# A QFD-AHP Method for Bridges Structural System Selection During the Conceptual Design Phase

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## Abstract

Selection of structural system for new highway bridges during the conceptual design stage is critical to the success of the project and meeting stakeholders' requirements. During bridge conceptual design, a large set of subjective requirements must be considered and evaluated in terms of multiple criteria. In addition, it is critical to incorporate client needs and expectation during the conceptual design stage to achieve their satisfaction toward the delivery stage of the project. For this reason, this paper is proposing an integrated methodology to improve the decision-making process during bridge conceptual design. The proposed methodology utilises the quality function deployment (QFD) method to translate client needs into design requirements and the analytic hierarchy process (AHP) to prioritizes competing alternatives based on multicriteria decision analysis. The main advantage of integrating QFD and AHP is their ability to rank the design alternatives in order of their effectiveness in meeting client needs. While the QFD analysis has the power to optimize the designers' solutions from the point of view of quality engineering, the AHP analysis helps to make the best decision in a multicriteria decision-making situation.

## Keywords
Bridges Structural System; Conceptual Design Selection; Quality Function Deployment (QFD); Analytic Hierarchy Process (AHP).

## 1. Introduction
The most important stage of the bridge design process is the conceptual design stage. It consumes the first 10–20% of total design time and has an impact on the entire design process (Wai-Fah and Lian, 2000). Moreover, poorly conceived design concept can never be compensated by a good, detailed design (Xu et al., 2005; Machwe and Parmee, 2007). The most important sub-stage in the conceptual design of a bridge is the selection of the bridge structural system, which is based on a wide range of factors including cost, maintenance considerations, aesthetic, construction time, function, sustainability, safety, environmental impacts, availability and many other design requirements.

Nowadays, many business organizations are looking for new strategy to stand out in the competitive market by offering the best possible products or services to their clients. One of the key processes to achieve this is by implementing a Quality Function Deployment (QFD) approach, which is based on listening to the client and translating their needs into design requirements. QFD implementations provide many advantages in terms of reducing quality-related issues. These advantages have been found to focus on the following headings: client requirements and expectations identification, planning, coordination, concurrency and uncertainty reduction. Adding the use of Analytic Hierarchy Process (AHP) will improve the multicriteria decision making process and ranking of the design alternatives. The objective of this research is to establish a framework for collecting and identifying client requirements for bridge structural system in a systematic manner and convert them into design objectives using an integrated QFD-AHP methodology.

## 2. Literature Review

This section reviews previous studies from books and journals that are related to quality function deployment and its application in different construction fields including bridges.

### 2.1 Quality Function Deployment (QFD)

From the literature, quality function deployment can be divided into four stages. Planning is the first stage where the client needs converted into design requirements. These requirements are ranked based on their importance, and the value of each design alternative are then determined. Subsequently, the ranked design requirements are inputted in the QFD's matrix. This matrix is called the House of Quality (HOQ). HOQ is the first and most significant step in the QFD method which can be explained in the following steps in Figure 1 adapted from Dale et al., 2016:

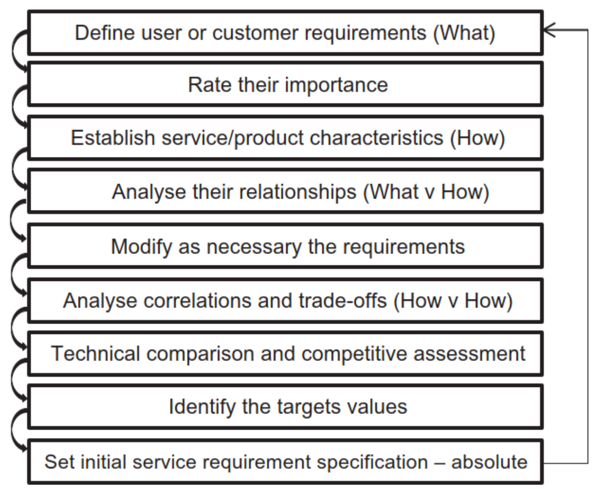


Figure 1 : QFD Method Steps (Dale et al., 2016)

While there is a slow increase in interest in QFD applications in construction, there are only a few research in QFD applications in the construction management literature. QFD was first applied in the construction filed by Shino and Nishihara (1990), in Japan. Majority of QFD studies in construction has concentrated on its application in design automation (Prasad et al., 2015). QFD applications in construction follows the traditional implementation by translating client needs into technical design specifications (Lim et al., 2015; Prasad et al., 2015). In general, existing research on QFD focuses on demonstrating QFD application through simple examples rather than using complex cases.

In a research done by Malekly et al. (2010), fuzzy integrated methodology was investigated for evaluating conceptual bridge design. The project specifications were translated into design requirements using QFD. Based on the weighted criteria obtained in the first step, the technique for order performance by similarity to ideal solution (TOPSIS) is used in the second phase to pick the best superstructure as an alternative. Throughout the processes, linguistic variables were used to define the rating values for each alternative and parameters in a fuzzy environment. Finally, a case study was introduced to show the integrated methodology for bridge superstructure design implementation process.

Different papers that studied the application of QFD in construction industry are shown in Table 1.

Table 1: Application of QFD in construction industry

| Application Area | Decision problems | Author(s) and Year |
|---|---|---|
| Construction | Assessing bridge condition prior to selecting the suitable maintenance, repair, or replacement action. | Alsharqawi et al., 2020 |
| Construction | Structured product planning and development. | John et al., 2014 |
| Construction | Temporary housing | Gilbert III et al., 2014 |
| Construction | Technique to evaluate expectation of housing customers. | Keivani et al., 2013 |
| Construction | Construction of the landscape of a new hotel. | Masoudi et al., 2013 |
| Construction | Large-scale photovoltaic system construction projects | Yuventi and Weiss, 2013 |
| Construction | Evaluate expectation of housing customers. | Jalali and Sameni Keivani, 2013 |
| Construction | Achieving quality in bridge maintenance by implementing (QFD) | Bolar at el., 2012 |
| Construction | Employed QFD for the design of a marine power plant. | Liu and Zeng, 2012 |
| Construction | Evaluate expectation of housing customers. | Dalle, 2010 |
| Construction | Fuzzy integrated methodology was investigated for evaluating conceptual bridge design. | Malekly et al., 2010 |

### 2.2 Analytic Hierarchy Process (AHP)

AHP was created by Saaty (1980) to deal with decision-making problems in complex and multicriteria situations (Saaty, 1990; Dyer and Forman, 1992). AHP supports in making decisions that are characterized by multiple interrelated and often competing criteria when placed within the framework of the decision objective, and it determines priority among decision criteria (Shapira and Goldenberg, 2005). AHP also helps to rank decision criteria according to their relative importance.

AHP is a multi-criteria decision process that represents a problem using hierarchical structures and then develops priorities for alternatives based on the user's assessment (Saaty, 1980). AHP consist of six essential steps explained briefly in below section (Lee et al., 2013):

1. Define the unstructured problem.
2. Developing the AHP hierarchy.
3. Pairwise comparison.
4. Estimate the relative weights.
5. Check the consistency.
6. Obtain the overall rating.

Because of the availability of extensive literature on its application, Decision-makers pay the most attention to AHP as the most commonly used Multi-Criteria Decision-Making (MCDM) method (Jato-Espino et al., 2014). It is thus important to better understanding of the particular decision problems that can be resolved by AHP. This would greatly increase interest in AHP applications in the construction industry, particularly in construction management.

AHP has been shown to be applicable to a lot of different fields of construction management. The reviewed papers from the literature showed that AHP has been successfully applied to a large number of decision-making problems related to construction. These results indicates that AHP is helpful in enabling strategic and sound decision-making in a wide range of construction management fields, which is consistent with the viewpoint of Jato-Espino et al. (2014).

Table 2 presents different papers and provides a reference guide and helpful information about the applications of AHP in construction management.

Table 2: Summary of applications of AHP in construction

| Application Area | Decision problems | Author(s) and Year |
|---|---|---|
| Risk management | Decision making for balanced risk allocation selection | Khazaeni et al., 2012 |
| Risk management | Evaluation of the risk in the construction industry | Subramanyan et al., 2012 |
| Sustainable construction | Life cycle assessment of highway designs | Lee et al., 2013 |
| Sustainable or green construction | Selection of Sustainable Building Material | Akadiri et al., 2013 |
| Sustainable or green construction | Analysis for sustainable industrial areas | Ruiz et al., 2012 |
| Sustainable or green construction | Improving infrastructure system decision-making. | Mostafa and El-Gohary, 2014 |
| Transportation | Developing a bridge health index (BH) for optimum allocation of resources for maintenance actions | Wakchaure and Jha, 2012 |
| Housing | Optimization in temporary housing projects | El-Anwar and Chen, 2013 |
| Building design | Improving decision-making at the early design stages | Schade et al., 2011 |
| Building design | Evaluating and selecting design alternatives | Cariaga et al., 2007 |
| Construction productivity | Predicting the impact of a technology on productivity | Goodrum et al., 2011 |
| Project delivery systems selection | Selection of optimal project delivery systems | Mafakheri et al., 2007 |
| Project delivery systems selection | Selecting the most suitable delivery method for projects. | Mahdi and Alreshaid, 2005 |
| Contractor performance evaluation | Contractors’ classification. | Nassar and Hosny, 2013 |
| Bidding | Improving bidding process. | Chou et al., 2013 |
| Planning and scheduling | Scheduling multiple projects with competing priorities. | Goedert and Sekpe, 2013 |
| Earned value management | Assessing project performance and monitor progress | Chou et al., 2010 |
| Value engineering | Identification of the most important features of a project | Cha and O’Connor, 2006 |
| Quality management | Solving Quality related issues. | Lam et al., 2008 |

### 2.3 Overview of the Joint Application of QFD and AHP

Combined QFD-AHP is one of the most widely used integrated AHP’s decision making techniques (Ho, 2008). While the QFD analysis can enhance the designers’ solutions from the quality engineering standpoint, the AHP analysis can assist in making the optimum decision in a multicriteria decision-making situation (Dziadak and Michalski, 2011).

The main objective of integrating QFD and AHP is to assist designers in developing the design by integrating client’s needs into the design specifications then prioritize each design element to determine its level of importance in achieving client needs.

The main benefit of integrating QFD and AHP is their effectiveness in ranking design specifications in order of their importance in meeting client needs mainly at the conceptual design stage (Mayyas et al., 2011; Mayyas and Omar, 2012). There is inconsistency in QFD as it is carried out using personal and subjective judgments. AHP helps to reduce this inconsistency when it is performed to QFD inputs during the consistency verification step (Mayyas et al., 2011;

Dziadak and Michalski, 2011). Table 3 shows wide range of applications of the integrated QFD-AHP approach with 5 application areas. It was manufacturing is the most common area for this integration.

Table 3: Joint application of QFD-AHP for decision-making

| Research Approach | Application Area | Purpose | Authors |
|---|---|---|---|
| QFD and AHP | Supply chain | Supplier selection | Khan et al., 2016 |
| QFD and AHP | Manufacturing | Technology selection | Singh et al., 2015 |
| QFD and AHP | Supply chain | Supplier selection | Scott et al., 2015 |
| QFD and AHP | Supply chain | Portfolio of supply chain resilience strategies selection | Chowdhury and Quaddus, 2015 |
| QFD and AHP | Manufacturing | Product design selection | Hu and Xu, 2014 |
| QFD and AHP | Manufacturing | Photovoltaic modules selection | Abdelhamid et al., 2014 |
| QFD and AHP | Supply chain | Supplier selection | Scott et al., 2013 |
| QFD and AHP | Service | Service features selection in a hotel landscaping design | Masoudi et al., 2013 |
| QFD and AHP | Higher education | Professional competencies selection | Liu et al., 2013 |
| QFD and AHP | Manufacturing | Products evaluation in support of mobility | Aguilar-Zambrano et al., 2013 |
| QFD and AHP | Manufacturing | Process selection | Qattawi et al., 2012 |
| QFD and AHP | Service | Bank selection | Paltayian et al., 2012 |
| QFD and AHP | Manufacturing | Eco-material selection | Mayyas and Omar, 2012 |
| QFD and AHP | Supply chain | Supplier selection | Dai and Blackhurst, 2012 |
| QFD and fuzzy AHP | Manufacturing | Robot selection | Merino et al., 2015 |
| QFD and fuzzy AHP | Supply chain | Supplier selection | Wang, 2015 |
| QFD and fuzzy AHP | Service | Service assessment | Huang and Hsu, 2016 |
| QFD, AHP and TPM | Strategy | TPM pillars prioritization | Sugumaran et al., 2014 |

### 2.4 Research Gap in the Literature Review

Overall, it was found that few papers only studied the application of QFD in bridge conceptual design. The previous researches that were done in the same topic studied the application of QFD approach in bridge superstructure design only and used different integrated methods, while this research will be focused in choosing full bridge structural system during the bridge conceptual design including superstructure conceptual design, substructure conceptual design, construction methodology and taking in consideration the aesthetic factor if required by the client.

There are variety of researches that integrated QFD with AHP in the areas of manufacturing, supply chain, higher education, strategy, service. However, very few papers used this integration in the construction industry, and it was not used it in bridge conceptual design.

## 3. Proposed Methodology

In order to enhance the bridge conceptual design selection, a methodology of applying the integrated approach using QFD and AHP has been developed through the steps listed below:

1. Identify client needs (WHATs): A questionnaire need to be conducted for the client to identify their needs in bridge structural system during conceptual design stage. The questioner will be in AHP format and results to be placed in (WHATs) in house of quality.

2. Group the client needs based in their category including Function, Time, Sustainability, Cost, and Aesthetic.

3. Determine the design specifications that achieve client needs (HOWs): Client needs for the bridge design to be studied deeply and needs to be translated into bridge design specifications by experts' team. Results to be placed in (HOWs) in house of quality.

4. Determine the importance weight of clients' needs for the proposed bridge using AHP: Client questionnaires to be circulated in order to determine the weight of each client need using AHP approach using the pairwise matrix then normalised pairwise matrix to get each criteria weight. Consistency needs to be checked to validate the results of the client survey in this step.

5. Calculate the relationship between design specifications and the client needs (Relationship matrix): The relationship between bridge structural system design specifications and the user requirements will be determined by the design team as part of QFD process. The impact of each design specification (HOW) on each client need (WHAT) were recorded as numerical value of (0 =No correlation, 1 =Weak correlation, 3 = Medium correlation, 9 = Strong correlation).

6. Calculate the weight of each design specifications for the proposed bridge (HOWs): This equals the sum of multiplying the level of importance to a need by the value of the relationship between that need and the corresponding design specification.

7. Computation of individual scores for each bridge superstructure design alternative using AHP: AHP process needs to be applied again to find the weight of each design alternatives compared to target criteria.

8. Rank the bridge structural system alternatives and select the best design: Based on results obtained from previous steps for the weights of each criterion and each design alternatives. Cross product matrix will be produced by multiplying the design alternatives importance matrix and the criteria importance matrix from the previous steps to determine the importance of each bridge superstructure design alternative and alternatives will be ranked accordingly.

Figure 2 illustrates a diagram for the proposed research methodology flow.

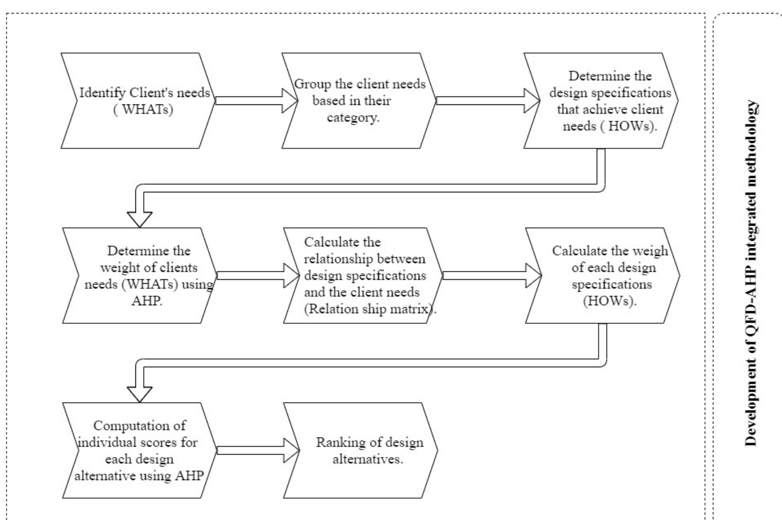


Figure 2 : Proposed Research Methodology

## 4. Results and Discussion

The previous literature that has been reviewed shows that QFD was successfully applied in many construction fields including maintenance, planning, evaluation, building construction, infrastructure and bridge design. Figure 3 shows the percentage of application in each area of the studied papers.

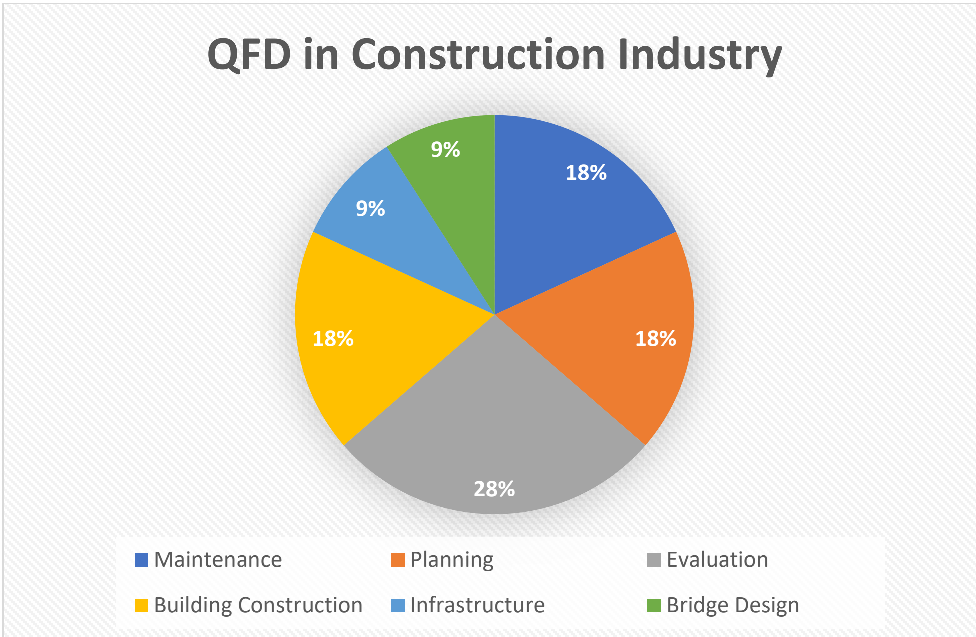


Figure 3 : QFD in Construction Industry

Figure 3 shows that around 30% of the studied papers in the application of QFD in construction industry were in the evaluation area, mainly in evaluating expectations of housing customers. Similar number of studies for planning and building construction were found with about 20% for each. Overall, it was found that only few papers studied the application of QFD in bridge conceptual design to increase the applicability and potential benefits of QFD to the bridge construction industry. There is a need to further investigate and find a functional approach to apply QFD allowing capturing client requirements during bridge conceptual design stage.

AHP was found to have a variety of applications in the construction industries including risk management, sustainable construction, transportation, building construction, project delivery systems, contractors' evaluation, value engineering, and quality management. Figure 4 shows the percentage of AHP application in each area of the studied papers.

Figure 4 shows that the most common application of AHP in construction industry are in building construction and sustainability. AHP was applied only in one infrastructure field which is Transportation. The studies show that AHP is an effective tool that has been widely used in different areas of construction management. However, with limited application in infrastructure fields and with no previous application in bridge design. This paper aims to extend the application of AHP to cover bridge conceptual design.

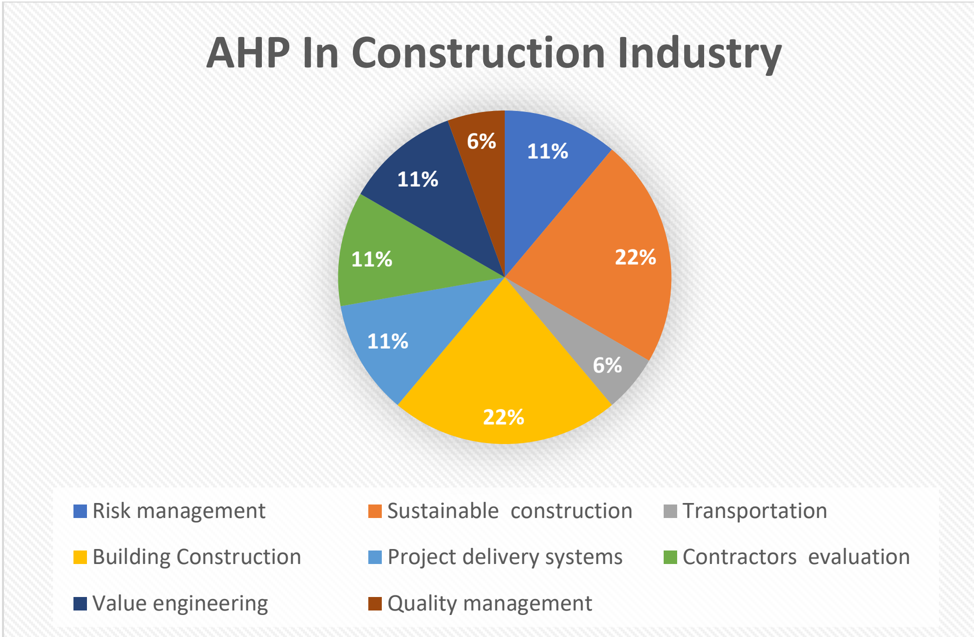


Figure 4 : AHP in Construction Industry

Variety of research integrated QFD with AHP in the areas of manufacturing, supply chain, higher education, strategy and service. This indicates that the integration of AHP and QFD is very effective and powerful tool. Figure 5 shows the percentage of QFD-AHP approach application in each area of the studied papers.

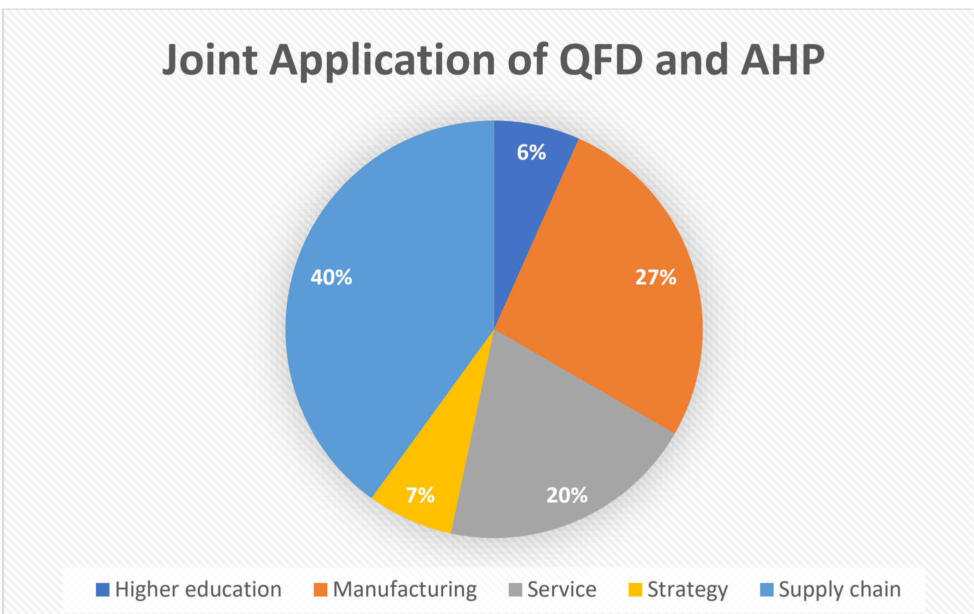


Figure 5 : Joint Application of QFD and AHP

Figure 5 shows that the integration of QFD and AHP is widely used in the industrial engineering field inlcuding supply chain and manufacturing. It also shows that there is no application for this integrated approach in the construction industry. Applying the integrated approach in bridge conceptual design will be a great begining for extending the application of QFD-AHP apporach to construction field and particularly to the field of bridge design. This research aims to develop an integrated approach using QFD-AHP method to achieve client satisfaction during bridge conceptual design stage. The reviewed articles proved that the QFD-AHP integration is applicable and will be effective to increase the client satisfaction and reduce the inconsistency in the decision-making process during bridge conceptual design.

## 5. Conclusion
In the construction industry, client needs, and expectations are rarely addressed in a systematic manner. Even if they are gathered prior to the design phase, they are frequently ignored and ultimately disappear as the construction phase progresses. Problems with buildability, delays due to incomplete designs, misunderstanding of client requirements, rework, and other issues have been observed as a result of a lack of integration between the parties involved in a project and a lack of attention paid to capturing client needs at these levels. Introducing the integrated approach for solving bridge structural system selection in conceptual design stage of highway bridge projects using QFD and AHP will help to improve client satisfaction by having a methodology that can translate client's needs to design specifications in bridge conceptual design stage. Utilizing the QFD-AHP approach will also improve the bridge conceptual design by providing a better planning tool to avoid future changes due to client unsatisfaction. This proposed methodology is expected to benefit consulting companies, governmental authorities and developers in solving bridge structural system selection during conceptual design stage of highway bridge projects, and the major sough benefit would be enhancing the incorporation of customer requirements in design.

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## Biographies

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**Mohammed Alsharqawi** is an enthusiastic Civil Engineering professional with interest in Construction and Infrastructure Management. He has over 10 years of experience in construction, infrastructure, and academia as it relates to asset management. Currently, Mohammed is leading the Township of South Stormont asset management program initiatives and providing guidance and support to the Township's public works services. Mohammed Alsharqawi holds a PhD from Concordia University, Canada as well as, a Master of Engineering Management from University of Wollongong, Australia and a Bachelor of Science in Civil Engineering from the American University of Sharjah, United Arab Emirates.