a comprehensive list of viable ABC and

conventional construction alternatives [28]. The ABC alternatives may include PBES, lateral slide techniques, and Self-Propelled Modular Transporters (SPMTs). The identified alternatives can subsequently be incorporated into the quantitative analysis component of the DST for further evaluation. Figure 9 illustrates the three-step qualitative component of the DST [28].

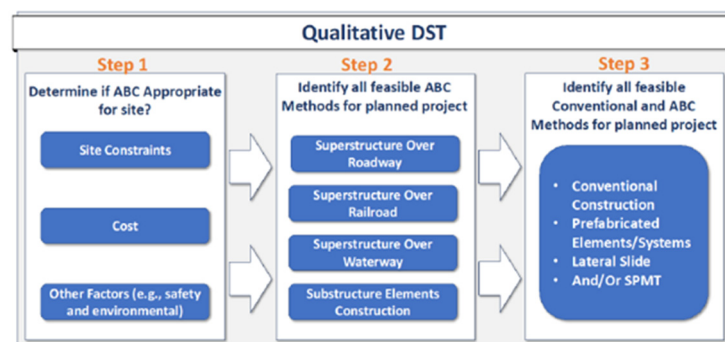


Figure 9. Three-step qualitative DST, reprinted with permission from [28], 2023.

The second phase of Salem's (2013) decision-making model incorporates a flowchart that provides conceptual guidance for identifying the most suitable ABC components and construction techniques for a given project [13]. This guidance was developed from an analysis of national survey data documenting prevailing practices among U.S. state DOTs.

2.2.2. Selection of Project Delivery Methods

Freese et al. (2020) provided an overview of contemporary practices related to ABC decision-making frameworks, contracting approaches, project delivery methods, alternative project delivery methods, and factors influencing their use [29]. The study placed particular emphasis on project delivery methods and lessons learned from completed ABC projects. The authors reviewed qualitative, quantitative, and hybrid approaches that have been used to support decision-making regarding the adoption of ABC methods. They also examined a range of contracting mechanisms, including lump-sum (fixed-price), unit-price, cost-plus, cost-plus with guaranteed maximum price (GMP), and time-and-material contracts. With respect to project delivery, the study described Design-Bid-Build (DBB), Design-Build (DB), and Construction Manager/General Contractor (CMGC), supported by comparative tables summarizing the key characteristics of each approach. Alternative project delivery methods and the associated decision considerations influencing their selection were also addressed.

The application of these approaches was illustrated through four ABC project case studies conducted in three U.S. states: Georgia, Indiana, and Minnesota [29]. The analysis further examined bid items, contracting methods, and lessons learned during project implementation. The study concluded that ABC is primarily adopted to reduce bridge closure durations and to enhance the safety of both construction workers and the travelling public. Successful implementation was found to depend, in part, on procurement and bidding strategies that incentivize contractors to minimize roadway closure durations. Overall, the findings suggest that ABC can be successfully implemented using the three delivery methods examined in the study: DBB, DB, and CMGC.

To further broaden the discussion of project delivery models, the following observations are made. Under the DBB model, project design is typically developed independently of the subsequent construction methods and project delivery activities. The project owner retains substantial control over the design throughout project development; however, the project preparation phase is generally longer. In contrast, the DB model integrates the

expertise of the designer and contractor, with the contractor assuming responsibility for both design and project delivery. This integrated approach can encourage the development of innovative construction methods and enhance project delivery efficiency. By integrating the design and construction processes, the DB model can improve project planning and preparation while reducing overall project delivery duration. However, the project owner relinquishes a significant degree of control over the final design. This approach has increasingly been reflected in governmental guidance documents. An illustrative example is provided by the Quebec government (2025) [30].

Under the CMGC model, both the designer and contractor are contracted directly by the project owner. By retaining control over the overall design, the owner can also influence the selection of construction methods that best align with project objectives. Similarly to the DB model, the CMGC approach promotes innovation in construction methods and may reduce project delivery duration through greater continuity and coordination between project planning and construction. Consequently, the CMGC model is frequently regarded as particularly well suited to ABC projects. Moreover, the closer integration of design development and construction methods inherent in the CMGC approach may have significant implications for the evaluation and selection of ABC alternatives. This approach is exemplified by the Quebec government (2025) [30].

In addition, Culmo (2011) and Salem (2013) also provided complementary guidance on project delivery strategies for ABC projects [13,27]. More recently, Pradhananga et al. (2023) examined the influence of Alternative Technical Concepts (ATC) on ABC project delivery [31]. Drawing on evidence from ABC project case studies, the authors highlighted that a key benefit of ATCs is the facilitation of early contractor involvement, which can foster innovation, enhance constructability, and contribute to cost optimization.

2.3. Sustainability and Life-Cycle Analysis

Life-Cycle Analysis (LCA) provides a holistic framework for evaluating infrastructure projects by considering resource consumption, environmental impacts, energy use, economic performance, and social dimensions throughout the asset life cycle. Accordingly, the following section briefly reviews selected international studies that apply LCA and LCCA methodologies to bridge infrastructure.

Jalaei et al. (2025) reviewed the application of LCA to bridge infrastructure through a comprehensive bibliometric analysis and a Canadian bridge replacement case study [32]. Their study highlighted the limited adoption of LCA methodologies for bridges compared with road infrastructure and identified challenges related to structural complexity, data collection, and methodological implementation. The case study demonstrated an LCA framework for assessing environmental impacts throughout a bridge's service life and showed that stainless steel reinforcement could reduce carbon dioxide emissions by more than 10% compared with conventional black steel reinforcement. The findings also emphasized the significant contribution of transportation activities to overall environmental impacts and the importance of selecting appropriate functional units for bridge LCA [32].

Cheng et al. (2023) evaluated the use of hybrid reinforced concrete for bridge edge beams exposed to deicing salts through combined LCCA and LCA [33]. By integrating conventional reinforcement with low-to-moderate fibre reinforcement, the proposed solution improves resistance to chloride-induced corrosion and extends the service life of edge beams by more than 58% compared with traditional reinforced concrete. The results demonstrated that increased durability can lead to substantial reductions in both Life-Cycle Costs and greenhouse gas emissions, highlighting the long-term economic and environmental benefits of hybrid reinforced concrete for bridge infrastructure [33].

Martínez-Muñoz et al. (2021) applied an LCA framework to compare the sustainability of four bridge deck alternatives across different span lengths, considering the manufacturing, construction, use and maintenance, and end-of-life phases [34]. Using the ReCiPe impact assessment method and the Ecoinvent 3.3 database, the study identified the most sustainable bridge deck configuration for each span range. The findings indicated that prestressed concrete slabs were generally preferred for short- and medium-span bridges, whereas for longer spans the optimal solution depended on the recycled content of structural steel. The study highlighted the significant influence of material selection and steel recycling on the environmental sustainability of bridge deck design [34].

Zhou et al. (2020) evaluated the environmental impacts of a three-tower cable-stayed bridge over its full life-cycle using LCA [35]. The analysis identified the operation and maintenance phases as the primary contributors to global warming potential, largely due to vehicle emissions and maintenance activities. The findings highlighted the importance of reducing traffic-related emissions and improving the durability of construction materials to enhance the environmental sustainability of bridge infrastructure [35].

Zhao et al. (2014) proposed an integrated framework for achieving sustainability in engineering design by combining performance-based design with LCA [36]. Recognizing that sustainable engineering should balance economic, social, and environmental objectives rather than focus solely on environmental performance, the framework established a six-step methodology integrating both approaches through common design objectives. The authors suggested that the framework could support more comprehensive and sustainable engineering decision-making while informing future design practices, project delivery processes, and engineering education [36].

Daigle and Lounis (2006) presented a comprehensive LCCA framework for reinforced concrete bridges that accounts for owner and user costs incurred throughout the bridge life-cycle, including construction, maintenance, rehabilitation, replacement, and disposal [37]. The framework also incorporated environmental impacts, notably greenhouse gas emissions and waste generation, while evaluating Life-Cycle Costs using the present value method. Applying this approach, the study compared high-performance concrete (HPC) containing supplementary cementitious materials with normal-performance concrete (NPC), demonstrating the long-term economic and environmental benefits of HPC through extended service life, reduced Life-Cycle Costs, and improved sustainability [37].

3. Synthesis of Cost Estimation Tools

3.1. Main Methodologies and Concepts

This section examines the principal methodologies and concepts underpinning cost-estimation tools developed to support evaluation and selection decisions related to ABC, which are typically conducted during the preliminary stage of project development. These tools differ from the more detailed cost-estimation procedures generally applied during subsequent engineering design and project optimization phases. Given the central importance of Life Cycle Cost Analysis (LCCA), its fundamental principles are first introduced, followed by a review of the relevant cost-estimation tools.

3.1.1. Life-Cycle Cost Analysis

Hawk (2003a, 2003b) provided a seminal U.S. reference by establishing procedures and guidance for conducting LCCA for bridge infrastructure [38,39]. The guidance is organized into two parts: the first defines standardized procedures and methodological guidelines for performing Life-Cycle Costing, while the second provides a guidance manual for applying LCCA to both new and existing bridges. The manual presents Life-Cycle Costing concepts, identifies relevant data sources, and describes the application of the

Life-Cycle Cost methodology. The key elements of Hawk's approach are summarized below to clarify the principles underlying LLCA, whose application in ABC evaluation and selection decisions has remained limited.

Service life is defined as the interval between initial construction and ultimate replacement [38,39]. During this period, bridges require routine and periodic maintenance, rehabilitation interventions, and ultimately replacement. Consequently, bridge assets incur a sequence of expenditures distributed throughout their life cycles, represented through a profile of activities, typically expressed as a cash-flow diagram of anticipated interventions. Sound economic decision-making therefore requires the explicit consideration of these Life-Cycle Costs.

Hawk's studies indicate that multiple maintenance and improvement alternatives may be applicable to a bridge exhibiting a given combination of distress conditions and contextual factors. Because feasible interventions vary according to jurisdictional practices and project-specific conditions, a structured set of candidate alternatives is developed based on combinations of distress indicators, traffic characteristics, and geometric attributes. Each alternative can then be evaluated according to its associated profile of activities and projected cash flows. Within this framework, LCCA is applied to determine the optimal timing and sequencing of bridge interventions [38,39].

Hawk's (2003a, 2003b) defines bridge Life-Cycle Cost (LCC) as the aggregation of "agency costs" and "user costs" [38,39]. "Agency costs" encompass direct costs associated with planning, design, construction, operation, maintenance, rehabilitation, and end-of-life costs, including disposal costs or residual value. "User costs", by contrast, affect a broad range of stakeholders, including motorists crossing the bridge as well as nearby business and residential communities whose accessibility and economic activity depend on the bridge infrastructure. These costs primarily result from disruptions associated with congestion and with maintenance, rehabilitation, or replacement activities. Core components include the monetized value of travel-time losses caused by delays, detours, and network inefficiencies. The study further notes that crash-related costs may also represent a significant component, reflecting the relationship between bridge characteristics, operational conditions, and crash occurrence.

The study further demonstrates that, although general LCCA models can be applied across transportation infrastructure systems, specialized models are often tailored to specific asset classes, such as bridges or pavements [38,39]. In Hawk's guidance manual, the comprehensive bridge LCCA methodology is operated through a software tool designed for application at the individual bridge-asset level. The software integrates both agency cost and user cost and includes functionality for vulnerability and uncertainty analyses. Collectively, the study report, guidance manual, and associated software constitute an integrated decision-support framework for evaluating repair strategies and selecting cost-effective alternatives for bridge asset management across short- and long-term planning horizons.

Importance of LCCA in ABC Evaluation and Decision-Making

Over time, the importance of LCCA in informing evaluation and selection decisions for ABC alternatives has been increasingly recognized. Illustrative examples are provided below.

Salem and Miller (2006) [7] indicated that minimizing Life-Cycle Costs constitutes one of the main objectives of the FHWA Accelerated Construction Technology Transfer (ACTT). Furthermore, based on survey responses, the authors reported that nearly half of the surveyed agencies incorporate LCCA into their decision-making processes [7]. Doolen et al. (2011) noted that many agencies are investigating economic tools such as LCCA to identify cost-effective alternatives and to communicate decision outcomes to the

public [11]. In this context, comparing alternatives requires an assessment of future agency expenditures and of the broader public benefits realized upon project completion.

Salem (2013) emphasized that selecting an appropriate accelerated construction strategy is critical, as inappropriate decisions may result in increased Life-Cycle Costs, higher user costs, and suboptimal overall outcomes [13]. Hadi et al. (2016) noted that while the scope of their ongoing research project is limited to the development of construction costs and user costs modules within an MCDM tool, their long-term vision is to develop a comprehensive decision analysis framework incorporating initial costs, maintenance and rehabilitation costs, and road user costs within an integrated Life-Cycle Cost–Benefit framework [40].

More recently, Attanayake and Aktan (2018) and El-Rayes et al. (2023) demonstrated the explicit integration of LCCA principles and associated computational procedures into cost-estimation models supporting the evaluation and selection of ABC alternatives relative to conventional construction methods [18,28].

3.1.2. Cost Estimation Modules

As noted earlier, Life-Cycle Cost is widely recognized as a key parameter in evaluation and decision-making tools for selecting between ABC and conventional construction methods. In this context, this section reviews key developments in cost-estimation modules for the principal components of Life-Cycle Costs, namely construction costs, road user costs, and maintenance and rehabilitation costs, as well as integrated modules that combine these components into a comprehensive Life-Cycle Cost assessment framework.

Construction Cost Module

Orabi et al. (2016) presented a parametric construction cost-estimation model for ABC projects, developed using data from 65 projects, constructed between 1998 and 2013 across 29 U.S. states [2]. The principal data source was the ABC Project Database, currently hosted by the ABC-UTC. Statistical analyses of construction cost data, supported by a classification and regression tree approach, identified annual average daily traffic, number of spans, types of materials (concrete or steel), and project location (urban or rural) as the principal factors influencing construction costs. These parameters were subsequently incorporated into a regression-based model designed to estimate the per-square-foot cost range of ABC projects.

Hadi et al. (2016) proposed a two-tier construction cost-estimation framework for ABC projects that integrates parametric cost estimation with detailed cost analysis [40]. Tier 1 comprises a high-level cost-estimation module derived from the parametric model developed by Orabi et al. (2016), providing preliminary construction cost estimates [2]. Tier 2 supports more comprehensive cost analyses by accounting for both direct and indirect costs. Direct costs include materials, labour, and equipment, whereas indirect costs encompass preliminary engineering, right-of-way, construction engineering, and inspection activities.

El-Rayes et al. (2023) proposed a construction cost-estimation module consisting of two sub-modules: (i) a Rough Order-of-Magnitude (ROM) sub-module, applicable during the early project phases for both conventional and ABC methods, and (ii) a detailed cost-estimation sub-module based on the final design specifications of all bridge elements [28]. The ROM sub-module incorporates predictive models intended to generate early-stage cost estimates for bridge projects. These models rely on preliminary planning variables, including overall project length, bridge dimensions, maximum span length, number of spans, location type, design type, geotechnical solutions, use of high-performance materials, and mobility impacts. Using Multiple Linear Regression (MLR) and Machine Learning (ML)

techniques, the predictive models were developed through four steps: (i) identification of dependent and independent variables; (ii) definition of model performance evaluation procedures for the developed predictive models; (iii) development of MLR- and ML-based cost-estimation models; and (iv) performance assessment to identify the most suitable model for each bridge construction method (Figure 10) [28]. The cost-estimation module was designed to compile and utilize historical construction cost data from projects delivered using both conventional construction and ABC methods.

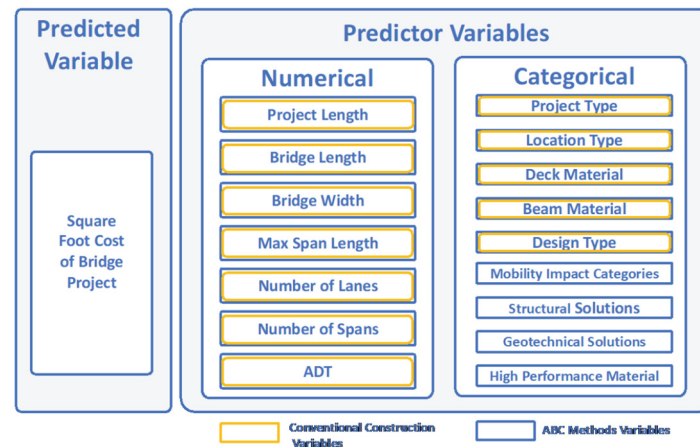


Figure 10. ROM sub-module: identified predicted and predictor variables in the ROM submodule, reprinted with permission from [28], 2023.

El-Rayes et al. (2023) reported that the ABC Project Database contained 124 projects that were constructed in 41 U.S. states [28]. Of these projects, 75 employed PBES, 17 used lateral slide techniques, 11 utilized SPMT, and one involved longitudinal launching. Following a data-cleaning process, the authors identified a subset of 89 ABC projects containing sufficient relevant data for cost-estimation purposes. Among these 89 ABC projects, 64 employed PBES, eight used lateral slide techniques, seven utilized SPMT, and 10 involved other equipment, such as high-capacity cranes. The study also described the bridge database maintained by the Illinois Department of Transportation (IDOT). After excluding non-construction projects, the database contained 243 IDOT projects with the data required to estimate ROM costs (expressed as cost per square foot), as well as other relevant project information. Of these projects, 181 were delivered using conventional methods, 60 employed PBES, and two used lateral slide techniques. The ABC Project Database and the IDOT database were subsequently merged, and project cost data were adjusted according to the procedures described in the study to account for variation in construction year and project location. This process resulted in a combined dataset of 181 conventionally constructed bridge projects and 155 ABC bridge projects. The study also presented four parametric cost-estimation equations used by the ROM sub-module to estimate per-square-foot construction costs for conventional, PBES, lateral slide, and SPMT construction methods, respectively.

Road User Cost Module

Mallela and Sadasivam (2011) produced a comprehensive report on work zone road user costs (WZ RUC) [41]. Work zones are defined as highway segments where construction, maintenance, or utility activities are undertaken. WZ RUC represent the additional costs incurred by road users and surrounding communities as a result of these activities. These costs typically include vehicle operating costs, delay costs, safety-related costs, and emission-related costs. The report proposed an economic framework, supported by extensive U.S. datasets, for quantifying these impacts through stepwise methodology, thereby supporting informed decision-making aimed at improving work zone safety and mobil-

ity. The authors noted that WZ RUC analyses are commonly integrated into LCCA and cost–benefit decision frameworks used by transportation agencies for highway assets such as pavements and bridges. The report further demonstrated how quantitative and qualitative aspects of WZ RUC can support Maintenance-Of-Traffic (MOT) alternatives within structured decision-making frameworks. It acknowledged that qualitative impacts, such as environmental, business, and societal effects, are increasingly incorporated into practice. In addition, the report highlighted the role of WZ RUC minimization in selecting project delivery and contracting strategies that reduce user impacts through accelerated project completion, as well as the use of incentive-disincentive provisions designed to influence contractor performance. Through case studies of completed projects, the report provided practical guidance on the application of WZ RUC concepts and methodologies.

Doolen et al. (2011) briefly addressed road user cost estimation within the broader context of LCCA, noting that road user costs are commonly incorporated into economic evaluations [11]. These costs capture the value of time lost due to congestion and additional vehicle operating expenditures. The authors provided examples of user cost documentation and discussed existing software tools. However, it should be noted that their study evaluated road user costs primarily in relative terms using AHP-based pairwise comparisons for indirect costs (which include user costs) when comparing ABC to conventional construction methods, rather than through explicit software-based numerical estimation of road user costs.

Hadi et al. (2017) and Jia et al. (2018) provided a detailed review of road user costs, including their key components, the modelling of driver diversion behaviour, microscopic traffic behaviour in work zones, and available traffic analysis tools, with particular emphasis on modelling and simulation-based approaches [23,24]. These developments were incorporated into their road user impact analysis and estimation modules, designed to support both planning-level and operational-level assessments, depending on data availability and the required level of modelling fidelity. In Hadi et al. (2017), the road user impact analysis and associated estimation module were applied at the planning level in two case studies (Interstates I-4 and I-595 in Florida), and at the operational level in one case study (I-595), owing to limited traffic data availability for I-4 [24]. At the planning level, simplified inputs derived from traffic performance measures were used to estimate road user costs. At the operation level, more detailed inputs were obtained through dynamic traffic assignment and traffic simulation tools, enabling the modelling of driver diversion and lane-merging effects on safety and mobility—factors of particular importance in smart work zones.

El-Rayes et al. (2023) presented procedures for calculating road user costs and work zone crash costs, together with a graphical user interface which displays total road user costs as the sum of these two components [28]. These costs are estimated as a function of the selected bridge construction method and the planned duration of road closures.

Maintenance and Rehabilitation Cost Module

El-Rayes et al. (2023) presented an equation for estimating maintenance cost that was derived from annual bridge maintenance expenditures, the applicable discount rate, and the difference between the planning horizon and the combined duration of design and construction phases [28]. The authors also proposed a second equation for estimating rehabilitation costs as a function of the cost of each rehabilitation activity, the discount rate, the expected number of bridge rehabilitation interventions, and the planning horizon. Both equations were adapted from Hawk (2003a, 2003b) [38,39]. Based on IDOT (2022), the module assumes a structural service life of 75 years for new bridges and adopts a 20-year planning horizon for cost projections [42]. The MiABCD model from Attanayake and Aktan (2018)

and Mohammed et al. (2014) incorporates maintenance and rehabilitation cost estimates over the service life of bridge alternatives as input parameters within the AHP hybrid decision-making framework described previously in Section Analytic Hierarchy Process (AHP) Hybrid Approaches [17,18]. The model further accounts for disposal costs or residual value as part of its overall economic assessment.

Life-Cycle Cost Module

The quantitative Decision-Support Tool (DST) by El-Rayes et al. (2023) [28] also includes a Life-Cycle Cost module that aggregates cost estimates generated from the construction cost, road user cost, and maintenance/rehabilitation cost modules. These components are subsequently compared across alternative bridge construction methods to support decision-making. The overall structure of the quantitative DST is illustrated in Figure 11 [28].

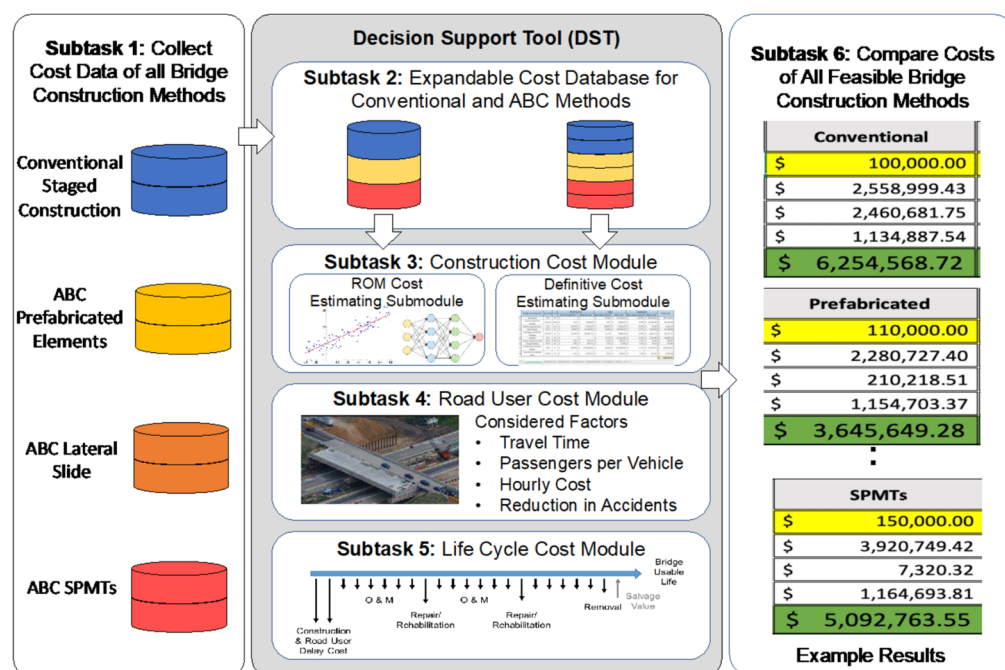


Figure 11. Quantitative DST, reprinted with permission from [28], 2023.

The study reported a performance evaluation of the DST based on two sets of case studies: five completed or ongoing projects and five future projects [28]. Figure 12 presents the LLCA results for one of the completed projects. The reported results further indicate that, for four completed projects, the ROM construction cost estimates achieved an accuracy of approximately 90% when compared with the corresponding actual construction costs.

Caltrans (2013) reported that the RealCost software, originally developed by the FHWA to conduct LCCA of road pavement alternatives, was subsequently adapted by Caltrans to better address California-specific requirements, resulting in RealCost version 2.5CA [43]. More recently, the application of RealCost has been extended to support LCCA of bridge alternatives (RealCost software version 3.0, Smith et al. 2023) [44]. Although RealCost has a well-established track record in pavement applications, its use for bridge evaluations remains relatively limited. A primary reason for this limitation lies in the fundamental differences in asset behaviour, deterioration mechanisms, and decision variables between pavements and bridges. Specifically, pavement deterioration generally follows more predictable patterns, whereas bridge deterioration is more complex due to interactions of multiple structural components and deterioration processes. RealCost assumes relatively predefined rehabilitation strategies, which align well with pavement management

where maintenance sequences are relatively standardized. In contrast, bridge interventions are much more project-specific and depend on structural condition, inspection findings, and engineering judgement. In addition, estimating bridge user costs is inherently more challenging because of the greater variability in traffic impacts. Finally, bridge project evaluation requires consideration of a broader set of decision criteria. However, in both pavement and bridge applications, LCCA and RealCost primarily rely on a present worth analysis (PWA) framework to enable the systematic comparison of alternative infrastructure investments over their service life. It is worth noting that some state DOTs have also published comprehensive bridge LCCA studies. For example, Leiva Maldonado and Bowman (2019) have conducted LCCA for short- and medium-span bridges on behalf of the Indiana DOT and Purdue University [45].

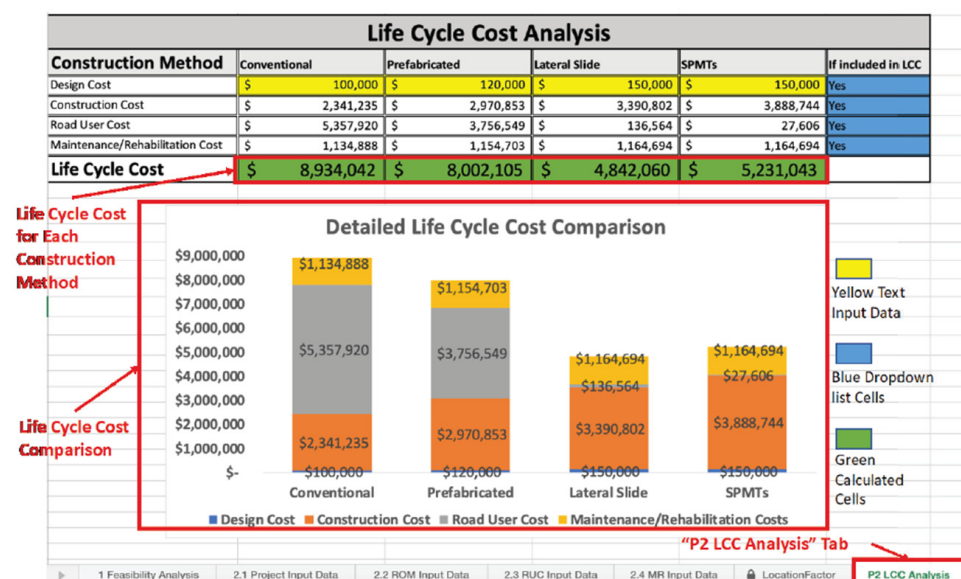


Figure 12. LLC comparison for all construction methods for a completed bridge (using PBES). ABC completed bridge project: IL 146 over Little Cache Creek in Vienna, Johnson, reprinted with permission from [28], 2023.

3.2. Durability and Long-Term Performance of PBES and Their Connection Systems

This section provides a brief review of U.S. experience regarding the durability and long-term performance of Prefabricated Bridge Elements and Systems (PBES) and their connection systems. Although prefabrication is generally expected to enhance the long-term durability and performance of ABC projects relative to conventional construction, these benefits ultimately depend on the quality of the fabrication, transportation, assembly, and erection processes of PBES and of their connection systems.

In this regard, the series of seven Lesson Learned Reports published by the Utah Department of Transportation (UDOT, 2023) provides valuable insights on the performance of ABC projects in Utah [46]. These reports are based on investigations involving cursory inspections of ABC-specific features and assessments of their overall performance across Utah's portfolio of relevant bridges, comprising 49 bridges as of 2023. As these bridges were constructed primarily during the 2000s and 2010s, they are generally 10 to 20 years old and therefore remain in the early to intermediate stage of service life. Readers are referred to the UDOT (2023) for a detailed discussion of the report findings, including ABC features and practices that performed well and those that performed less successfully [46].

Garber and Shahrokhinasab (2019) reported that full-depth precast concrete (FDPC) deck panels have been widely used in bridge construction since the 1970s because of their ability to accelerate construction while potentially improving long-term deck durability [47].

Despite the widespread perception that confined precast concrete performs as well as, or better than, conventional cast-in-place (CIP) concrete, comprehensive comparative evaluations have been limited. To address this gap, the authors assessed the in-service performance of FDPC deck panels compared to CIP bridge decks and identified both successful and problematic design and construction details. A survey of U.S. state DOTs was conducted to develop an FDPC deck panel database, which served as the basis for evaluating field performance and current engineering practices [47].

Readers are also referred to Jahromi et al. (2020)'s study, which develops a comprehensive framework for the service life design of closure joints in ABC [48]. The study recognizes that, although strength-based design approaches are well established, ensuring long-term durability remains a significant challenge. The proposed framework integrates project requirements, closure-joint selection, identification of deterioration mechanisms and mitigation strategies, service life prediction, and LCCA to identify optimal joint configurations. The framework was demonstrated through the design of an approximately 427 m-long bridge in Boston, Massachusetts, where several closure-joint configurations—including normal-strength concrete and ultra-high-performance concrete (UHPC) with various re-inforcement details—were evaluated. The results indicate that UHPC overlays combined with bottom sealers yielded the lowest Life-Cycle Costs, while the use of UHPC in closure joints extended repair intervals and enhanced long-term durability. Overall, the study demonstrated that integrating service life design with LCCA can improve both the durability and economic performance of ABC bridge connections [48].

4. Critical Review and Perspectives

Following a chronological and in-depth examination of the most relevant literature, the resulting synthesis revealed a dense and complex body of work that is rich in detail yet remains fragmented across multiple evaluation and decision-making approaches, cost-estimation methods, and unresolved methodological and conceptual challenges.

4.1. Evaluation and Decision-Making Tools

Overall, the review of the key methodologies and concepts underlying screening-level evaluation and decision-making tools for selecting between ABC and conventional construction methods yields the following observations.

4.1.1. Limitation of Qualitative and Quantitative Approaches

Both qualitative and quantitative approaches, largely grounded in expert judgement and practical experience, have been employed by U.S. state DOTs to support the evaluation and selection of ABC alternatives. While these approaches are effective for comparing analogous or relatively homogeneous alternatives within a defined context, their ability to adequately address the variability and complexity inherent in ABC technologies as well as their associated characteristics remains limited.

In this context, qualitative approaches may overlook key evaluation criteria and generally lack quantitative rigour. Conversely, quantitative approaches may omit relevant criteria or introduce bias through subjective weighting or scoring procedures. Although integrating qualitative flowcharts that incorporate broader considerations can complement quantitative evaluations by enabling early-stage decisions to be revisited and refined, more robust and integrated screening-level approaches are needed.

4.1.2. Traditional AHP-Based Approaches and Consistency Challenges

Traditional AHP approaches should continue to be applied with caution, as their validity depends on maintaining acceptable levels of consistency in pairwise comparisons. Previous studies have identified consistency-related challenges, particularly when com-

parisons involve unrelated criteria or a large number of criteria and alternatives. These challenges are further exacerbated by (i) the limited availability of quantitative data for the key attributes of the alternatives, which can lead to insufficiently informed pairwise comparison judgments; and (ii) difficulties in maintaining acceptable consistency ratios when local priorities are derived using approximate calculation methods. As the dimensionality and complexity of the decision problem increase, the consistency of traditional AHP methods tends to decline. Although AHP hybrid models represent a significant advancement by mitigating several of these limitations, further improvements are required to support the coherent integration of all relevant factors influencing the evaluation and selection of ABC methods.

4.1.3. Need for Improvement in Evaluation and Decision-Making

Current screening-level models are not explicitly designed to support iterative evaluation and decision-making processes. Although repeated assessments are possible, they remain operationally cumbersome. Furthermore, existing qualitative, quantitative, and hybrid approaches exhibit limitations in supporting integrated multicriteria evaluations. The prevailing reliance on one-dimensional criteria implemented through spreadsheet-based calculation tools, combined with predominantly two-dimensional outputs (e.g., tables and figures), is insufficient to adequately capture the variability and complexity of the key attributes involved in comprehensive, integrated, coherent, and iterative evaluations of ABC projects. These attributes include project objectives and requirements; site conditions and constraints; selected ABC technologies and techniques, together with their associated designs, construction methods, and implementation strategies; traffic management strategies for minimizing disruption; and maintenance and rehabilitation schemes.

Conceptualizing these attributes as interconnected functions and systems provides a more robust analytical foundation and underscores the need for advanced, agile, and automated tools that integrate analytical, visual, diagnostic, and predictive capabilities. Such developments could strengthen the evaluation and selection of optimal ABC solutions while enhancing their overall sustainability. Ongoing advances and future developments in artificial intelligence are also expected to further expand these capabilities.

4.2. Cost Estimation Tools

For the present review, decoupling evaluation and decision-making tools from cost-estimation tools has proven valuable for clarifying the evolving limitations of cost-estimation practices in the context of selecting ABC methods at the screening level. These cost-estimation approaches differ substantially from the detailed estimates developed during the subsequent engineering design and project development phases. Given the importance of Life-Cycle Cost Analysis (LCCA), its foundational principles provide an appropriate framework for this discussion.

4.2.1. Initial Emphasis on Construction and Road User Cost Estimation

Early cost-estimation approaches primarily focused on short-term construction costs and road user costs associated with the construction phase. However, aggregating these components into a single “total cost” metric neglected long-term Maintenance and Rehabilitation (M&R) costs incurred over the bridge service life. This practice is inconsistent with the recognized importance of Life-Cycle Cost (LCC) considerations and implicitly assumes that long-term M&R costs are equivalent for ABC and conventional construction methods. Further research is required to substantiate or challenge this assumption.

The M&R component of ABC projects depends on the durability and the long-term performance of their PBES and of their connection systems. As discussed in Section 3.2, U.S.

experience has revealed both successful and problematic design and construction details and has highlighted remaining challenges that require further investigation [46–48].

Given that sustainability is a principal objective of modern infrastructure management, LCC estimation should comprehensively incorporate long-term M&R expenditures over the entire service-life of bridge infrastructure. Achieving this objective requires careful examination of the timing and sequence of expenditures in relation to the corresponding profile of M&R activities. It also necessitates the development of a structured set of candidate M&R strategies derived from combinations of bridge distress conditions and relevant contextual factors. Within this framework, integrating sustainability into LCC analysis extends well beyond the quantification of annual expenditures; rather, it requires a holistic evaluation of the long-term economic, operational, and performance-related consequences associated with alternative bridge management strategies [39,40].

4.2.2. Accounting for the Long-Term Performance and Durability of Sustainable ABC Projects: M&R and LCC Implications

The accumulated knowledge derived from long-term M&R practices associated with ABC projects warrants systematic and comprehensive investigation to generate practical, project-specific insights. Particular emphasis should be placed on evaluating the long-term performance and durability of PBES, including their connection systems, as well as on assessing ABC-specific M&R techniques and their associated implications for LCC estimation. Advancing research in these areas is essential to enhancing the long-term performance, durability, resilience, and overall sustainability of ABC projects throughout their service life. Readers are referred to the previously discussed studies by UDOT (2023) [46], Garber and Shahrokhinasab (2019) [47], and Jahromi et al. (2020) [48] for further details.

4.2.3. Challenges from Integrating Cost into Relative-Importance-Based MCDM Tools

With the introduction of Multi-Criteria Decision-Making (MCDM) techniques, particularly the AHP, and the recognition that cost-focused evaluations alone are insufficient, cost-estimation methodologies continued to evolve alongside the expansion of the evaluation criteria incorporated into ABC decision-making frameworks. However, integrating cost into relative importance-based assessments has introduced additional challenges, particularly regarding its appropriate representation and weighting. In practice, cost has been treated inconsistently: either as a primary criterion or excluded from the evaluation framework while being implicitly represented through financial constraints. This inconsistency raises fundamental questions about the role of cost within MCDM-based evaluation frameworks and contrasts with the explicit recognition of the importance of LCCA in selecting appropriate ABC strategies.

4.2.4. Cost Estimation as an Outcome of Iterative Evaluation and Decision-Making

Conceptually, cost should be recognized as a consequence—or an outcome—of the iterative evaluations and decisions based on the key attributes of the ABC project under consideration. Treating cost as an input parameter introduces potential issues of redundancy and circularity, as most evaluation criteria have direct or indirect cost implications. Conversely, treating cost as an outcome refined through an iterative evaluation process is conceptually more coherent. In this context, cost warrants treatment that is distinct from that of the other project attributes throughout the evaluation and decision-making process.

4.2.5. Updated Parametric Cost Estimation

Future research should prioritize the continuous development, maintenance, and updating of comprehensive databases of completed ABC projects. In addition, variability in cost data across U.S. states should also be systematically examined, particularly with

respect to reporting requirements, data standardization, and broader data-management and analytical methodologies. Building on predictive modelling techniques, including multiple linear regression and machine learning methods, future cost-estimation frameworks have significant potential to improve Rough Order-of-Magnitude (ROM) construction cost estimates. Such advancements would strengthen the robustness of cost-estimation when cost is treated as an outcome of screening-level, iterative evaluation and decision-making processes. In parallel, the further development of detailed cost-estimation sub-modules would contribute to improving the accuracy and reliability of ABC cost assessments.

5. Future Perspectives

The literature review allowed the identification of the following areas that require more investigation and clarification:

- A priority area for future development is the improved integration and treatment of cost estimation within the evaluation process. Particular emphasis should be placed on Life-Cycle Cost Analysis (LCCA), especially with respect to long-term Maintenance and Rehabilitation (M&R) costs and associated intervention strategies. Future research should prioritize the continued development, maintenance, and updating of databases containing completed ABC projects in the United States while addressing interstate challenges related to reporting requirements, data standardization, and broader data-management and analytical methodologies.
- While AHP-based approaches have been applied to ABC projects in the U.S., the application of alternative MCDM techniques remains largely unexplored. Consequently, future research should investigate the potential of alternative MCDM methodologies for ABC decision-support applications. Given the remaining methodological challenges and knowledge gaps, this represents a priority area for future research.
- Conceptualizing the key attributes characterizing an ABC project as interconnected functions and systems provides a more robust analytical foundation and underscores the need for advanced, agile, and automated tools integrating analytical, visual, diagnostic, and predictive capabilities. Such advancements could strengthen the identification and selection of optimal ABC solutions from the earliest stages of alternative development and evaluation and would also provide capabilities that extend well beyond those of current tools.

6. Conclusions

The present review provides a comprehensive perspective on the evolution of the key methodologies and concepts underpinning screening-level evaluation and decision-making tools for the selection of ABC projects, in the United States since the mid-2000s, as well as the cost-estimation tools used to support these processes. The review also assesses the principal limitations of current tools and identifies priority areas for methodological improvement and future research.

The review indicates that existing qualitative and quantitative evaluation and decision-making approaches remain practically useful for the selection of ABC methods but exhibit limited methodological robustness when applied to support decisions across a broad range of influencing factors. Hybrid approaches, based on the Analytic Hierarchy Process (AHP), represent an important step toward more structured Multi-Criteria Decision-Making (MCDM). However, the consistency of traditional AHP methods tends to decline as the dimensionality and complexity of the decision problem increase. AHP hybrid models represent a significant advancement beyond traditional AHP approaches by mitigating several of their limitations. Nevertheless, further improvements remain necessary to enable

the coherent integration of all relevant factors influencing the evaluation and selection of ABC methods.

Within evaluation and decision-making frameworks, early cost-estimation approaches primarily focused on short-term construction costs and on road user costs associated with the construction phase. With sustainability becoming a principal objective of modern infrastructure management, Life-Cycle Cost (LCC) estimation should comprehensively incorporate long-term Maintenance and Rehabilitation (M&R) expenditures throughout the entire service life of bridge infrastructure. In this context, LCC analysis requires a holistic evaluation of the long-term economic, operational, and performance-related consequences associated with alternative bridge management strategies. Particular emphasis should be placed on evaluating the long-term performance and durability of Prefabricated Bridge Elements and Systems (PBES), including their connection systems, as well as ABC-specific M&R techniques and their implications for LCC estimation. Furthermore, while LCC estimation remains a central component in the evaluation and selection of ABC projects, a reconceptualization of cost as an outcome derived from iterative evaluations could enhance the analytical coherence of the framework.

The current context presents significant opportunities to further advance screening-level MCDM tools for the evaluation and selection of ABC alternatives. Such developments should enable comprehensive, integrated, coherent, and iterative frameworks for assessing the key attributes characterizing an ABC project under consideration. Conceptualizing these attributes as interconnected functions and systems provides a more robust analytical foundation and highlights the need for advanced, agile, and automated tools integrating analytical, visual, diagnostic, and predictive capabilities. Collectively, these improvements could strengthen the identification and selection of preferred ABC alternatives during the earliest stages of project development while enhancing their long-term sustainability.

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