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INTEGRATING BRIDGE INFORMATION MODELING (BrIM) WITH COST ESTIMATION AT THE CONCEPTUAL DESIGN PHASE OF BRIDGES

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Abstract: Integration of bridge information modeling (BrIM) with bridge management systems and computer-aided engineering design solutions had inspired many researchers over the past few years. Several successful integrations of BrIM with these solutions had significantly leveraged downstream processes of bridge projects. Over the years, one of the major obstacles encountered by BrIM integration experts was the functional interoperability with other solutions. In this study, research objectives are intended to demonstrate the viability of integrating BrIM with cost estimation while resolving BrIM integration with computer-aided structural analysis solutions interoperability issues. In this paper, an integrated prototype that fosters operational efficiency and cost savings for multiple types of bridges is presented. The proposed research methodology includes a preliminary estimation system comprising cost optimization modules which is developed in a .NET framework. The developed prototype will be capable of receiving and automatically incorporating 3D real-time information reflecting site alterations and corresponding effects on project overall cost. A case project was defined to validate the model and illustrate its corresponding numerical capabilities. Results presented in this study will enhance estimation techniques for bridge contractors and stakeholders by the inclusion of all direct and indirect costs associated with the different phases of a bridge project ranging from design conceptual phases to substructure, including heavy earthmoving operations, and superstructure. The prototype model is anticipated to be of major significance to contractors and considered a "brand-new" contribution to BrIM integrated technologies with cost management approaches.

Keywords: Bridge Information Modeling (BrIM), Conceptual Design, Integrated Cost Estimation, 3D-CAD

1. INTRODUCTION AND MOTIVATION

Bridge information modeling (BrIM) is a newly born "sister-approach" to building information modeling (BIM) and may be comprehended as an innovative approach to inform downstream processes of infrastructure projects. An interview with BrIM inventors back in late 2009 illustrated the significance of the closely related information modeling approaches by affirming that the difference between both approaches is by far the additional "r". As part of developing this research incentive, it was understood that integrating basic BrIM into bridge conceptual design and preliminary cost estimation was possible only if objectives were kept simple, focused, and organized. In the past, several attempts had been witnessed in terms of developing computational tools for supporting various aspects of design and construction of bridges; however, these aspects were tackled independently from impediments arising due to availability of multiple data resources. Nowadays, few industries only have moved forward in terms of incorporating integrated design with industrial processes in parallel with "broadly-accepted" interoperability standards. Although the deployment of powerful object-oriented software technologies such as 'C++ ' and 'C#' in the bridge construction industry supported by metadata file transfer capabilities had resulted in less error-prone data duplication, many engineers and researchers are still unaware of the economical values of utilizing such technologies in cost estimation at the conceptual design phase of bridge projects. Given the above-mentioned, a reliable determination of overall project total costs necessitates the development of a thorough, reliable, and user-friendly cost estimation system to assist contractors in making cost-effective decisions between myriad established and innovative design alternatives. Towards the goal, a wider insight into integrating BrIM with a cost estimation system was artistically and objectively created and deployed. This paper; however, presents only partial results of the successful integration of a bridge information model as a technology to resolve interoperability issues with a cost estimation system at the conceptual design phase to foster operational efficiency and cost savings.

In an attempt to synchronize the marshal of enormous bridge information, a schematic view of the interrelations among the 3D computer-aided design (CAD) solutions with the developed Integrated Preliminary Cost Estimation System (IPCES) is illustrated in Fig. 1. A proper harmony and handling of modeling data will result in less error-prone outcomes as a result of duplication or amalgamation of inconsistent bridge database resources. The flow of geometric and architecture informatics for the different types of bridges starting from heavy earthmoving operations, passing by the substructure, and reaching at the superstructure will be presented in more details. It is important to note that the 3D-CAD solution investigated in this study and shown in Fig. 1 is an exemplar of a particular application commonly used in the industry.

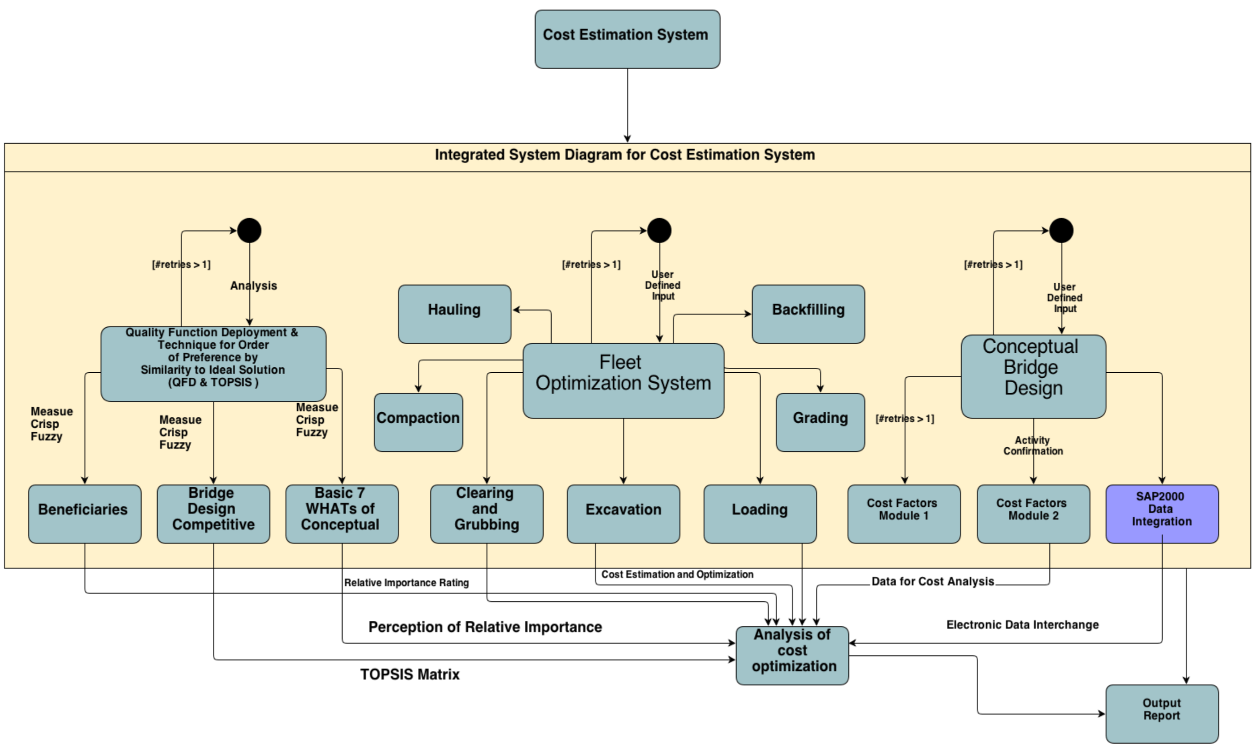


Figure 1: Integrated Preliminary Cost Estimation System (IPCES) Flow Diagram

2. REVIEW OF THE LITERATURE

The majority of BrIM applications and computational studies focused on myriad complex factors; however, none of the studies were to include or perform cost estimation comprising all direct and indirect costs associated with bridge substructure, including heavy earthmoving operations, and the superstructure. For example, Don Peters (2009), BrIM Director at Bentley Systems, presents in a simple article two major and complex bridge construction projects that were conducted utilizing BrIM technologies. The aim of the study is to emphasize the significance of incorporating BrIM into a complete set of bridge design processes. He had summarized the problem definitions of executing the Sutong Bridge in China and the Stonecutters Bridge in Hong Kong. Design factors ranging from bearing capacity to typhoon and seismic analyses of the bridge sub- and super-structure were considered. Moreover, myriad factors evolving from a construction perspective were capable of being integrated with the information model. According to Peters (2009), “BrIM benefits the entire bridge lifecycle, project selection through rehabilitation, resulting in the development of new best practices”. One study conducted by Shim et al. (2011) investigated the application of 3D BrIM to the design and construction of bridges. The main goal of the study was geared towards the enhancement of information modeling for bridges. In an attempt to enhance BIM techniques for civil infrastructure projects, a construction project lifecycle management system specifically targeted for bridges was developed. As part of the system development, an architectural framework was established and comprised of the actual bridge information model as well as architectural design layers. Furthermore, in order to enhance the interoperability of 3D information model with other solutions, the architectural framework was established in the neutral file format, XML. This study is of major significance at the conceptual stage of a bridge project and may be utilized to assist in detecting anticipated clashes during construction stages. Furthermore, another study conducted by Lee et al. (2011) presented the application of 3D BrIM to the design and construction of concrete box-girder bridges. A construction project life-cycle management system was proposed in order to integrate all design and construction valuable parameters. The objective of the study was the deployment of prefabricated bridge construction techniques through the development of a 3D BrIM. As part of developing the model, main design parameters and the relationships among them were defined. The model encompassed multi-layered information for the different users (i.e. designers, contractors and owners). Bill of material for the fabrication of five different types of concrete box-girder segments was then defined and implemented into the information model which was then utilized to optimize geometry control and reduce time and cost overflows during construction. At the end, the developed model was comprehended by the authors as a design guideline for prefabricated concrete box-girder bridge projects. On the other hand, Kivimäki and Heikkilä (2009) developed a prototype system capable of integrating 5D product models with 3D on-site surveying of bridges via an internet connection. The proposed system was implemented in a Microsoft environment utilizing ‘C#’ programming attributes. As part of the bridge model definition, a surveying instrumentation, total station, and the 3D structural analysis software, TEKLA structures CAD, were utilized. The study was targeted to enhance correspondence sessions among team players of a particular construction project. The study was found to be of major significance at the initial stages of a bridge project and is capable of enhancing the cost effectiveness of a bridge surveying session. In another study, Heikkilä et al. (2003) presented the development of a new methodology for 3D design of concrete bridges in connection with 3D site measurements. In their paper, modern technologies in site measurements utilizing ground-based laser scanners were recalled. The 3D design concept developed was designed to be utilized during the construction phase of the bridge project. Therefore, a 3D bridge design guideline was proposed while taken into consideration the construction stage of the project, 3D site geometry control measurements, and post-construction phases. Towards the end, the developed design concept was tested via the implementation of real time computer-aided designed/computer aided manufacturing (CAD/CAM) measurements utilizing a 3D robot tachometer as a device tool hand in hand with a MicroStation. Two types of the latest 3D laser scanning techniques were recalled from earlier studies and utilized for testing of site control measurements. A “dome-like” laser scanner, Callidus, and a “fan-shaped” laser scanner, Cyrax were evaluated under the same circumstances. At the end, it was concluded that “fan-shaped” laser scanner was found to be superior for geometrical measurements of bridge structures. However, it was found that the developed 3D design concept was restricted in terms of measured point clouds and direct tolerance comparisons which limits direct deviation controls and deteriorates accuracy requirements. Furthermore, researchers have focused on developing bridge information international and interoperable widely-accepted guidelines in an attempt to assist design engineers in detecting “before-hand” clashes, develop less error-prone models, and foster operational efficiency during the multiple and, sometime, long term construction phases of bridge projects including suspended bridges. These studies; however, did not incorporate a cost estimation based on their corresponding innovative integrated approaches nor they have included the influence of the developed computational tools and applications on project cost. Kivimäki and Heikkilä (2010) presented results and findings of the Finnish bridge cluster consortium (5D-Bridge). One of the main findings of the consortium was the development of the national bridge information modeling draft guideline in Finland. Another study by Shirole et al. (2009) summarized earlier research conducted to demonstrate the acceptance of integrated project delivery approach, utilizing bridge information modeling, among stakeholders in design and construction. Integration and deployment of earlier advancements in BrIM technologies were illustrated. Dataflow diagrams and computer-aided design as well as engineering software amalgamations for steel and concrete alternatives of a bridge design were demonstrated to summarize design and verification via XML-coded extensions. Their study included most of the 3D-CAD software integrations utilized to enhance BrIM at its maximum; however, a major lack of interoperability and compatibility among the above-mentioned technologies is considered a major pitfall and the authors stated that industry-wide standards must amalgamate to reinforce this widely-accepted integrated project delivery approach. As discussed above, the majority of the studies presented in the literature did not consider cost estimation applications for bridge projects. In contrast, major studies considered numerous important factors for enhancing bridge information modeling techniques; however, none of them had specifically viewed a bridge project as a task or process that needs to be completed following critical budget constraints. Therefore, the proposed cost estimation tool incorporates an economical estimation tool which provides universally accepted metrics of cost to evaluate the success of a construction project.

3. PROBLEM DEFINITION

Inspired by the Innovations Deserving Exploratory Analysis (IDEA) program, the main objective of this study was geared towards the deployment of an Integrated Preliminary Cost Estimation System (IPCES) for 3D BrIM projects as shown in Fig. 1. The subject matter presented hereby mainly focuses on a product by focusing on the methodology followed while taking into consideration interoperability concerns. According to Shim et al. (2011), existing 3D-CAD solutions are not sufficient for the utilization of information models for bridges as technical improvements are a necessity for the effective exchanging of information among interoperable software. In their study, a neutral file format accompanied with an XML schema was deployed via a coded-link to enhance interoperability. Furthermore, Gallaher et al. (2004) clearly stated that the absence of efficient interoperability among 3D modeling solutions could substantially restraint users from reaping remarkable benefits. Up to date, there exists no literature or single data on the effect of BrIM integration with a cost estimation system at the conceptual design phase of bridges on time and cost savings during construction phases. Moreover, it is important to note that integrating a complete set of processes for a particular bridge construction could significantly influence design alternatives and consequent notable cost savings at the very initial stages of the design phase.

4. MODEL DEVELOPMENT METHODOLOGY

The cost estimation prototype is developed in an object-oriented .NET framework "C#" while utilizing, SQLite, which is implemented for the first time in BrIM studies and considered as an innovative adoption of a database server application based on windows system without the "actual" requirement of a server for enhanced performance and data-recall efficiency. SQLite database application was found to resolve interoperability issues among the "sub-database" applications within the developed prototype. By altering a user's platform, bandwidth, and average file size specifications, it is possible to accurately reflect expected or planned environments. Table 1 summarizes average transaction response time capabilities of SQLite database application for engineering cost estimating applications.

Table 1: SQLite Average Transaction Response Times for Multiple User Specifications

Test No.	Percentage of Transactions (%)	Response Time (sec)
1	90	2
2	95	1
3	99	0.5

Model development comprises of the following four main phases; (a) data collection, (b) heavy equipment selection, (c) conceptual bridge design (BrIM), and (d) preliminary cost estimation. Three main modules are then categorized according to actual conceptual bridge design activity sequencing. The modules are as follows: 1) fleet cost optimization system; includes operation analyses modules that contain multiple equipments' comprehensive economical analysis; 2) selection of bridge design type; comprises of an automated QFD (Quality Function Deployment) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) analyses strategies for selection of the best bridge design alternative based on a specified list of parameters; 3) cost estimation system; contains a comprehensive database of costing factors that is automatically linked to the BrIM software technical database complete with a report module that displays instantaneous output reports of preliminary costing estimations.

4.1 Data Collection

Prior to developing the model, the most important step is to understand the characteristics of the Integrated Preliminary Cost Estimation System (IPCES); which in turn reflects the "type" of estimate required to successfully bid on a project. Therefore, diverse database resources pertaining to heavy equipment specifications (including scope of work related parameters) and cost estimations were extracted from the Caterpillar® Performance Handbook and R.S. Means for Heavy Construction Cost Data Handbook respectively, and successfully incorporated into a set of modules to conclude the data collection phase. The selection of the database resources mentioned-above was based upon their popular employment among the industry.

4.2 Heavy Equipment Selection

Heavy equipment selection for civil earthmoving operations is an essential component of IPCES; and therefore, operation analysis for selected types of equipment based on comprehensive owning and operating costs is performed for major activities of earthwork as illustrated in Fig.2. Following user's input of all necessary scope of work related parameters, the developed fleet optimization system (FOS) is designed to efficiently undertake operational analysis mathematical formulations. After that, output data will be stored and recalled latter for owning and operating costs computations which would be further analyzed for optimization as summarized in Fig. 2. The FOS user-friendly interface which is integrated and implemented as a sub-module within the developed IPCES is displayed in Fig. 3.

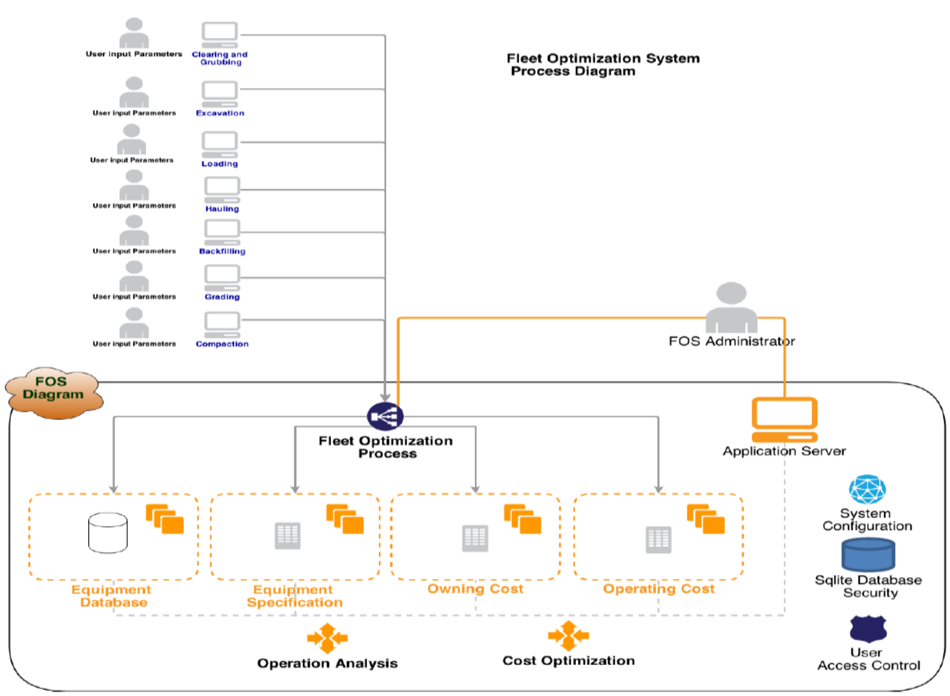


Figure 2: Fleet Optimization System Process Diagram

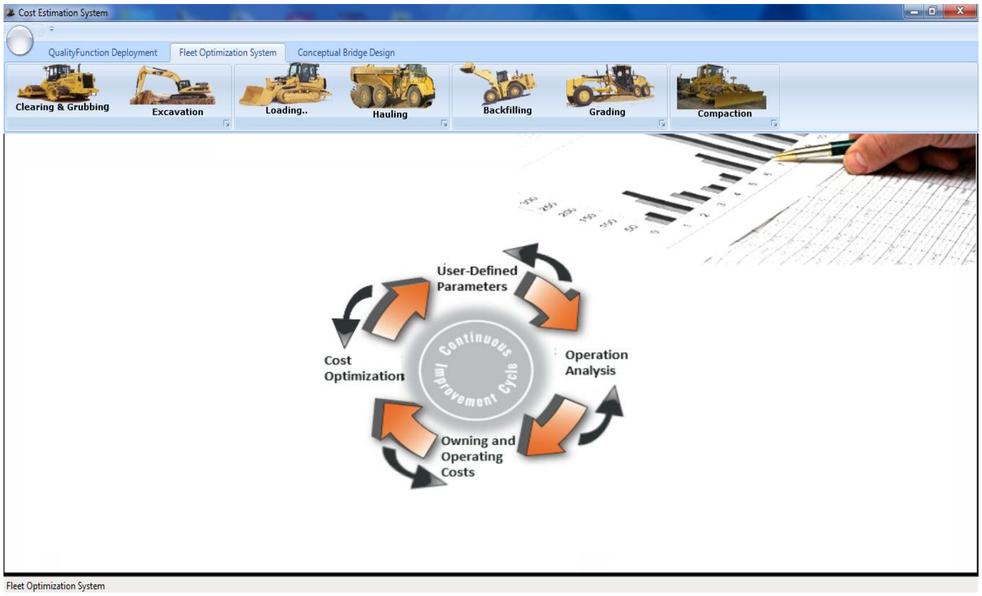


Figure 3: Fleet Optimization System Module Interface

4.3 Conceptual Bridge Design

Currently, subjectivity is the main factor that influences the bridge design at conceptual phases and substantially the corresponding type, system, and material. Otayek et al. (2012) had studied the integration of a decision-support system based on a proposed machine technique as part of artificial intelligence and neural networks (NN). In their study, the authors had recommended further and continuous development in decision-support systems in an attempt to assisting bridge designers in selection bridge type at conceptual phases. On the other hand, Malekly et al. (2010) had proposed a methodology of implementing QFD and TOPSIS for bridge selection. In this paper, Malekly's methodology was adopted and integrated in a novel-oriented approach, while overcoming interoperability issues among the disperse databases. Fig. 4 illustrates the flow diagram of the QFD and TOPSIS deployment technology for bridge type selection at conceptual stages.

Prior to estimating preliminary construction costs of a bridge project, it is necessary to determine the bridge design type. Conceptual bridge design is significantly influenced by the following seven main parameters: (a) technical; (b) functional; (c) safety; (d) construction; (e) economics; (f) aesthetics; and (g) material. A fuzzy-logic scoring system ranging from 1 to 10 was developed for assisting the user in predicting bridge beneficiaries' perception pursuant to bridge types. Bridge beneficiaries were identified from relevant studies and summarized as follows: (i) stakeholders/government; (ii) designers/engineers; (iii) contractors/builders; and (iv) public/residents.

Moreover, the following nine common bridge types were also identified and included into the database of the QFD and TOPSIS analyses: (a) beam bridges; (b) truss bridges; (c) cantilever bridges; (d) arch bridges; (e) tied-arch bridges; (f) suspension bridges; (g) cable-stayed bridges; (h) movable bridges; and (i) double-decked bridges. The developed QFD and TOPSIS analytical technologies utilized for bridge type selection is presented in Fig. 5.

Once the user is provided with a TOPSIS matrix for bridge type selection, geometrical parameters of the bridge model are inputted into the BrIM software, SAP2000, for preliminary load application and design analysis. Bridge design reports illustrating required bridge girder sections with corresponding load and moment resistance capacities will be readily displayed for preliminary cost estimation which shall be discussed in further details in the following paragraph.

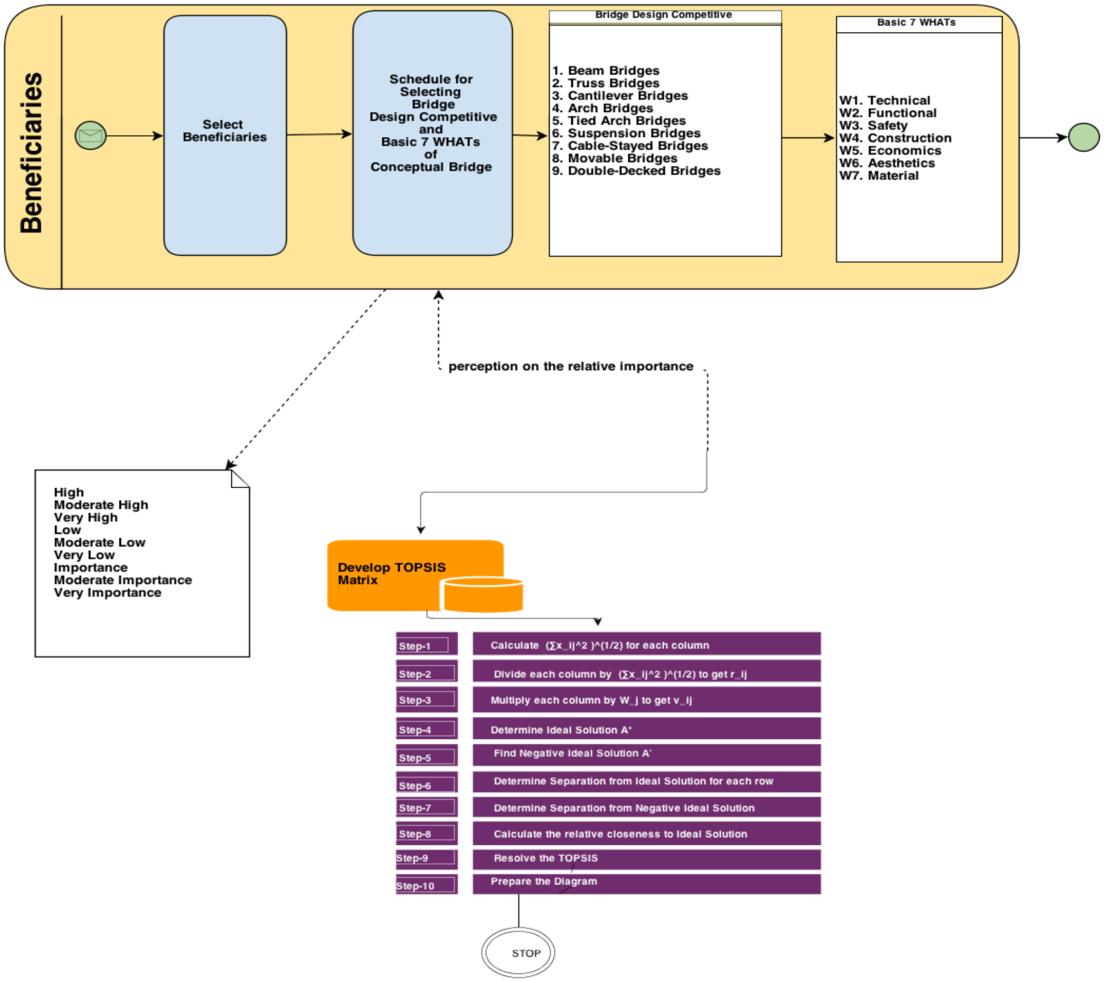


Figure 4: QFD and TOPSIS Process Flow Diagram

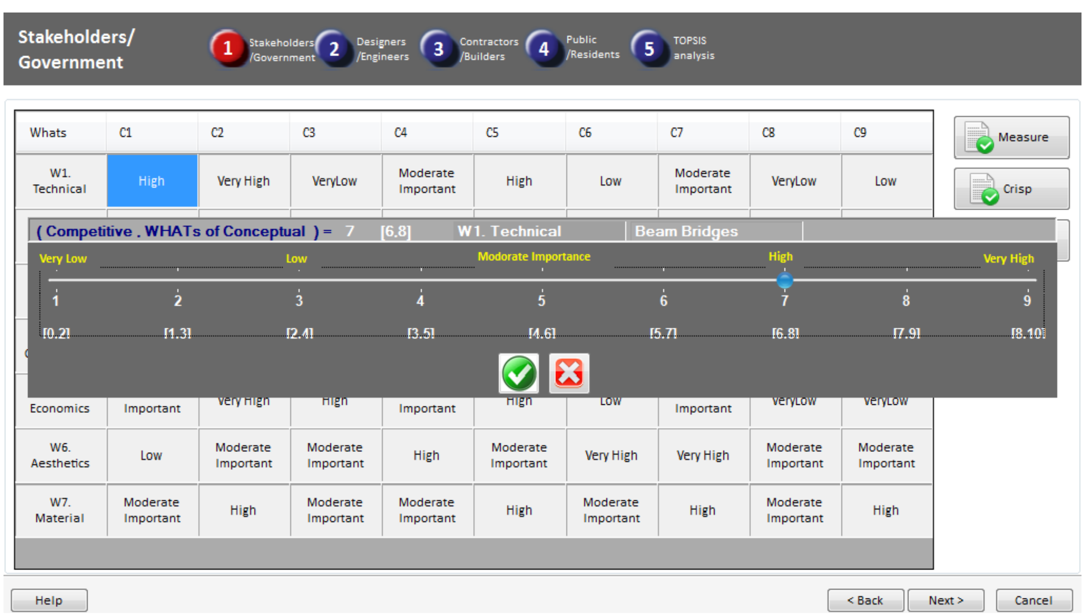


Figure 5: QFD and TOPSIS Analysis Module Interface

4.4 Preliminary Cost Estimation

Cost data pertaining to heavy equipment comprehensive owning and operating costs are necessary for optimizing selection. It is, after all, about minimizing the cost while taking into consideration factors and constraints that govern the selection process. The fleet optimization system proposed as part of the developed IPCES, comprises the following ownership costs: (a) delivery price, (b) interest, (c) taxes, (d) insurance and storage, (e) depreciation, and (f) original tires. On the other hand, corresponding operating costs include: (a) fuel, (b) service, (c) tires replacement, (d) emergency reserves, (e) wages, and (f) wear items. Caterpillar® Performance Handbook is used for extracting data pertaining to heavy equipment ownership and rental costs. Whereas, bridge construction unit costs are obtained from R.S. Means for Heavy Construction Cost Data Handbook.

Bridge construction rudiments were identified and organized as follows: (1) site overheads; (2) mobilization/demobilization; (3) temporary fencing; (4) environmental barriers; (5) site clearance; (6) dewatering; (7) temporary shoring; (8) earthmoving operations; (9) granular sub-base; (10) substructure, which includes diverse design alternatives; (11) substructure concrete material; (12) substructure reinforcing steel; (13) superstructure bearing material; (14) bridge girders ; which includes multiple design types; (15) concrete waterproofing system; (16) superstructure reinforcing steel; (17) posting-tensioning steel; (18) railings and barriers; (19) expansion joints; (20) retaining walls; (21) noise wall; (22) detour bridge; (23) road pavements; (24) curbs, footways, and paved areas; (25) traffic signs and road markings; (26) road lighting columns and brackets; (27) electrical work and communications; (28) drainage work; (29) landscape and ecology; and (30) testing and commissioning.

5. MODEL IMPLEMENTATION

The model is developed in an object-oriented programming (OOP) approach utilizing C# ‘C Sharp’ and implemented in a classical .NET framework. The main purpose of the model is to facilitate the interface between bridge design at conceptual phases, heavy equipment operational analyses, user-defined input, and cost estimating functions.

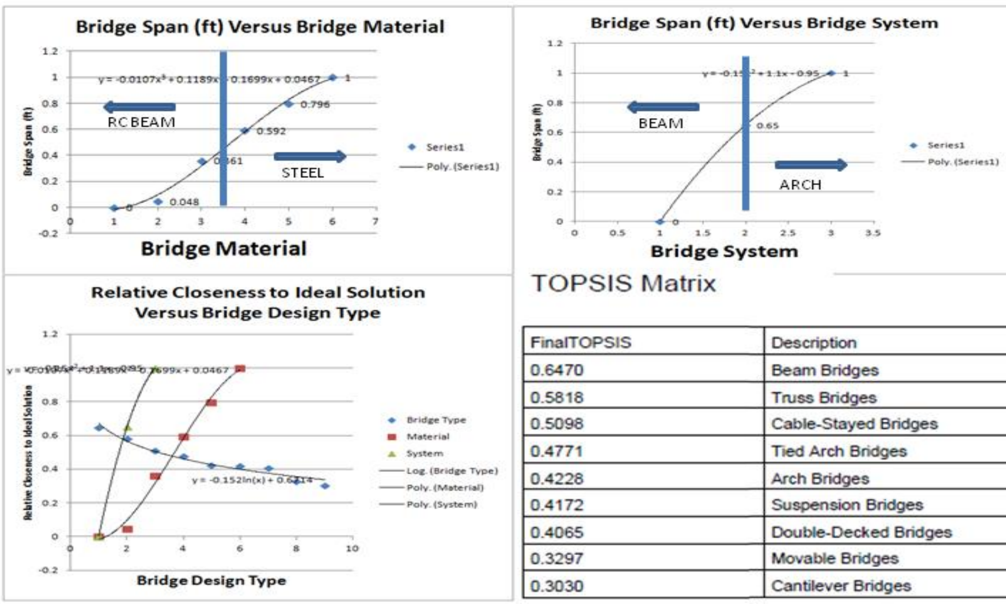
At first, the user would input bridge design survey results based on the developed fuzzy-logic scoring system for the parameters of the bridge types for all beneficiaries defined earlier into QFD and TOPSIS module as shown in Fig. 5. Afterwards, a beneficiary comparative matrix is established where parametric weights are assigned for TOPSIS analysis commencement. Afterwards, a set of bridge design parameters comprising of; (i) technical span; (ii) functional span; and (iii) foundation type are required as per the Bridge Design Handbook design recommendations. At this time, the user will be provided with a set of three curves that serve as guidelines for the recommended bridge type, system, and material for BrIM implementation. Moreover, logarithmic and polynomial functions for three set of results will also be developed in order to provide the user with a ‘virtual’ numerical measure of the nominated bridge design alternative relatively as shown in Fig. 6. Following QFD and TOPSIS, the user is guided to the next module where he/she is instructed to input relevant data pertaining to heavy earthmoving operations and fleet cost optimization. After that, equipment operation analyses complete with comprehensive owning and operating cost calculations will be undertaken followed by optimum fleet results. Towards the end, project cost items pertaining to the substructure and superstructure are extracted from the BrIM via an Electronic Data Interchange (EDI) interface and multiplied by their corresponding unit costs as illustrated in Fig. 7. Few cost items are required to be inputted by the user as they cannot be defined within the initial BrIM. It is important to note that BrIM output files were extracted for IPCES utilization via an EDI interface which is implemented for the first time in BrIM studies and found to foster system efficiency besides resolving database interoperability issues.

6. CASE EXAMPLE

To validate the workability of the developed model, a case project comprising a concrete box-girder bridge with a total span of 200 (feet) supported with a central interior bent at 100 (feet) was modeled in

SAP2000. The challenge underlying the model validation is to provide a preliminary cost estimation of the bridge profile necessary to execute the construction.

Prior to inputting data, a list of main parametric design assumptions were made as follows: (a) abutment = skewed at 15 degrees and supported at bottom girder only; (b) pre-stressing = 4 nos. 5 in^2 tendons with a 1,080 kips capacity each; (c) interior bent: 3 nos. 5 ft square columns; (d) deck = parabolic variation ranging from 5-10 ft in nominal depth; (e) pile cap = 3 nos. 13' x 13' x 4'; and (f) pile = 9 nos. 14" DIA steel pipe filled with reinforced concrete at each pile cap. It is important to note that the following list of assumptions was made based on normal job conditions. However, if geographical constraints were encountered, these factors may increase or decrease accordingly. For example, if the job terrain encountered is rough, substructure concrete and pile design factors will increase and subsequently significantly influencing overall project cost. These changes in factors will also influence heavy equipment production rate which in turn affects optimum fleet results.



FinalTOPSIS	Description
0.6470	Beam Bridges
0.5818	Truss Bridges
0.5098	Cable-Stayed Bridges
0.4771	Tied Arch Bridges
0.4228	Arch Bridges
0.4172	Suspension Bridges
0.4065	Double-Decked Bridges
0.3297	Movable Bridges
0.3030	Cantilever Bridges

Figure 6: Conceptual Bridge Design Curves and Final TOPSIS Matrix

Cost Estimation

Description	Unit	Cost
Site Overheads	%	$ 242199
Mobilization/Demobilization	%	$ 151375
Temporary Fencing	LF	$ 4540
Environmental Barriers	SF	$ 300
Site Clearance	LS	$ 12000
Dewatering	LS	$ 25000
Temporary Shoring	LS	$ 1000
Earthmoving Operations	LS	$ 150000
Granular Subbase	CY	$ 25000
Substructure		
Steel Piling	LF	$ 9112
Cofferdam Footing	SF	$ 111781
Substructure Concrete		
Concrete	CY	$ 58258
Shell Fill	CY	$ 1269
Reinforcing Steel	LB	$ 6416
Superstructure		
Bearing Material		
Capacity in Kips	EA	$ 53210
Bridge Girders		
Parapet Wall	FT	$ 13656
Cast-in-Place Superstructure Concrete	CY	$ 585594
Concrete Waterproofing System	SY	$ 360
Reinforcing Steel	LB	$ 42922
Post-tensioning Steel	LB	$ 6664
Railings and Barriers		
Traffic Barrier	LF	$ 11262
Pedestrian Railing	LF	$ 14588
Bicycle Railing	LF	$ 17660
Expansion Joints		
Strip Seal	LF	$ 172800
Road Pavements	SY	$ 16000
Curbs, Footways, & Paved Areas	LF	$ 6350
Traffic Signs & Road Markings	LS	$ 10000
Road Lighting Columns & Brackets	LS	$ 25000
Electrical Work and Communications	LS	$ 30000
Drainage Work	LS	$ 65000
Landscape and Ecology	LS	$ 25000
Testing & Commissioning	LS	$ 13000
SUB TOTAL		$ 1907319
Contingency (5%)		$ 95366
Overhead and Profit (10%)		$ 190732
TAXES	%	$ 285144
TOTAL COST		$ 2478561

Figure 7: Integrated Cost Estimation System (IPCES) Output Report

7. SUMMARY AND CONCLUSIONS

This paper had discussed the successful development of an integrated cost estimation model, IPCES, that assists stakeholders and contractors conceptually plan for bridge construction projects by integrating BrIM with equipment specification and cost data resources besides user-defined input. Comparative analyses of disperse bridge types was conducted utilizing QFD and TOPSIS systematic approaches to assist users in bridge type selection at conceptual design stages. Furthermore, operation analyses of different types of equipment were carried out to enhance IPCES capability in determining the productivity of heavy equipment and identifying an optimized fleet for heavy equipment selection. The actual accuracy of the model is highly dependent upon the technical and functional constraints as well as user-defined entries. The developed prototype was then validated via a case example defined in one of BrIM widely-used software technology, SAP2000, which contains a dedicated stand-alone bridge module. It was concluded that the model possess some limitations pursuant to complex and combined bridge sub- and super- structures designs. It is necessary to mention that the estimation model was developed as a tool that can be used to estimate preliminary costs for a particular bridge project. The proposed model may be utilized in bridge projects that involve a large volume of earthwork compiled with BrIM integration. This capability provides the model a great advantage over other cost estimation algorithms, prototypes, or models published earlier in literature. Also, results presented in this paper are anticipated to be of major significance to the bridge construction industry and would be a novel contribution to BrIM integrated project delivery approaches, bridge selection at conceptual stages, and cost estimation systems.

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