A decision tool for accelerated bridge construction

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- Although the potential advantages of accelerated bridge construction are recognized, it is difficult for transportation specialists to quantify the risks and benefits for specific bridge replacement or rehabilitation projects.

- This paper presents a tool set, based on the analytic hierarchy process, to help transportation specialists determine whether accelerated bridge construction is more effective than traditional construction for a given bridge replacement or rehabilitation project.

- The decision model hierarchy has been incorporated into decision-making software. The software was tested through evaluating a set of actual construction projects.

Accelerated bridge construction is recognized as an important method to construct and rehabilitate highway structures. Accelerated bridge construction uses both new technology and innovative project management techniques to mitigate the effects of bridge construction on the public and to reduce construction costs. In the early stages of a construction project, engineers need to assess whether elements of accelerated bridge construction are achievable and effective for a specific bridge location. The use of decision-making tools in the early stages of planning is advocated as a mechanism for helping decision makers assess alternatives with more confidence and for preventing investment in alternatives that are more costly.

In December 2009, the Oregon Department of Transportation initiated a pooled fund study to develop a tool that could assist decision makers in identifying whether accelerated bridge construction should be applied to a specific project. In addition to the Oregon Department of Transportation, departments of transportation from seven other states and the Federal Highway Administration (FHWA) were involved in this study. A decision-making tool based on the analytic hierarchy process was developed. This tool was targeted at transportation specialists and decision makers and was developed to determine whether accelerated bridge construction techniques are more effective than traditional construction for a given bridge replacement or rehabilitation project. The tool is user friendly, flexible to accommodate a range of construction situations, and customizable to maintain future relevance. Details from two applications of the tool are presented and discussed. The tool was developed to support the decision-making process by creating a hierarchy of criteria relevant to the decision-making process. The decision hierarchy of criteria was developed, in part, based on a review of relevant literature. The next section summarizes some of this literature.

Literature review

Accelerated bridge construction

A large number of successful accelerated bridge construction projects are reported in the literature.[1–3] Accelerated bridge construction approaches include the application of technical innovations and management techniques. Technical innovations include rapid embankment construction, specialized structural placement methods, and prefabricated bridge elements and systems, such as superstructure systems (composite units, truss spans), substructure systems (abutments, caps and columns, piers), and totally prefabricated bridges.[4] Examples of management practices used as part of accelerated bridge construction include staged construction, cost-plus-time contracting, incentive/disincentive contracting, and lane rentals in which contractors must include the cost to the public as well as construction costs.

There is a propensity from both community and industries involved in construction projects and federal organizations toward standardization of accelerated bridge construction methods. Federal organizations have also conducted several projects to develop, implement, and promote accelerated bridge construction. Because of the success of accelerated bridge construction projects to date, FHWA has increased its support and provided resources to further advance the development of these systems into more conventional practices nationwide.[4]

The literature includes recommendations from the American Association of State Highway and Transportation Officials (AASHTO) and FHWA for updating highway emergency response plans for extreme events.[5] Community members want to deliver bridge construction projects quickly to reduce congestion and improve safety.[4] To address these concerns, guidelines have been developed for the use of accelerated bridge construction approaches in designing bridges for emergency events.[6]

The focus of recent national initiatives by AASHTO and FHWA has included innovative prefabricated bridge elements and systems, such as bent caps, abutments, full-depth deck panels, and totally prefabricated superstructures and substructures.[7] Federal organizations have supported several initiatives to foster the development, implementation, and promotion of accelerated bridge construction by departments of transportation. Addressing the challenge of reducing congestion through accelerated reconstruction of obsolete and deficient bridges, states and localities have undertaken successful accelerated bridge construction projects. These projects provide valuable insight for decision makers who are considering accelerated bridge construction for the first time or who have had limited exposure to the variety of accelerated bridge construction tools and techniques.

The need for accelerated bridge construction decision-making tools

The U.S. Department of Transportation's strategic plan for 2006–2011 identified the use of decision-making tools as a key strategy to reduce congestion and deliver longer-lasting, high-performance infrastructure. The use of decision-making tools in the early stages of planning helps decision makers assess alternatives with greater confidence and prevent investment in more costly alternatives. In addition, data-driven decision-making tools are consistent with cost-saving recommendations from the U.S. Government Accountability Office.

Three different approaches for accelerated bridge construction project decisions were identified in the literature. The first two had already been applied to bridge replacement, whereas the third was not. The first decision-making approach developed by FHWA is based on a framework for prefabricated bridge elements and systems decision making.[8] In this framework, a flowchart and matrix incorporating a set of decision criteria are used to help decision makers choose between conventional and accelerated bridge construction alternatives[9] (**Fig. 1** and **Table 1**). The flowchart assists the users in making a high-level decision on whether a prefabricated bridge might be an economical and effective choice for the specific bridge under consideration. The matrix provides users with additional details and may provide additional assistance in making a high-level decision about the type of construction and approach to apply to a particular project.

The second approach identified in the literature for decision making is a method for evaluating bridge construction plans. This technique helps designers balance the effects of bridge construction plans on project performance, traffic flow, and business activities. The model incorporates five major factors: safety, accessibility, carrying capacity, schedule performance, and budget performance.[10] These factors were extracted through observation of actual construction projects and further validated by industry experts and application to actual construction cases. Model factors were weighted by experts and were then used to develop an objective matrix.

Factors are scored on a scale of 1 to 10, and the final score for each plan is calculated in Eq. (1).

$$W_sS_i + W_aA_i + W_cC_i + W_tT_i + W_bB_i + W_qQ_i \qquad (1)$$

where

W_s = weight of safety

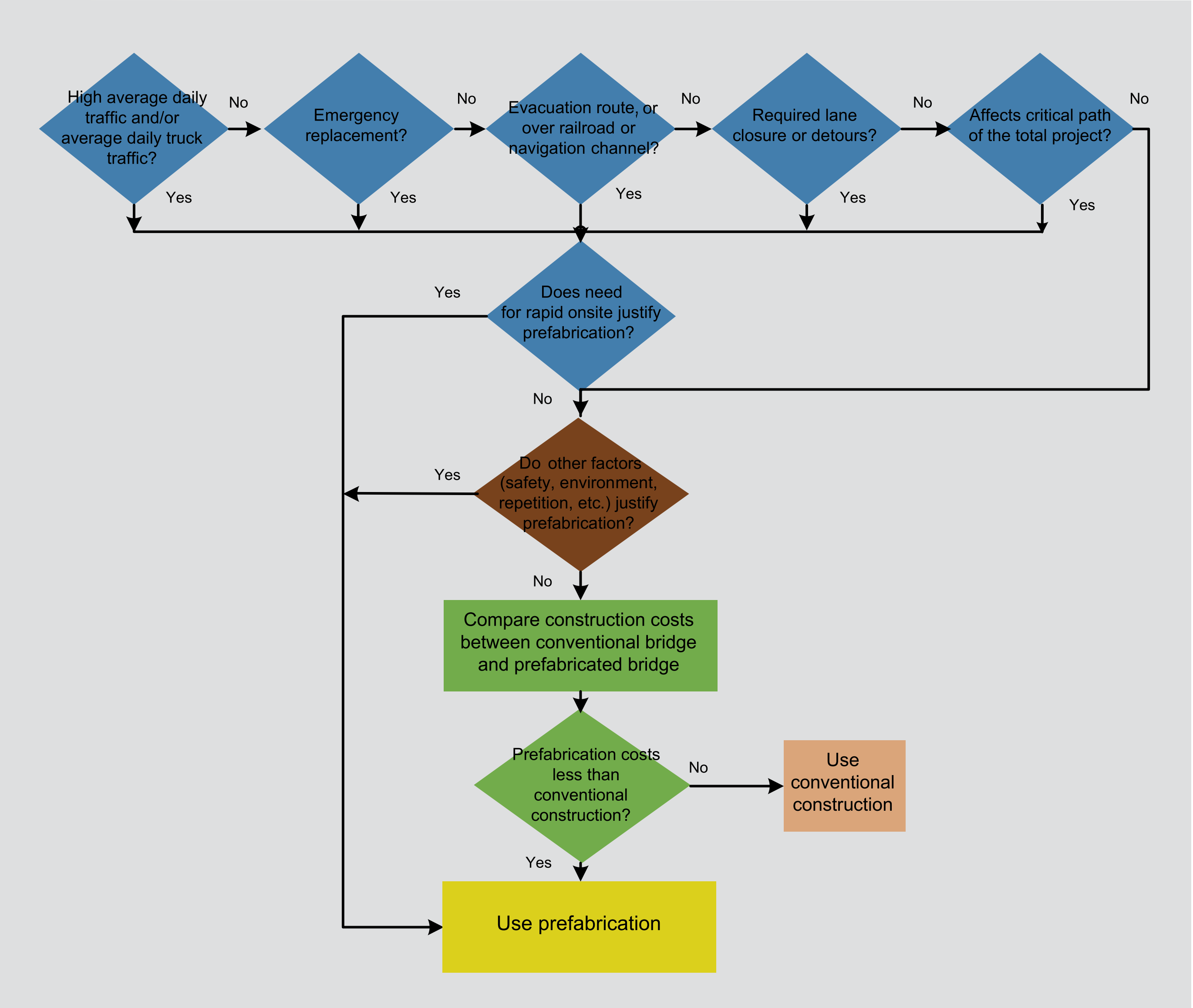

Figure 1. Flowchart for high-level decision on whether a prefabricated bridge should be used in a certain project. Source: FHWA 2006.

S_i = safety score

W_a = weight of accessibility

A_i = accessibility score

W_c = weight of carrying capacity

C_i = carrying capacity score

W_t = weight of schedule performance

T_i = schedule performance score

W_b = weight of budget performance

B_i = budget performance score

W_q = weight of project specific factors

Q_i = project specific factors

The FHWA framework for prefabricated bridge elements and systems and the model for evaluating bridge construction plans both have two major drawbacks. First, every project is unique and has its own specific requirements. Specific numerical values for the importance of various factors cannot be universally applied. Second, both methods lack a systematic and justifiable procedure for criteria weighting. A third approach, analytic hierarchy process, taken from the literature,[11,12] addresses both of these deficiencies.

The analytic hierarchy process uses pairwise comparisons to evaluate the importance of defined factors relative to other factors using either a numerical or verbal scale. In the simplest form, the analytic hierarchy process consists of three components: the overall goal of the decision, a hierarchy of criteria by which the alternatives will be evaluated, and the available alternatives (**Fig. 2**). Factors

Table 1. Matrix questions for high-level decision on whether a prefabricated bridge should be used in a certain project

Question	Yes	Maybe	No
Does the bridge have high average daily traffic (ADT) or average daily truck traffic (ADTT), or is it over an existing high-traffic-volume highway?			
Is this project an emergency bridge replacement?			
Is the bridge on an emergency evacuation route or over a railroad or navigable waterway?			
Will the bridge construction impact traffic in terms of requiring lane closures or detours?			
Will the bridge construction impact the critical path of the total project?			
Can the bridge be closed during off-peak traffic periods, e.g., nights and weekends?			
Is rapid recovery from natural/manmade hazards or rapid completion of future planned repair/replacement needed for this bridge?			
Is the bridge location subject to construction time restrictions due to adverse economic impact?			
Does the local weather limit the time of year when cast-in-place construction is practical?			
Do worker safety concerns at the site limit conventional methods, e.g., adjacent power lines or over water?			
Is the site in an environmentally sensitive area requiring minimum disruption (e.g., wetlands, air quality, and noise)?			
Are there natural or endangered species at the bridge site that necessitate short construction time windows or suspension of work for a significant time period, e.g., fish passage or peregrine falcon nesting?			
If the bridge is on or eligible for the National Register of Historic Places, is prefabrication feasible for replacement/rehabilitation per the Memorandum of Agreement?			
Can this bridge be designed with multiple similar spans?			
Does the location of the bridge site create problems for delivery of ready-mix concrete?			
Will the traffic control plan change significantly through the course of the project due to development, local expansion, or other projects in the area?			
Are delay-related user costs a concern to the agency?			
Can innovative contracting strategies to achieve accelerated construction be included in the contract documents?			
Can the owner agency provide the necessary staffing to effectively administer the project?			
Can the bridge be grouped with other bridges for economy of scale?			
Will the design be used on a broader scale in a geographic area?			
Totals:			

Source: FHWA 2006.

affecting the decision (that is, criteria and subcriteria) are decomposed from general criteria in the upper levels of the hierarchy to more specific and particular criteria in the lower levels of the hierarchy. Hierarchies can include both tangible and intangible decision factors and criteria. As a result, the analytic hierarchy process has been applied in a variety of domains and has the potential to be a useful and reliable technique for accelerated bridge construction decision making.

Decision-making approaches

Decision making can be challenging. The increasing complexity of the decision-making process resulting from the complexity of problems being solved in the world today has motivated the search for approaches that are more flexible and more practical than classic decision-making approaches. The appropriateness of different multicriteria approaches for a given problem and the establishment of a unified framework in multicriteria decision making that allows for a better understanding of decision-making tech-

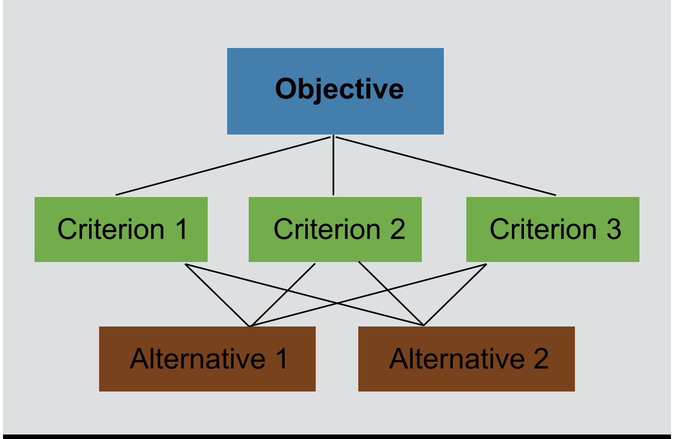

Figure 2. Schematic representation of decision hierarchy.

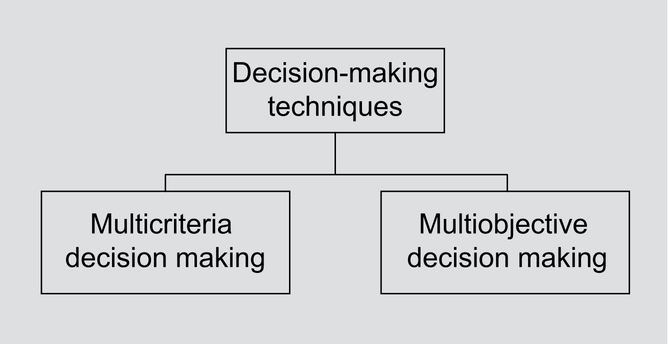

Figure 3. The two categories of decision-making techniques. Source: Triantaphyllou 2000.

niques are two topics that challenge both researchers and practitioners.[13] In general, decision-making techniques can be divided into two main categories (**Fig. 3**).

The first category is multiobjective decision making. This category of decision-making techniques focuses on decision problems in which the decision space is continuous. A typical example is a mathematical programming problem with multiple objective functions.

The second category is multicriteria (multiattribute) decision making. These techniques concentrate on problems with discrete decision spaces. In these problems, the set of decision alternatives has been predetermined. Multicriteria decision-making methods are diverse. However, many of them share certain elements, such as the notion of alternatives and attributes (also called goals and decision criteria).

For this research study, the focus was on multicriteria techniques that would be applicable to decision-making problems with both discrete and continuous decision factors. **Table 2** presents a summary of multicriteria decision-making approaches that are commonly used in practice. Each of these methods uses numeric techniques to help decision makers choose from among a discrete set of alternatives.[14]

Analytic hierarchy process

Analytic hierarchy process is a multicriteria decision-making approach that was introduced by Saaty.[11,12] Due to its wide applicability and ease of use, this method has been studied extensively in the literature and has been used in a wide variety of applications in the past 25 years.[15] Despite the longtime use of this process in other domains, particularly manufacturing, the analytic hierarchy process has not been widely used in civil and structural engineering applications. As a result, many transportation person-

Table 2. Summary of multicriteria decision-making approaches

Method	Description	Data types handling	Highlights
Weighted sum model	The most commonly used approach in single dimension problems. This method works based on the additive utility assumption. The best alternative is the one that generates the maximum score.	Quantitative criteria only	In this method, all the units must be the same (for example, dollars, feet, or seconds).
Analytical hierarchy process	This method decomposes a complex multicriteria decision making problem into a system of hierarchies. The method evaluates the relative preference for the alternatives in terms of each criterion.	Both quantitative and qualitative criteria	This method shows its power when the decision maker does not have quantitative data for all criteria.
ELECTRE	This method deals with “outranking relations” by using pairwise comparisons among alternatives under each criterion separately. The focus is on the alternatives instead of the criteria.	Both quantitative and qualitative criteria (for qualitative variables, need a defined scale)	Need thorough knowledge of the alternatives. Most appropriate for analyzing problems with a large set of alternatives.
TOPSIS	In this method, an ideal alternative and a negative-ideal alternative are defined. The chosen alternative should be as close to the ideal solution as possible and as far from the negative-ideal solution as possible. Proximity to each solution is measured by square root of the sum of the squared distances along each access in the attribute space.	Both quantitative and qualitative criteria (for qualitative variables, need to define a scale)	Concentrates on the alternatives. Difficult (or even impossible) to define the ideal alternative for some cases. Easier to implement for quantitative criteria.

Table 3. The fundamental scale of the analytic hierarchy process pairwise comparison

The fundamental scale for pairwise comparisons		
Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favor one element over another.
5	Strong importance	Experience and judgment strongly favor one element over another.
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice.
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation.

Note: Intensities of 2, 4, 6, and 8 can be used to express intermediate values. Intensities 1.1, 1.2, 1.3, etc., can be used for elements that are close in importance. Source: Saaty, 1990.

nel may be unfamiliar with it. This section will discuss the steps involved in the analytic hierarchy process and how it can help decision makers. To help frame this discussion, a simple example on the analytic hierarchy process's application is presented.

In a decision to buy a car, a decision maker might consider factors (decision criteria) such as reliability, fuel consumption, and price. The decision maker wishes to select between two different cars, considering these three decision criteria. In the first step, pairwise comparisons among decision criteria (reliability, fuel consumption, and price) must be performed to obtain the relative importance (priority) of these factors. The next step is comparing the two alternatives (cars) that the decision maker has chosen, with regard to each criterion (for example, the degree to which one alternative satisfies the decision maker's requirements with regard to fuel consumption). The analytic hierarchy process uses this input to determine which alternative is preferable to the decision maker.

Saaty proposed the analytic hierarchy process as a multicriteria decision-making technique that combines a hierarchy of decision criteria (both tangible and intangible factors) to obtain the priorities associated with the alternatives.[11] The approach consists of three main operations: construction of a decision hierarchy, priority analysis, and consistency check. In the first step, the decision makers have to break down a complex decision problem into a series of decision factors that can be arranged into multiple hierarchical levels. Next, the decision makers need to perform a series of pairwise comparisons among all factors within each level. These pairwise comparisons are performed with respect to the overall goal of the decision problem and are based on the decision makers' experience and knowledge.

Pairwise comparisons in the analytic hierarchy process are performed using pairs of homogenous elements. When users are unable to apply quantitative measures to a particular criterion, the analytic hierarchy process fundamental scale may be used instead to assess the relative preference level for two criteria being compared. **Table 3** summarizes the analytic hierarchy process fundamental scale. This analytic hierarchy process scale is a one-to-one mapping between a set of discrete linguistic choices available to the decision maker and a discrete set of numbers that represent the importance or weight of the choices.[12] This scale has been validated for effectiveness, not only in many applications by a number of people, but also theoretically.[16]

In 1846, Weber, a well-known 19th century psychologist,[14] stated his law regarding a stimulus of measurable magnitude. In Weber's law, the difference threshold or "just noticeable difference" is the minimum amount by which stimulus intensity must be changed to produce a noticeable variation in sensory experience. According to his psychological theory, a change in sensation is noticed if the stimulus is increased by a constant percentage of the stimulus itself. That is, people are not able to make choices from an infinite set. For example, people cannot distinguish between two close values of importance, for example, 3.00 and 3.02.[17] This is the main reasoning used by Saaty to establish 9 as the upper limit of his scale and 1 as the lower limit, with a unit difference between successive scale values.[16] The basis for Saaty to select nine gradations is that human factors studies show that an individual can hold 7 ± 2 objects in the short-term memory at the same time (in this case, the nine definitions for the nine intensity levels shown in Table 3). Thus, Saaty's fundamental scale of comparison ensures that the capacity of the short-term memory is not exceeded.

Because the comparisons are performed by personal or subjective judgments, some degree of inconsistency may occur. A consistency check is performed to measure the degree of consistency among the pairwise comparisons through the computation of a consistency ratio.

Vaidya and Kumar[18] have reported more than 150 articles that summarize the application of analytic hierarchy process in a range of domains. The literature has proposed the application of analytic hierarchy process-based techniques in the finance sector,[19] education, engineering, government, industry and manufacturing, political and social fields, and sports.[18] Its wide application is due in part to its simplicity and ease of use, as well as its ability to incorporate both qualitative and quantitative decision factors.[15]

Research methods

Decision criteria for choosing a bridge construction technique

In a series of brainstorming sessions, representatives from the eight departments of transportation involved in the pooled fund study discussed criteria currently considered by their states to decide whether conventional or accelerated bridge construction techniques would be used. The focus of these brainstorming sessions was to identify a comprehensive list of factors affecting decisions about the type of construction techniques used in bridge replacement/rehabilitation projects.

From the brainstorming sessions as well as criteria identified in the review of the literature, it was determined that bridge construction decisions are based on both quantitative and qualitative criteria. In addition, it was determined that some of the criteria that enter into the decision-making process are difficult to fully quantify at the time when decisions must be made. Having these diverse types of criteria makes finding a suitable decision-making technique challenging because many decision-making techniques are not able to integrate both qualitative and quantitative criteria simultaneously. Based on the literature review, the research team recommended the analytic hierarchy process as a suitable approach for this project.

After identifying the decision criteria, the team grouped them into mutually exclusive categories and developed a hierarchy of criteria that could be analyzed using the analytic hierarchy process. Arranging all of the criteria in a hierarchy provides an overall view of the complex relationships and helps the decision maker assess whether the elements in each level are of the same magnitude so that they can be compared accurately.[20]

The criteria included in the developed hierarchy were homogenous at each level and captured the same level of specificity. If one level 1 criterion is safety, for example, then another level 1 criterion might be cost. An inappropriate level 1 criterion would be construction cost. Construction cost is more specific than cost and would be inconsistent with the level 1 criterion of safety. However, construction cost would be an appropriate level 2 criterion under the cost criterion within the hierarchy. Similarly, an appropriate level 2 criterion under the safety criterion would be worker safety. Furthermore, a decision maker can insert or eliminate levels and elements as necessary to clarify the pairwise comparison or to sharpen the focus on one or more parts of the system. Sometimes the less important elements can be dropped from further consideration if the judgments and prioritization show a relatively minor effect on the overall objective.

Figure 4 shows the final criteria hierarchy, developed after several meetings among representatives of the departments of transportation. The hierarchy consists of two levels. The highest level consists of five criteria: direct costs, indirect costs, schedule constraints, site constraints, and customer service. Each of these criteria is further specified by several subcriteria.

Detailed definitions for all criteria and subcriteria were created based on the experiences and expertise of the study participants. Job titles of participants included senior bridge engineer, research coordinator, bridge financial analyst, senior project manager, bridge management engineer, and bridge design engineer. A definition list helps users understand the decision hierarchy and provides consistency among users who are completing the pairwise comparisons. **Table 4** includes the definitions for all subcriteria developed for this study.

Using the analytic hierarchy process for a bridge construction decision-making problem

The first step in conducting the analysis is to perform a series of pairwise comparisons among the decision criteria. In this study, a survey form was designed to collect the pairwise comparison data. The survey form contained all of the pairwise comparisons among the high-level criteria (that is, direct costs, indirect costs, schedule constraints, site constraints, and customer service), the subcriteria in each high-level criterion, and the bridge construction alternatives. The survey was sent to the experts in the departments of transportation involved in this study. The experts completed the pairwise comparisons for a particular bridge replacement or rehabilitation project in their state and returned the survey to the research team for further analysis. Pairwise comparisons were performed from either actual measurements or using a qualitative scale to measure the relative strength of preferences.

After collecting the required data, the analytic hierarchy process was applied to extract priorities for both decision criteria and the construction alternatives. The pairwise comparison data were then entered into a matrix (Fig. 4) to calculate the priorities for all the criteria and alternatives on each level of the hierarchy. To clarify the calculation process, an example matrix from the hierarchy of criteria is presented.

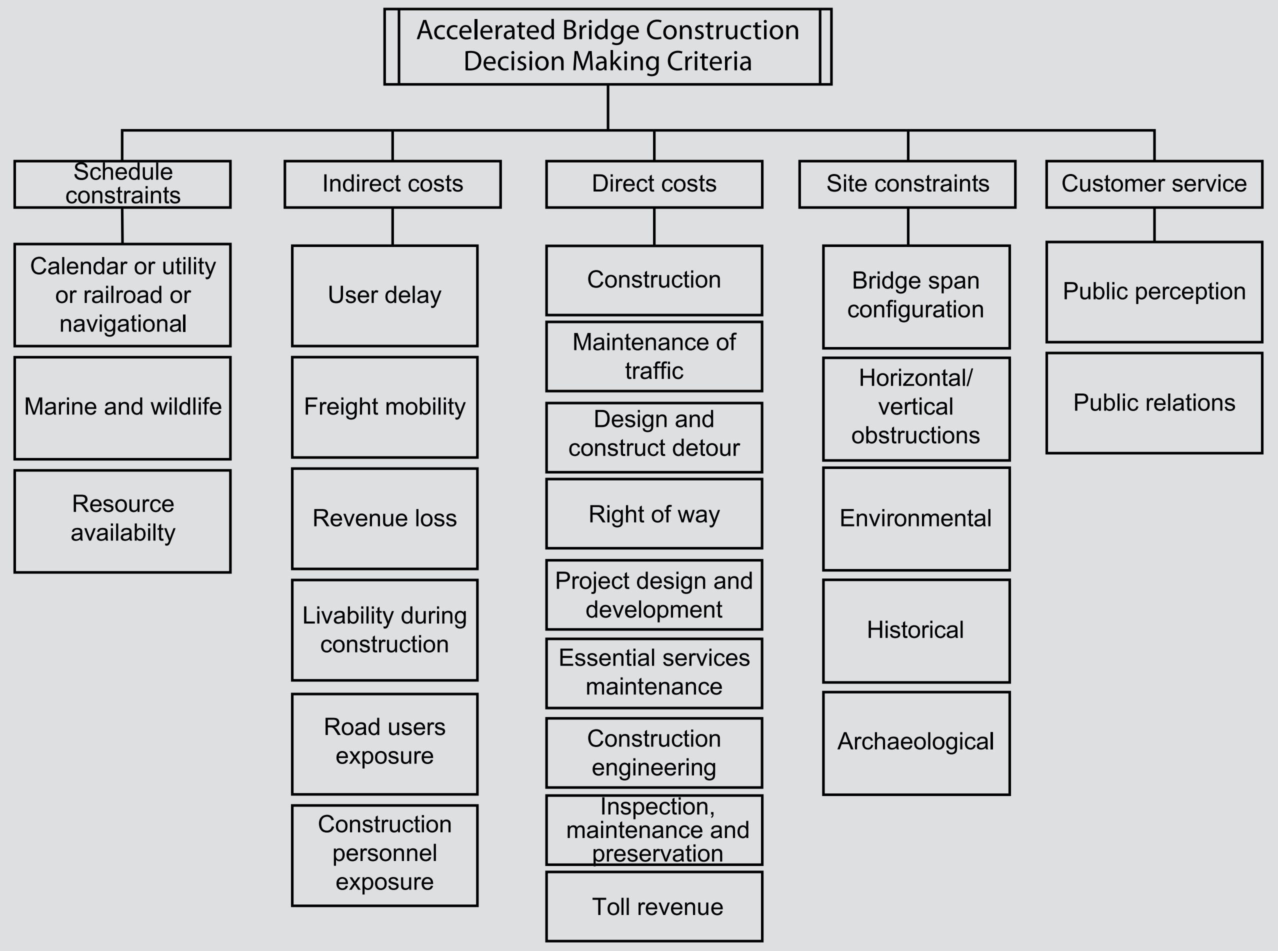

Figure 4. Hierarchy of accelerated bridge construction decision-making criteria.

Calculations

Suppose that the subcriteria in the schedule constraints category are to be compared and prioritized. In this case there are three subcriteria: calendar or utility or railroad or navigational, marine and wildlife, and resource availability. Therefore, there will be three pairwise comparisons and hence a 3 × 3 matrix. **Figure 5** shows the completed pairwise comparisons for this category. The marked values in these pairwise comparisons are entered in a 3 × 3 matrix in the following manner: the diagonal elements of the comparison matrix are always 1, and it is necessary only to fill the upper triangular matrix because the lower triangular matrix will be the reciprocal of the upper one. To fill the lower triangular matrix, the reciprocal values of the upper diagonal are calculated. If a_{ij} is the element of row i and column j of the matrix, then the lower diagonal is filled in as a_{ij} equals $1/a_{ij}$. **Table 5** presents the comparison matrix for the pairwise comparisons in Fig. 5.

The priorities for each subcriterion can be obtained using the normalized Eigen vector of the comparison matrix. The theoretical approach to obtain Eigen values is complex. Therefore, an approximation of Eigen values was used in this study. In the approximation, each column was normalized. To normalize the comparison matrix, the summation of each column in the comparison matrix was calculated and then each element of the matrix was divided by the summation of the column. Table 5 presents the normalized matrix for the comparisons in Fig. 5.

The normalized principal Eigen values, which represent the priorities for each subcriterion, can be obtained by averaging each row. These values are the relative weights of the subcriteria based on the pairwise comparisons completed by the decision maker. Table 5 summarizes the priorities for the three subcriteria shown in Fig. 5.

To complete the analysis, pairwise comparisons are completed for all three levels of the hierarchy. In the first level, the high-level criteria in the developed hierarchy (that is, direct costs, indirect costs, site constraints, schedule constraints, and customer service) are compared with each other. In the next level, the user compares the subcriteria within each high-level criterion separately (again in a pairwise fashion). In the final step, the user must determine the level of preference for two alternatives relative to each other for each of the subcriteria. As mentioned before, the rating

Table 4. Definitions for all criteria included in the accelerated bridge construction decision-making hierarchy

High-level criteria	Subcriteria	Definition
Direct costs	Construction	This factor captures the estimated costs associated with the construction of the permanent structure(s) and roadway. This factor includes premiums associated with new technologies or innovative construction methods. Premiums might result from factors such as contractor availability, materials availability, and contractor risk. It may include incentive/bonus payments for early completion and other innovative contracting methods.
	Maintenance of traffic	This factor captures the maintenance of traffic costs at the project site. Maintenance of traffic costs may affect preference due to their effect on total costs. This factor includes all costs associated with the maintenance of detours before, during, and after construction. Examples of this factor include: installation of traffic control devices; maintenance of detour during construction including flagging, shifting of traffic control devices during staged construction; and restoration associated with the temporary detours upon completion of construction.
	Design and construct detours	This factor captures the costs to design and construct temporary structures and roadways to accommodate traffic through the project site.
	Right of way	This factor captures the cost to procure right of way. This factor includes either permanent or temporary procurements/easements.
	Project design and development	This factor captures the costs associated with the design of permanent bridge(s) and costs related to project development based on the construction method.
	Maintenance of essential services	This factor captures the costs associated with the need to provide essential services that may be affected by construction. Examples of this factor include alternate routes or modes of transportation to provide defense; evacuation; emergency access to hospitals, schools, fire station, and law enforcement. This criterion is for situations where measures needed to be implemented beyond those already considered in the other criteria.
	Construction engineering	This factor captures the costs associated with the owner's contract administration of the project.
	Inspection, maintenance, and preservation	This factor captures the life-cycle costs associated with the inspection, maintenance, and preservation of individual bridge elements.
	Toll revenue	This factor captures the loss of revenue due to closure of a toll facility.
Indirect costs	User delay	This factor captures costs of user delay at a project site due to reduced speeds and/or off-site detour routes.
	Freight mobility	This factor captures costs of freight delay at a project site due to reduced speeds and/or off-site detour routes.
	Revenue loss	This factor captures lost revenues due to limited access to local business resulting from limited or more difficult access stemming from the construction activity.
	Livability during construction	This factor captures the effect on the communities resulting from construction activities. Examples include noise, air quality, and limited access.
	Road users exposure	This factor captures the safety risks associated with user exposure to the construction zone.
	Construction personnel exposure	This factor captures the safety risks associated with worker exposure to construction zone.

Table 4. Definitions for all criteria included in the accelerated bridge construction decision-making hierarchy (cont.)

High-level criteria	Subcriteria	Definition
Schedule constraints	Calendar or utility or R×R or navigational	This factor captures the constraints placed on the project that might affect the timing of construction as a result of weather windows, significant or special events, railroad, or navigational channels.
	Marine and wildlife	This factor captures the constraints placed on the project by resource agencies to comply with marine or wildlife regulations. Examples include in-water work windows, migratory windows, and nesting requirements.
	Resource availability	This factor captures resource constraints associated with the availability of staff to design and oversee construction. For example, a state may be required to outsource a project, which may result in additional time requirements.
Site constraints	Bridge span configurations	This factor captures constraints related to bridge span configurations. This element may affect owner preference regarding bridge layout, structure type, or aesthetics.
	Horizontal/vertical obstructions	This factor captures physical constraints. Examples include bridges next to fixed objects such as tunnels, right of way limitations, sharp curves or steep grades, or other urban area structures that constrain methods and/or bridge locations.
	Environmental	This factor captures the constraints placed on the project by resource agencies to minimize effects on natural resources including marine life, wildlife, and flora.
	Historical	This factor captures historical constraints existing on a project site.
	Archaeological constraints	This factor captures archaeological constraints existing on a project site.
Customer service	Public perception	This factor captures both the public's opinion regarding the construction progress and their overall level of satisfaction.
	Public relations	This factor captures the costs associated with the communication and management of public relations before and during construction.

of each pairwise comparison can be based on available quantitative data or by using Saaty's fundamental scale.

By processing the data obtained from a complete set of pairwise comparisons, the relative weights for each criteria and subcriteria preference levels for each alternative with respect to each criterion are obtained. By synthesizing the criteria priorities and alternative weights (for each individual criterion), a dimensionless value called the *utility level* is then calculated for each alternative and used to provide an assessment of each alternative under consideration. The higher the utility level is, the more preferable the alternative.

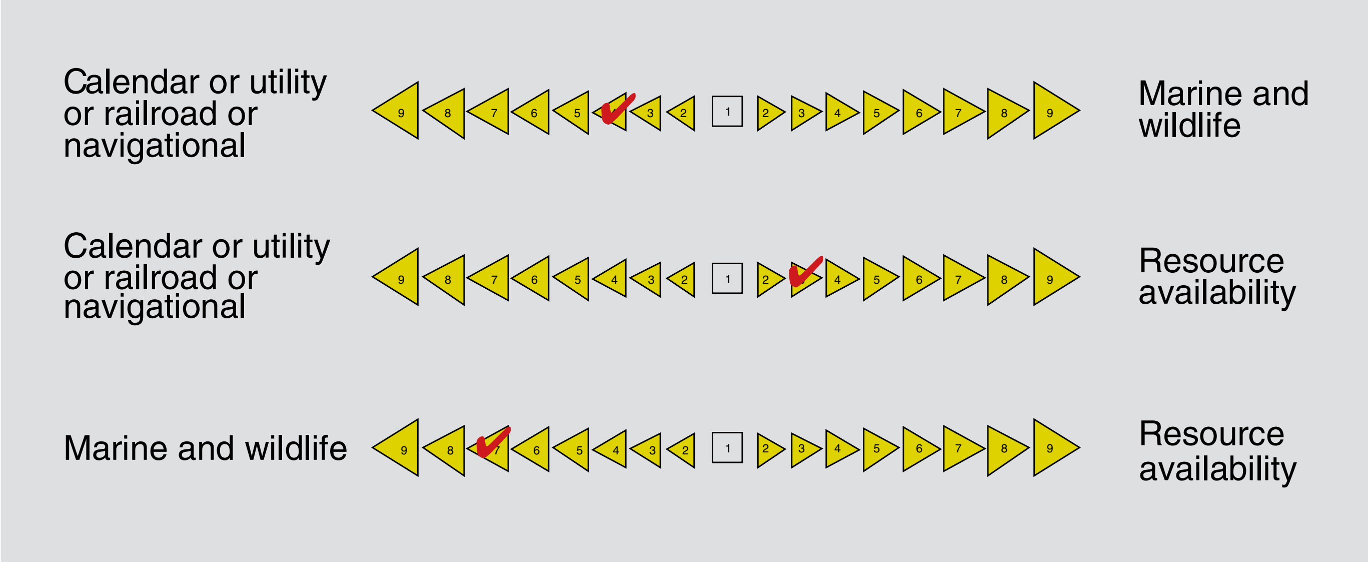

Figure 5. Completed pairwise comparisons for schedule constraints subcriteria.

Table 5. Matrices and priority values for schedule constraints subcriteria

	Comparison matrix			Normalized matrix			Priority values
	Calendar or utility or railroad, or navigational	Marine and wildlife	Resource availability	Calendar or utility or railroad or navigational	Marine and wildlife	Resource availability	
Calendar or utility or railroad or navigational	1	4	0.33	0.24	0.78	0.04	0.35
Marine and wildlife	0.25	1	7	0.06	0.19	0.84	0.36
Resource availability	3	0.14	1	0.71	0.03	0.12	0.28

Accelerated bridge construction and analytic hierarchy process decision software

To facilitate the process of completing the pairwise comparisons at different levels and calculating utility levels for each alternative, a decision tool was developed for this study. The tool was developed as a standalone application that can run on a variety of Windows operating systems. The next section presents the details of two different analytic hierarchy process analyses completed for two different bridge replacement projects.

Application of the analytic hierarchy process to bridge replacement projects

To check the completeness and robustness of the hierarchy and the analytic hierarchy process model, the research team validated the process using actual bridge construction projects. These cases were used to confirm the suitability of the analytic hierarchy process to aid in decision making about whether various elements of accelerated bridge construction should be applied to a particular project. In addition to comparing each criterion and subcriterion in terms of its importance to a particular project, the technical experts also identified at least two different construction alternatives being considered for a particular project. The experts evaluated each alternative relative to all criteria and subcriteria.

In this phase, a total of 15 case studies was completed. In each case study, two distinct alternatives were compared. In the majority of the cases used to validate the approach, one of the alternatives distinctly outweighed the other when evaluated using most of the selection criteria. However, in two projects the decision-making processes were more complex. In these cases, an alternative that was

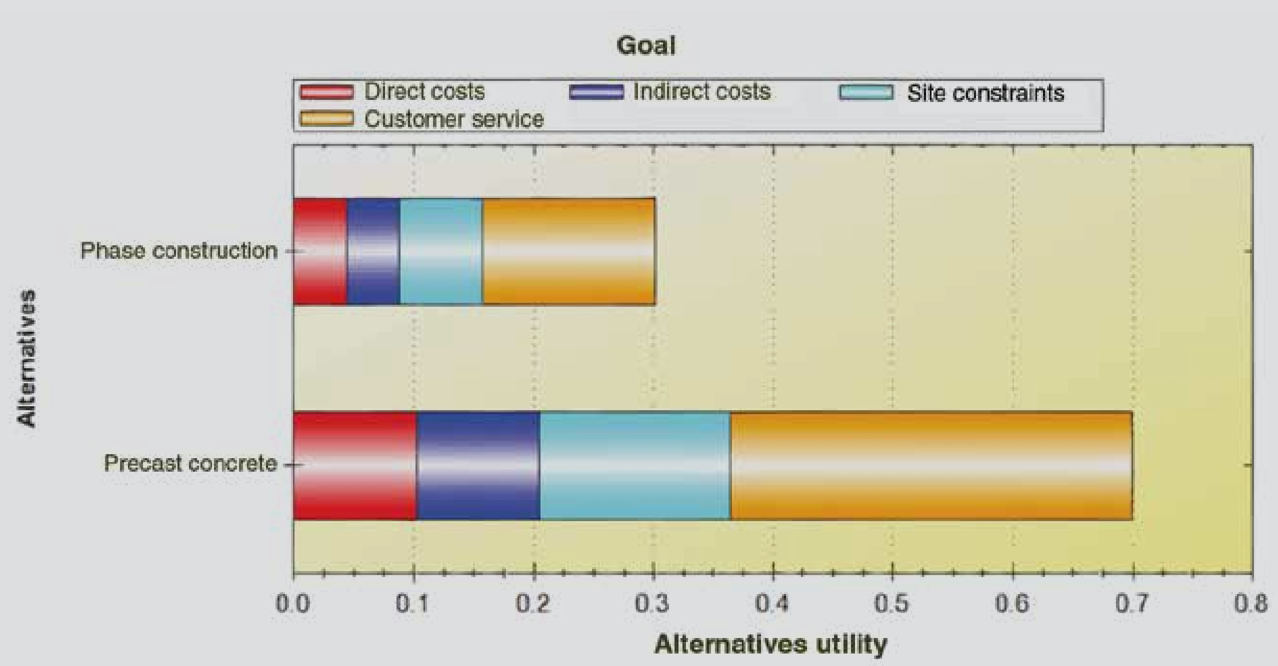

Figure 6. Alternatives' utility levels calculated for the Montana project.

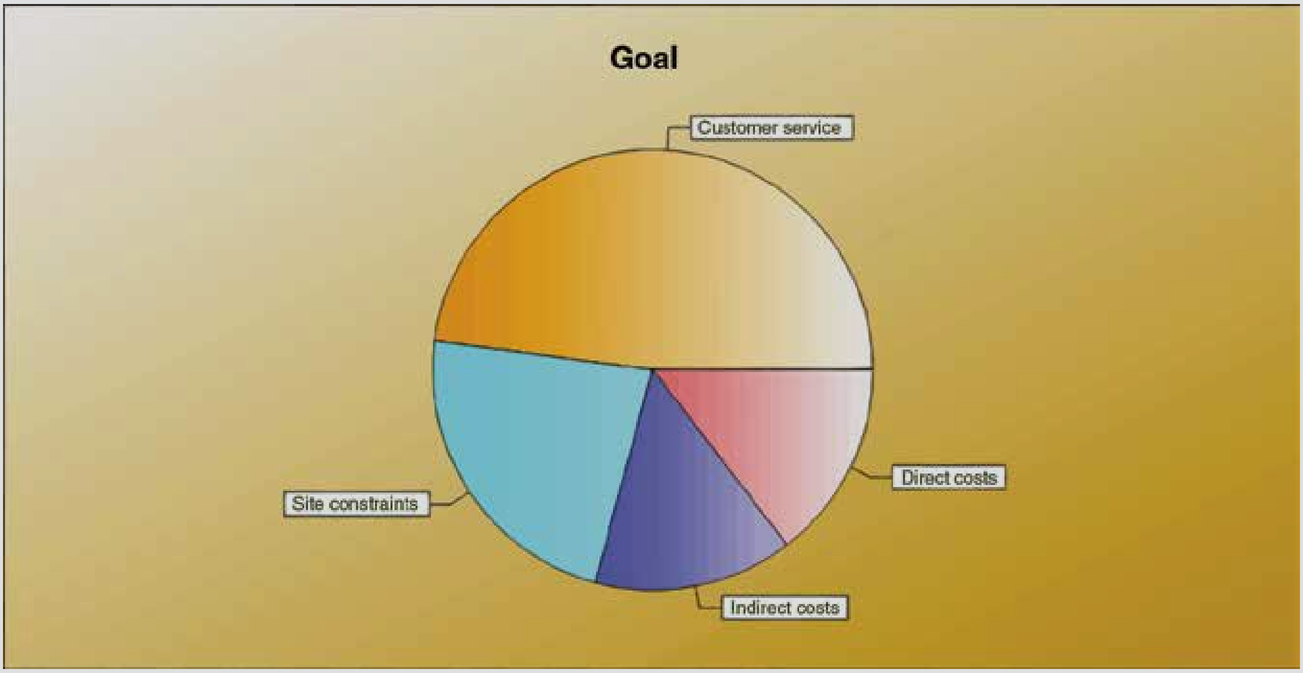

Figure 7. High-level criteria relative weights calculated for the Montana project.

strongly preferable based on a number of criteria eventually had to be disregarded because of a marginally more favorable evaluation for the other alternative when *all* of the criteria were considered. Therefore, the decision makers needed an approach to assist them in prioritizing the criteria and choosing the alternative that would address as many project requirements as possible.

Case studies

Custer Interchange The Custer Interchange project is located within the urban limits of Helena, Mont. The project was intended to implement a portion of the improvements included in the Interstate 15 (I-15) corridor final environmental impact statement and record of decision. The improvements included reconstruction to provide four lanes, median turn lanes, and a bike/pedestrian envelope on both sides of Custer Avenue; accommodations for four lanes to I-15 through the project corridor; and various improvements to roads and streets around the project in anticipation of heavier traffic volumes during and after construction of the interchange. The total project length, including ramps and both sides of the affected interstate, was 5.28 mi. (8.5 km). The average daily traffic on Custer Avenue was 15,000 before the construction project. The expected design average daily traffic was 41,000. In this project, the compared construction alternatives were precast concrete and phase construction (conventional method).

Experts from the Montana Department of Transportation completed the pairwise comparisons for this case study. The results presented in this section were generated using the accelerated bridge construction decision-making software developed by the research team. The decision makers removed schedule constraint from the list of high-level criteria because they considered it irrelevant. The precast concrete alternative was highly preferred for this project. The calculated utility levels for the precast concrete and phase construction approach were 0.699 and 0.301, respectively.

Figure 6 summarizes the alternatives' utility levels and the contribution of each criterion to the alternatives' utility level. A more detailed analysis of the results illustrated the underlying complexity of this particular project. If only indirect costs were considered, the precast concrete alternative would be preferred over phase construction. The utility levels of precast concrete and phase construction would be 0.84 and 0.16, respectively. This was also the case for the customer service criterion. The utility levels of precast concrete and phase construction were 0.86 and 0.14, respectively. However, the results also show that phase construction was preferred in terms of direct costs and site constraints.

In this situation, the relative weights of the four high-level criteria were key to the decision. Based on the pairwise comparison data, customer service and site constraints had the greatest effect on selecting precast concrete as the best alternative. The pie chart in **Fig. 7** indicates the relative weights of the four high-level criteria considered in this project.

Summit Park Bridge The Summit Park Bridge along Interstate 80 (I-80) in Utah is in Summit County at mile marker 141. I-80 is considered a rural interstate at this loca-

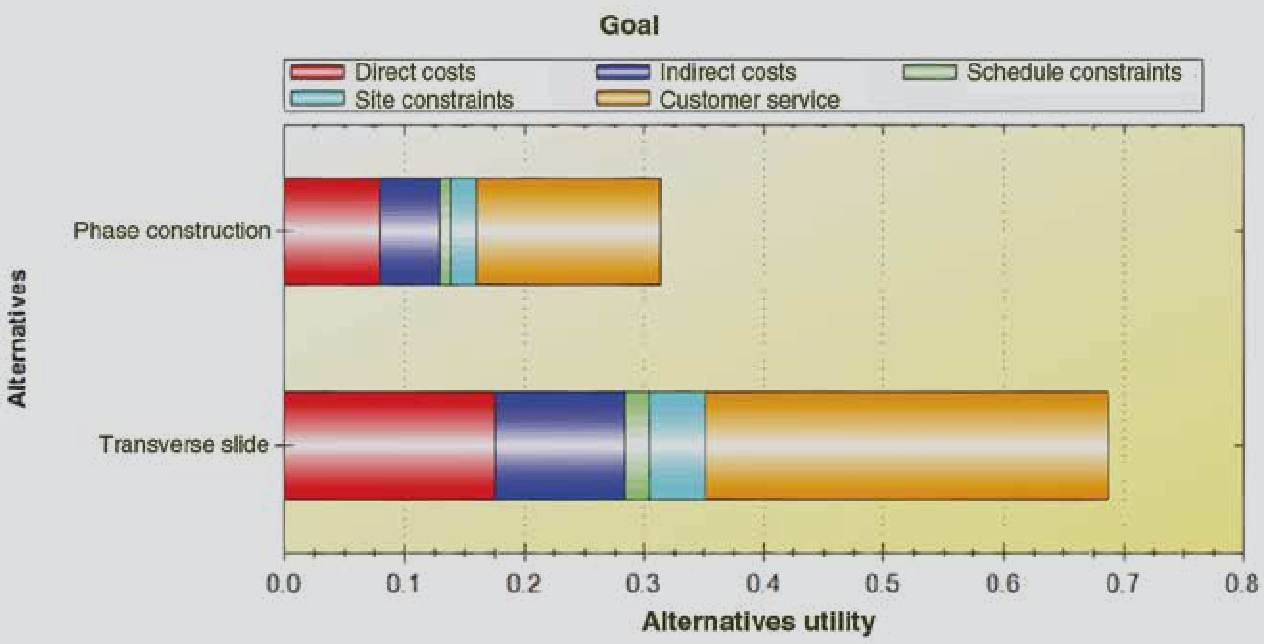

Figure 8. Alternatives' utility levels calculated for the Utah project.

tion. The bridge was in need of deck replacement. Both the westbound and eastbound bridges consisted of a 130 ft (40 m) single-span steel girder superstructure, which incorporated lightweight concrete. In this project the compared alternatives were transverse slide and phase construction.

Experts from the Utah Department of Transportation provided the required data for this analysis. Based on the analytic hierarchy process results, transverse slide was a more suitable alternative for the project. The calculated utilities for the transverse slide and phase construction alternatives were 0.686 and 0.313, respectively.

Figure 8 shows the alternatives' utility levels along with the level of contribution of each high-level criterion to the utility levels. A detailed analysis showed that even though the transverse slide was preferred with regard to direct costs, indirect costs, and customer service, the phase construction alternative was strongly preferred with regard to schedule constraints and site constraints. Considering only direct cost, the utility levels of transverse slide and phase construction alternative were 0.56 and 0.44, respectively. Also, for indirect costs, the utility levels of transverse slide and phase construction alternative were 0.84 and 0.16, respectively. The last criterion that showed the preference of transverse slide over phase construction was customer service, with regard to which the utility levels of transverse slide and phase construction alternative were 0.81 and 0.19, respectively. The results show that phase construction was preferred in terms of the other criteria, site constraints and schedule constraints.

Again, the relative weights of the criteria played a key role in identifying the best alternative for this project. Customer service was the most influential criterion, followed by direct costs and indirect costs (**Fig. 9**). Overall, the analytic hierarchy process indicated that transverse slide is the most suitable alternative for this project.

Conclusion

In the early stages of a bridge construction project, engineers and decision makers have to determine whether elements of accelerated bridge construction are achievable and effective for a specific bridge location and whether these elements are preferable to other conventional construction methods. These decisions are even more difficult because multiple criteria and diverse perspectives must be considered.

Road user cost is defined as the estimated daily cost to the traveling public resulting from construction work being performed. That cost primarily results from lost time caused by a road closure. Although accelerated bridge construction techniques may cost more than conventional construction methods, one cannot ignore the amount of time road users can save by significantly reducing road closure times. Also, accelerated bridge construction can significantly improve the safety of road users and construction workers as well as reducing the impact on the environment surrounding the construction zone.

One of the challenges in bridge construction projects is that while many decision makers can justify the use of the accelerated method for large projects, most transportation specialists felt that it was difficult to know exactly when to

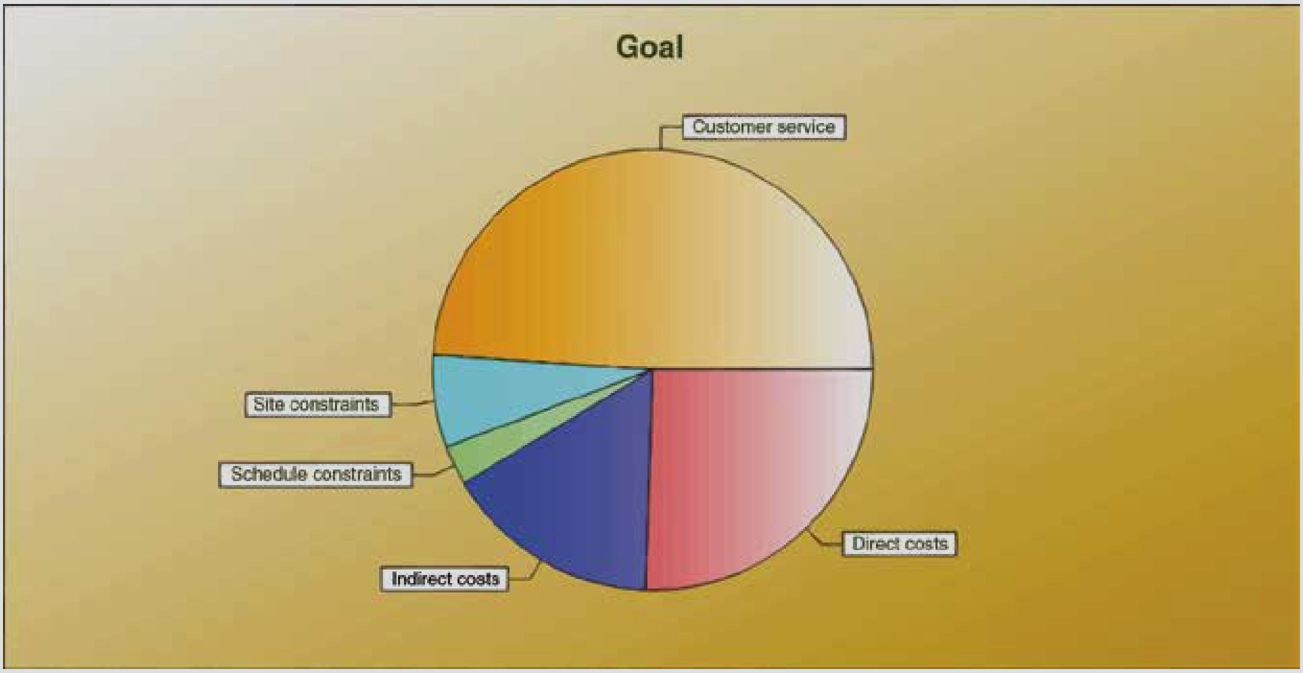

Figure 9. High-level criteria relative weights calculated for the Utah project.

use accelerated bridge construction on routine and typical bridges. This study provides a set of tools that facilitate decision-making for these types of projects. Furthermore, in some cases, decision makers may believe that accelerated bridge construction methods are the best alternative, but it is often hard to justify their costs to stakeholders. The tool developed for this study provides a common language for decision makers and stakeholders and can help decision makers explain the reasons for a specific decision.

This research developed a robust approach, based on the analytic hierarchy process, for decision makers to evaluate the suitability of accelerated bridge construction approaches for a particular project, which allows the decision maker to take into account a wide range of criteria. In this study a comprehensive criteria hierarchy for a bridge construction or rehabilitation was developed. The decision hierarchy was incorporated into a software tool. The tool provides the decision maker with the flexibility to select a subset of decision criteria that are most relevant to a particular project.

The tool was successfully tested on 15 projects from eight states. In these cases, the required data were collected, using a survey form containing the pairwise comparisons among the criteria, through the departments of transportation involved in this study. The data were analyzed through the analytic hierarchy process to suggest an alternative that best met the requirements of the project based on the prioritization of the criteria and subcriteria in the defined hierarchy. The feedback received from the experts in the departments of transportation participating in this study confirmed the soundness of the recommended approaches resulting from the analyses.

Due to the presence of various transportation experts with different backgrounds in this study, the decision criteria were defined in a way that allows the comparison of the two bridge construction alternatives from many different aspects. Each decision maker compares the two alternatives with regard to each decision criterion based on his/her own judgment. This decision-making approach is directly influenced by the input data provided by the decision maker. Therefore, the designed tool does not favor the selection of an accelerated or conventional method by itself.

As the number of decision alternatives increases, the complexity of the analytic hierarchy process grows exponentially. With advancements in bridge construction techniques, the number of alternatives available to transportation decision makers also increases. In some cases, the decision makers have to deal with more than 20 alternatives at the same time. The analytic hierarchy process technique used in this study is most effective when applied to problems with a fairly small number of alternatives. Future research can be conducted to enhance the proposed decision-making approach to address this limitation.

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Notation

A_i = accessibility score

B_i = budget performance score

C_i = carrying capacity score

Q_i = project specific factor(s)

S_i = safety score

T_i = schedule performance score

W_a = weight of accessibility

W_b = weight of budget performance

W_c = weight of carrying capacity

W_q = weight of project specific factor(s)

W_s = weight of safety

W_t = weight of schedule performance

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Abstract

Accelerated bridge construction is recognized as an important method for bridge owners to accelerate the delivery of highway bridge projects. While the potential advantages of accelerated bridge construction are recognized, it is difficult for transportation specialists to quantify the risks and benefits of using accelerated bridge construction compared with conventional construction for specific bridge replacement or rehabilitation projects. A tool set, based on the analytic hierarchy process, is prepared for transportation specialists and decision makers to determine whether accelerated bridge construction is more effective than traditional construction for a given bridge replacement or rehabilitation project. To accommodate this task, a comprehensive literature review was completed on a number of relevant domains, such as accelerated bridge construction techniques and decision-making approaches. The findings were summarized into a decision model hierarchy that was also incorporated into the decision-making software. The software was tested through evaluating a set of real-world construction projects.

Keywords

ABC, Accelerated bridge construction, analytic hierarchy process, bridge, decision making.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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