

**An Expert System Integrated with a Bridge Information Management System
(BrIMS), Cost Estimating, Deterioration Forecasting, and Linear Scheduling
at the Conceptual Design Stage**

Nizar Markiz

**Thesis submitted
in partial fulfillment of the requirements
for the Doctorate in Philosophy Degree in Civil Engineering**

**Department of Civil Engineering
Ottawa-Carleton Institute for Civil Engineering
University of Ottawa**

© Nizar Markiz, Ottawa, Canada, 2018

To My Family

ABSTRACT

An Expert System Integrated with a Bridge Information Management System (BrIMS), Cost Estimating, Deterioration Forecasting, and Linear Scheduling at the Conceptual Design Stage

Major bridge stakeholders such as federal and provincial transportation agencies are in dire need for objective knowledge-based systems that assist decision-makers in the selection of bridge type. Besides that, estimating bridge construction costs at the conceptual design stage is an increasing necessity for accurate budgeting and effective allocation of funding. Whilst multiple bridge management systems have already been developed; they still possess major drawbacks pertaining to interoperability and integration with complex time and cost optimization-related problem solving. In another perspective, infrastructure restoration has been backlogged with multifaceted factors that have captured the attention of municipal and federal authorities. Several successful integrations of bridge information management systems (BrIMS) with decision support systems and computer-aided engineering design solutions have significantly leveraged downstream processes of bridge maintenance operations and inspired many researchers. The subjective nature of evaluating bridge conditions and deteriorations is the main factor that influences bridge maintenance, repair, and replacement decisions. In order to overcome this shortcoming, the objectives of this study are intended to demonstrate the viability of integrating a decision support system with a stochastic gamma deterioration model utilizing a probabilistic fuzzy logic strategic approach at the conceptual design stage.

In summary, this study presents a systematic multi-objective knowledge-based approach for selecting bridge type, forecasting elemental deteriorations, linear scheduling, and estimating construction costs at the conceptual design stage. The proposed methodology comprises a framework to deploy a system that automatically generates conceptual cost estimates by integrating objective functions with bridge information modeling (BrIM) through an external data interchange protocol in synchrony with interoperability standards. Deployment of the developed system shall minimize the degree of subjectivity involved while decision makings pertaining to bridge projects and assists designers and cost engineers obtain results in an integrated quantitative, qualitative, and systematic manner. The successful deployment of the expert system signifies a technological achievement of novelty pertaining to the integration of bridge information modeling (BrIM) concept with probabilistic fuzzy logic strategic approaches at the conceptual design stage of bridges.

Acknowledgement

I would like to express my gratitude to my supervisor, Dr. Ahmad Jrade, whose expertise, understanding, and patience added considerably to my graduate experience. I appreciate his vast knowledge and skill in many areas and his assistance in writing reports.

I would also like to thank my thesis committee members, Dr. Amin Hammad, Dr. Elena Dragomirescu, Dr. Hassan Aoude, and Dr. Linda Newton, for allowing me to defend my thesis, and for their positive feedback, comments, and suggestions.

Many thanks are extended to my friends; Engr. Atef Sahloul and Engr. Anil Ojha for their continuous efforts and diligent guidance on computer programming to enhance my coding skills.

Lastly, I would like to express my sincere appreciation from the bottom of my heart to my family for the support they provided me throughout the course of my Ph.D. degree and in particular, I must acknowledge my mother, Afaf Ghader; father, Nazih Markiz; wife, Farah Madi; brothers, Mohammad and Nasser; sisters, Nasrine, Najwan, and Nadine without whose sacrifice, encouragement and assistance, I would not have successfully completed this thesis.

TABLE OF CONTENTS

LIST OF FIGURES.....	xii
LIST OF TABLES.....	xvi
LIST OF SYMBOLS.....	xvii
LIST OF ACRONYMS.....	xxi

CHAPTER 1

INTRODUCTION.....	1
1.1 Overview.....	1
1.2 Background of Study.....	1
1.3 Problem Statement.....	2
1.4 Research Objectives.....	3
1.5 Development Methodology.....	5
1.5.1 Review of Literature.....	6
1.5.2 Professional Feedback.....	7
1.6 Thesis Organization.....	7

CHAPTER 2

BrIM, COST ESTIMATION, AND DECISION SUPPORT.....	9
2.1 Introduction.....	9
2.2 Computer-Integrated Construction (CIC).....	10
2.2.1 CIC Objectives	11
2.2.2 CIC Prerequisites.....	12
2.3 Bridge Information Modeling (BrIM).....	12
2.3.1 Purpose of BrIM.....	13
2.3.2 Benefits of BrIM.....	13
2.4 3D CAD Modeling.....	14
2.5 Summary.....	15
2.6 Compensation Management System.....	16
2.7 Cost Estimation.....	17
2.7.1 Estimation Rationale.....	18
2.7.2 Cost Estimation Types.....	19
2.7.3 Estimate Accuracy.....	19
2.7.4 Conceptual Estimates.....	20
2.7.4.1 Estimate Characteristics.....	22

	2.7.4.2	Estimate Preparation.....	22
	2.7.4.3	Estimate Work Breakdown Structure(WBS).....	23
	2.7.4.4	Rationale.....	24
	2.7.5	Parametric Estimates.....	25
	2.7.6	Preliminary Estimates.....	26
2.8		Heavy Equipment Selection.....	27
	2.8.1	Technological Advancement of Equipment.....	28
	2.8.2	Previous Research Work.....	29
	2.8.3	Equipment Economics.....	32
	2.8.4	Ownership Costs.....	34
	2.8.5	Depreciation Calculation Methods.....	34
	2.8.6	Operating Costs.....	35
	2.8.6.1	Caterpillar® Methods to Calculate Ownership and Operating Costs.....	35
	2.8.7	Equipment Classification.....	35
	2.8.7.1	Factors Affecting Equipment Selection.....	36
	2.8.7.2	Methods in Optimizing Equipment Productivity.....	36
	2.8.7.3	Forces Affecting Motion of Equipment.....	37
	2.8.7.4	Effects of Altitude.....	37
2.9		Summary.....	38
2.10		Decision Support System.....	39
2.11		Fuzzy Logic Theory.....	41
2.12		Artificial Intelligence.....	42
	2.12.1	Intelligent Computational Agents.....	43
	2.12.2	Simulated Annealing.....	44
2.13		Linear Scheduling	46
	2.13.1	Introduction.....	46
	2.13.2	Related Research Work.....	46
	2.13.3	Constraint-Based Simulation.....	48
2.14		Summary.....	49

CHAPTER 3

		RESEARCH METHODOLOGY AND DEVELOPMENT.....	50
3.1		Introduction.....	50
3.2		Data Collection.....	51
3.3		System Architecture and Components.....	52
3.4		System Integration	54
3.5		System Modules.....	55
	3.5.1	Module 1: Conceptual Bridge Design.....	55
	3.5.2	Module 2: Fleet Selection.....	60
	3.5.3	Module 3: Preliminary Cost Estimation.....	65
	3.5.4	Module 4: Deterioration Forecast	67
	3.5.5	Module 5: Bridge Line of Balance.....	71

3.6	System Databases.....	74
3.6.1	Data Collection and Conceptual Modeling.....	75
3.6.2	Data Categorization and Mapping.....	77
3.6.3	Cost Estimation.....	80
3.7	System Framework.....	81
3.7.1	Data Collection.....	81
3.7.1.1	Equipment Selection Factors.....	82
3.7.1.2	Equipment Operational Analysis.....	83
3.7.1.3	Equipment Specifications.....	84
3.7.1.4	Cost Data.....	86
3.8	Fundamentals of Earthmoving.....	87
3.9	Nature of Earthwork Material.....	87
3.9.1	Forces Affecting Motion of Equipment.....	88
3.9.2	Equipment Power.....	88
3.10	Estimating Equipment Productivity.....	88
3.10.1	Estimating Excavator Productivity.....	89
3.10.2	Estimating Dozers Productivity.....	90
3.10.3	Estimating Scrapers Productivity.....	91
3.10.4	Estimating Loaders Productivity.....	92
3.10.5	Estimating Haulers Productivity.....	93
3.10.6	Estimating Graders Productivity.....	95
3.10.7	Estimating Compactors Productivity.....	95
3.11	Cost and Time Analysis.....	96
3.12	Near-Optimum System.....	96
3.12.1	Data Collection.....	97
3.12.2	Cost Optimization Process.....	98
3.13	Integration Platform.....	99
3.14	Interoperability.....	100
3.15	Summary.....	101

CHAPTER 4

TECHNICAL PAPER I.....	103
(Published in International Journal of Sustainable Built Environment, ELSEVIER)	

Integrating a Fuzzy Logic Decision Support System with Bridge Information Modelling and Cost Estimation at Conceptual Design Stage of Concrete Box-girder Bridges.....	103
--	-----

4.1	Brief Background.....	104
4.2	Problem Statement.....	104
4.3	Motivation and Objectives.....	105
4.4	Review of the Literature.....	106
4.5	Model Overview.....	110
4.6	Research Methodology.....	111
4.6.1	Data Collection.....	113

4.6.2	Fuzzy Logic Decision Support.....	114
4.6.3	TOPSIS.....	119
4.6.4	Conceptual Bridge Design.....	123
4.6.5	Preliminary Cost Estimation.....	124
4.7	Integration Platform.....	125
4.8	Interoperability.....	126
4.9	Model Development.....	127
4.10	Model Validation.....	130
4.11	Summary, Conclusions, and Recommendations.....	142
4.12	References.....	143

CHAPTER 5

TECHNICAL PAPER II.....	146
(Published in Journal of Construction Engineering, HINDAWI)	

An Integrated Expert System for Linear Scheduling of Heavy Earthmoving Operations	146
---	-----

5.1	Introduction.....	147
5.2	Literature Review.....	148
5.3	Methodology and Development.....	151
5.3.1	Earthmoving Operations Analysis Phase.....	153
5.3.1.1	Estimating Activity Duration.....	157
5.3.1.2	Normal Distribution Fitting.....	158
5.3.1.3	Quality of Fitting.....	159
5.3.2	Linear Scheduling Phase.....	160
5.4	Cost Minimization Phase.....	162
5.4.1	Uniform Dependence Algorithms.....	164
5.4.2	Linear Schedule Minimization Process.....	166
5.4.3	Simulated Annealing.....	166
5.4.3.1	Constraint-Based Simulation.....	167
5.4.3.2	Metropolis Algorithm.....	168
5.4.3.3	Neighborhood Sequencing.....	169
5.4.3.4	Rule of Acceptance.....	169
5.4.4	Global Duration Minimization.....	172
5.5	System Implementation.....	173
5.5.1	Estimation of k-value.....	175
5.5.2	Fleet Selection System.....	176
5.5.3	Earthmoving Linear Schedule System.....	178
5.6	System Validation.....	179
5.7	Summary and Conclusions.....	187
5.8	References.....	189

CHAPTER 6

TECHNICAL PAPER III.....	192
(Addressed Comments and Resubmitted to Journal of Information Technology in Construction, ITCon)	
Integrating Fuzzy-Logic Decision Support with a Bridge Information Management System (BrIMS) at the Conceptual Design Stage of Bridge Design.....	192
6.1 Introduction.....	193
6.2 Problem Definition.....	194
6.3 Research Objectives.....	195
6.4 Literature Review.....	196
6.5 Methodology and Development.....	201
6.6 Fuzzy-Logic Decision Support System.....	203
6.6.1 Quality Functions.....	205
6.6.2 Techniques for Order of Preference by Similarity to Ideal Solution (TOPSIS).....	214
6.6.3 Gamma Deterioration Model	217
6.6.4 Determination of Deterioration Function.....	219
6.6.4.1 Estimation of Deterioration Parameters.....	220
6.7 System Implementation	221
6.7.1 Quality of Fitting.....	222
6.7.1.1 Probabilistic Matrix Factorization.....	224
6.7.1.2 Error Minimization.....	225
6.7.1.3 Regularization.....	227
6.8 System Validation.....	228
6.9 Discussion of Results.....	241
6.10 Summary and Conclusions.....	242
6.11 References.....	244

CHAPTER 7

TECHNICAL PAPER IV.....	248
(Submitted to Journal of Construction Engineering, HINDAWI)	
Integrating an Expert System with BrIMS, Cost Estimation, and Linear Scheduling at the Conceptual Design Stage of Bridge Projects.....	248
7.1 Brief Background.....	249
7.2 Problem Definition.....	250
7.3 Research Objectives.....	250
7.4 Literature Review	252
7.5 Methodology and Development.....	256
7.5.1 System Architecture.....	257
7.5.2 System Integration.....	258
7.5.3 System Module.....	262

7.5.3.1	Module 1: Conceptual Bridge Design.....	262
7.5.3.2	Module 2: Fleet Selection.....	263
7.5.3.3	Module 3: Preliminary Cost Estimation.....	264
7.5.3.5	Module 4: Deterioration Forecast.....	264
7.5.3.6	Module 5: Bridge Line of Balance.....	265
7.6	Normalization of Multi – Attribute Decision Making Approach (TOPSIS).....	265
7.7	Decision-Support System Integrated Platform.....	271
7.8	System Implementation.....	274
7.8.1	Linear Scheduling Optimization.....	276
7.8.2	Simulated Annealing System Process.....	277
7.8.3	Global Optimization.....	277
7.9	System Validation.....	278
7.10	Discussion of Results.....	293
7.11	Summary and Conclusions.....	295
7.12	References.....	297

CHAPTER 8

CONCLUSIONS, LIMITATIONS, CONTRIBUTIONS, AND FUTURE WORK.....		301
8.1	Conclusions.....	301
8.2	Limitations of the Developed System.....	303
8.3	Contributions.....	305
8.4	Future Work.....	306

CHAPTER 9

REFERENCES.....	307
APPENDIXES.....	317
Appendix I.....	318
Bridge Experts' Interview Questionnaire.....	318
Appendix II.....	328
Equipment Specifications and Mathematical Formulations.....	328
Appendix III.....	350
XML Index Algorithm for Converting System Databases into Digital Table Formats.....	350
Appendix IV.....	353
Snapshot of Developed Plug-ins.....	353
Appendix V.....	354
Hard-Code of Developed Plug-ins.....	354

LIST OF FIGURES

Figure 2.1	Bridge Information Modeling Features.....	13
Figure 2.2	Diverse Techniques and Models for Equipment Selection.....	29
Figure 2.3	Equipment Economic Analysis.....	33
Figure 3.1	Research Methodology Process.....	51
Figure 3.2	System Architecture.....	53
Figure 3.3	System Components.....	54
Figure 3.4	Conceptual Bridge Design Module Process Flowchart.....	59
Figure 3.5	Fleet Selection Module's Components.....	61
Figure 3.6	Fleet Selection Module Process Flowchart.....	63
Figure 3.7	Preliminary Cost Estimation Module Process Flowchart.....	66
Figure 3.8	Deterioration Forecast Module Process Flowchart	69
Figure 3.9	Bridge Line of Balance Module Process Flowchart	73
Figure 3.10	Entity Relationship Diagram for Preliminary Cost Estimation Module....	75
Figure 3.11	Preliminary Cost Estimation Modules Data Model Mapping.....	77
Figure 3.12	Physical Relationship of the Preliminary Cost Estimation Module.....	79
	Database	
Figure 3.13	Conceptual Operational Analysis System.....	83
Figure 3.14	Methodology for Estimating Equipment Productivity.....	89
Figure 4.1	Integrated Preliminary Cost Estimation System (IPCES) Process.....	111
Figure 4.2	Model Development Flowchart.....	112
Figure 4.3	Fuzzy-Logic Scoring System.....	115
Figure 4.4	Quality Function Deployment Chart.....	116
Figure 4.5	Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) Process Flow.....	120
Figure 4.6	IPCES Model Development Process.....	128
Figure 4.7	IPCES Quality Function Deployment Module Interface.....	129
Figure 4.8	IPCES Bridge Conceptual Design Curves and Final TOPSIS Matrix.....	130
Figure 4.9	Case Project Conceptual Design Bridge Information Model Parameters..	131

Figure 4.10	Stakeholders/Government Assessment of WHATs Criteria on Bridge Competitors in Measure Form.....	132
Figure 4.11	Stakeholders/Government Assessment of WHATs Criteria on Bridge Competitors in Crisp Form.....	133
Figure 4.12	Stakeholders/Government Assessment of WHATs Criteria on Bridge Competitors in Fuzzy Form.....	133
Figure 4.13	Stakeholders/Government Relative Importance Perception on WHATs Criteria	134
Figure 4.14	Beneficiary Competitive Matrix Analysis.....	134
Figure 4.15	IPCES Bridge Substructure and Superstructure Material and Profile Recommendations.....	136
Figure 4.16	IPCES Recommendation of Bridge Material Based on Bridge Span Selection.....	137
Figure 4.17	IPCES Recommendation of Bridge System Based on Bridge Span Selection	137
Figure 4.18	IPCES Recommendations of Bridge Design Type, Material, and System.....	138
Figure 4.19	IPCES Preliminary Construction Costs Output Report.....	139
Figure 5.1	Proposed System Architecture.....	152
Figure 5.2	Linear Schedule System Overview.....	161
Figure 5.3	Cost Minimization Process Flow.....	163
Figure 5.4	Linear Programming Process Flowchart.....	164
Figure 5.5	Simulated Annealing Process.....	172
Figure 5.6	Fleet Selection System Gateway.....	177
Figure 5.7	Clearing and Grubbing Operation Input Form I.....	177
Figure 5.8	Selected Earthmoving Equipment Output Report.....	181
Figure 5.9	Modified Number of Selected Equipment and Corresponding Productivity.....	182
Figure 5.10	Linear Schedule Input Form I.....	182
Figure 5.11	Global Time Minimization Form.....	184
Figure 5.12	Simulated Annealing Form.....	184

Figure 5.13	Near-Optimum Linear Schedule Form	185
Figure 6.1	Proposed System Architecture.....	202
Figure 6.2	Fuzzy-logic Scoring System.....	205
Figure 6.3	Quality Function Deployment Process Flow	206
Figure 6.4	TOPSIS Process Flow.....	215
Figure 6.5	Conceptual Bridge Design Information Model.....	229
Figure 6.6	Deterioration System Gateway Module	230
Figure 6.7	Bridge User Importance Rating on Bridge Components.....	231
Figure 6.8	Relative Importance Rating on Bridge Components.....	232
Figure 6.9	Bridge User Competitive Matrix on Bridge Components.....	232
Figure 6.10	Improvement Goals for Bridge Components.....	233
Figure 6.11	TOPSIS Analysis Module.....	233
Figure 6.12	Final Ranking of Bridge Components.....	234
Figure 6.13	Bridge User Importance Rating on MR&R Alternatives	235
Figure 6.14	Bridge Components Competitive Matrix on MR&R Alternatives.....	236
Figure 6.15	Final Ranking of Bridge MR&R Alternatives	237
Figure 6.16	Mean Resistance Deterioration Module	239
Figure 6.17	‘Approach Slab’ Regression Analysis at 15% Deterioration.....	240
Figure 7.1	Proposed System Architecture.....	258
Figure 7.2	Flowchart of Integrated Process.....	259
Figure 7.3	TOPSIS Main Criteria	266
Figure 7.4	QFD/TOPSIS Data Process flow Diagram.....	271
Figure 7.5	Fuzzy-logic Scoring System.....	272
Figure 7.6	Quality Function Deployment Flowchart.....	273
Figure 7.7	Bridge User Assessment on WHAT’S Criteria.....	279
Figure 7.8	WHAT’S Criteria Weights.....	279
Figure 7.9	Conceptual Bridge Design Recommendation.....	281
Figure 7.10	Externally Created Plug-in Tools Embedded in BrIM.....	282
Figure 7.11	Conceptual Bridge Design Information Model.....	283
Figure 7.12	Fleet Selection Module Gateway and Input Forms.....	284

Figure 7.13	Modified Number of Selected Equipment and Corresponding Productivity.....	285
Figure 7.14	Cost Minimization of Ownership and Operating Cost Factors Module....	286
Figure 7.15	Selected Fleet Total Owning and Operation Costs.....	287
Figure 7.16a	Preliminary Cost Estimation Sub-Modules Input Form I.....	288
Figure 7.16b	Preliminary Cost Estimation Sub-Modules Input Form II.....	288
Figure 7.17	Bridge Preliminary Cost Estimation Output Report.....	290
Figure 7.18	Bridge Components Final Ranking.....	291
Figure 7.19	Bridge Line of Balance.....	292

LIST OF TABLES

Table 3.1	SQLite Average Iteration Response Times for Equipment Operation Analysis.....	84
Table 3.2	Types of Selected Equipment.....	85
Table 4.1	Bridge Material Type Based on Technical Span.....	122
Table 4.2	Reinforced Concrete Bridge System Based on Functional Span.....	123
Table 4.3	Reinforced Concrete Bridge Foundation Material Based on Geotechnical recommendations.....	123
Table 4.4	Cost Estimation Output Report Categories and Elements.....	125
Table 4.5	Comparison of Box-Girder Bridge Elemental Costs (2012 Values).....	141
Table 5.1	Scope of Earthwork Fill (BCY) at Three Different Operational Stages.....	180
Table 5.2	Comparison of Expected Duration (Days) Results per Earthmoving Activity	186
Table 6.1	Maintenance, Repair, and Replacement Decisions Versus Extent of Deterioration (%).....	210
Table 6.2	Approach Slab Mean Deterioration Resistance Data at Diverse Years.....	238
Table 6.3	Comparison of Forecasted Bridge Maintenance Deterioration Results...	242
Table 7.1	Fuzzy Logic Scoring System WHATs Criteria and Sub-Criteria	274
Table 7.2	Comparison of Estimated Bridge Cost (CAD) and Duration (Days) Results.....	294

LIST OF SYMBOLS

Greek Symbols

ϕ	Normalization factor
μ	Mean
σ	Standard deviation
α	Cooling parameter
ε	Value at which an algorithm is terminated

Latin Symbols

A	Minimum unit cost of previous project
A^*	Positive ideal solution
A'	Negative ideal solution
a	Scaling factor
B	Average unit cost of previous project
BV	Book value
C	Maximum unit cost of previous project; Cycle time
C_i^*	Relative closeness to positive ideal solution
C_r	Coefficient of traction
D	Depreciation value; Delay time; Total out-of-pocket hourly cost
D_m	Depreciation value at a specific year
d	Travel distance
E	Measure of entropy by a discrete probability distribution for WHATs criteria; Expected duration time; Operational efficiency

EU	Equipment unit cost
e	Gear efficiency
e_m	Weight of a WHATs criterion
F	Salvage value
F_i	Fixed time
Δf	Change in probability functions values
g_{mk}	Relative importance perception on a criterion in crisp form
$\tilde{g}_{mk}$	Relative importance perception on a criterion in fuzzy form
HP	Horsepower of the engine
i	Number of bridge competitors; Integer; Number of equipment
J	Set of beneficial attributes or criteria
J'	Set of negative ideal attributes or criteria
j	Summation counting variable
k	Bridge beneficiary; Hourly cost per unit of capacity
L	Loading time; Thickness of the lift to be compacted
L_p	Loader production rate
M	Amount to be depreciated; Most likely duration time
m	Specific year
N	Number of years the equipment has been owned; Number of passes required
n	Number of hauler units
n_s	Initial number of simulations
O	Optimistic duration time

OF	Operating factor
RP	Maximum rim-pull
RR	Rolling resistance
P	Initial price; Production rate of loading facility; Pessimistic duration time; P is the number of passes required
p_L	Probability distribution
P_t	Probability that one or more haul units is available
P_{acti}	Actual productivity rate at the i^{th} location
P_{sug}	Suggested productivity rate at the i^{th} location
p_{mk}	Probability distribution of WHATs criteria assessment on bridge competitors
r	Ratio of arrival rate to loading rate
r_{ij}	Normalized scoring value of bridge beneficiaries on bridge competitors' criteria
S	Segment slope; Average compactor speed
S_{opt}	Optimum size of hauling unit
S_i^*	Separation from positive ideal solution
S_i'	Separation from negative ideal solution
T	Travel time; Cycle time except loading time
T_C	Truck capacity
TF_{max}	Maximum tractive force
t_o	Initial temperature

t_i	Current temperature
Δt	Temperature decreasing rate
UC	Forecast unit cost
V	Speed; Variable time; Average grading speed
V_B	Bank volume
V_H	Travel speed while loaded
V_L	Loose volume
V_R	Travel speed while empty
v_j^*	Weighted positive scoring values of beneficiaries on bridge competitors' criteria
v_j'	Weighted negative scoring values of beneficiaries on bridge competitors' criteria
v_{ij}	Weighted normalized element of TOPSIS matrix
W	Weight on driving wheels or tracks; Effective grading width; Effective compaction width
W_E	Weight empty
W_F	Weight loaded
W_m	WHATs criterion
w_i	WHATs criterion weight value
X	Bridge beneficiaries' comparison matrix; Degree of Acceleration
X	Random variable
X_{ij}	"m x n" matrix with 'm' bridge competitors and 'n' criteria
x_m	Total of bridge beneficiary assessment of all bridge competitors on each of the WHATs criteria
x_{mk}	Bridge beneficiary assessment on a WHATs criterion
x_{mlk}	Bridge beneficiary assessment of a bridge competitor on a WHATs criterion

LIST OF ACRONYMS

AACE	American association of cost estimation
AI	Artificial intelligence
AIT	Artificial intelligence technique
API	Application programming interface
BCY	Bank cubic yard
BEADS	Bridge expert analysis decision support
BIM	Building information modelling
BrIM	Bridge information modelling
BrIMS	Bridge information management system
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CCY	Compacted cubic yard
CIC	Computer-integrated construction
CM@R	Construction manager at risk
CMT	Concrete maturity testing
CU-AL	Completed unit algorithm
DBB	Design-bid-build
DC	Direct cost
DLL	Dynamic link library
ER	Entity relationship
ERD	Entity relationship diagram
FOS	Fleet optimization system
GMP	Guaranteed maximum price

GPS	Global positioning system
ICL	Incentive compensation layer
IDEA	Innovations deserving exploratory analysis
IFC	Industry foundation classes
IFOA	Integrated form of agreement
IPCES	Integrated preliminary cost estimation system
IPD	Integrated project delivery
IPT	Integrated project team
IRS	Internal revenue service
LEED	Leadership in energy and environmental design
LCY	Loose cubic yard
MACRS	Modified accelerated cost recovery system
MEP	Mechanical, electrical, and plumbing
MR&R	Maintenance, repair, and replacement
NIST	National institute of standards and technology
NN	Neural network
OBMS	Ontario bridge management system
OH	Overhead
OOP	Object-oriented program
PMI	Project management institute
QFD	Quality function deployment
RDBMS	Relational database management system
SIMoFIT	Simulation of outfitting processes
STFN	Symmetrical triangular fuzzy logic number
SQS-AL	Sequence step algorithm

TOPSIS	Technique of preference by similarity to ideal solution
VBA	Visual basic for applications
WBS	Work breakdown structure
XML	Extensible Mark-up Language

CHAPTER 1

INTRODUCTION

1.1 Overview

Over past decade, capital investment in North American infrastructure has been enormous and has contributed towards the success of the economy. Infrastructure asset management has become the main focus of transportation authorities through a systematic approach that emphasizes operations of an infrastructure facility. Highway networks are a major infrastructure system, most crucially major bridges and motorways. It is quite important to highlight that proper handling of highway networks plays a major role in enhancing the effectiveness and functionality of a bridge network. Furthermore, strategies which aim to sustain these infrastructure assets over the long run lead to better bridge management. In addition, continuous advancements in bridge information management technologies and in the construction industry have evolved bridge management dramatically. More recently, federal and municipal transportation authorities have recognized the need for a bridge management system that can assist decision makers at the conceptual design stage of a bridge. Nowadays, bridge stakeholders and decision makers forecast the feasibility of a bridge based on the conceptual cost estimate. It is this estimate that is used to determine if the project can proceed to the next stage, i.e. placed in the capital programs. Hence, developing bridge cost estimates at the conceptual design stage is a crucial project milestone that decision makers rely upon for approving the construction of a bridge.

1.2 Background of Study

Nowadays, most bridge stakeholders forecast the feasibility of a bridge project strictly based on life cycle analyses and readily-available estimation tools. Besides that, diverse methods

and models have been developed to assist stakeholders optimize equipment selection for different types of bridge earthmoving operations. On the other hand, linear scheduling has been utilized in numerous projects as an alternative tool for scheduling phased repetitive operations during construction and operational stages. Also, complex expert systems have been developed to assist stakeholders select elemental treatment scenarios pertaining to MR&R based on condition assessment approaches during operational stage. In addition, bridge information technologies have been developed to assist design engineers in detecting linear scheduling clashes and fostering operational efficiency during the construction phase. Extending published research that combines bridge information management system (BrIMS) with cost estimation, this study introduces the idea of a decision support system framework for diverse bridge types at the conceptual design stage. The resulting system produces competitive priority ratings that minimize subjectivity in bridge life cycle cost estimation.

Most bridge stakeholders are reluctant to pay for preventive maintenance, which appears to be of no benefit or which bridge asset managers have found to be unsuccessful in preventing a bridge structure from deteriorating.

1.3 Problem Statements

In the past, several attempts have been made to develop computational tools for supporting various aspects of bridge design; however, these aspects were analyzed independently due to the unavailability of resources. Presently, few industries have incorporated integrated design with industrial processes, along with introducing “broadly-accepted” interoperability standards. Although the deployment of BrIMS has reduced error-prone data duplication, many engineers and researchers are still unaware of its benefits to estimate the cost of bridge projects at the conceptual design stage. For example, incorporating a fuzzy logic decision support system for bridge type selection assists decision makers in determining the most

economical bridge type. Based on the afore-mentioned, the following list summarizes problem statements identified from current practice:

Majority of cost estimation tools do not consider a bridge project as a task that needs to be completed within critical time and budget constraints.

1. Lack of comprehensive and economical numerical analyses of heavy earthmoving operations based on equipment performance parameters which significantly impacts productivity rates and optimum scheduling at the conceptual design stage.
2. Most of linear scheduling techniques developed possess a major shortfall in determining near-optimum bridge linear schedule including heavy earthmoving operations at the conceptual design stage.
3. Reluctance to invest in preventive maintenance which resulted in repair costs that exceed annual or semi-annual maintenance costs during operational stage.
4. Existing expert systems do not incorporate the influence of the advancements in CIC computational tools and applications to bridge selection at the conceptual design stage.

In order to overcome these afore-mentioned shortcomings, the application of BrIMS at the conceptual design stage enables bridge stakeholders to estimate bridge costs, forecast linear schedules, and predict elemental deteriorations at the conceptual design stage.

1.4 Research Objectives

As part of defining research scope, it is understood that integrating a fuzzy logic decision support system with BrIM and cost estimation for bridges is possible only if its objectives are kept simple, focused, and organized. Therefore, BrIM processes have been researched, recalled, and analyzed. According to Bentley bridge solutions (Peters, 2009), the eight processes of BrIM are: (1) bridge type selection; (2) 3D CAD model; (3) technical analysis;

(4) planning for construction; (5) production; (6) phases of construction; (7) maintenance; and (8) remediation.

Based on the afore-mentioned, the main objective of this study is to develop a systematic multi-objective fuzzy logic decision support system using complex quality functions integrated with cost estimating, deterioration forecasting, and linear scheduling at the conceptual design stage in an attempt to improve the effectiveness of bridge information management systems (BrIMS) at the conceptual design stage. In addition, research sub-objectives to supplement the scope and main objective have been established and summarized below:

- Sub-Objective I

Build a decision support system to assist project stakeholders in their selection of bridge design and type at the conceptual design stage.

- Sub-Objective II

Establish an efficient rule-based expert system that considers comprehensive owning and operating costs and numerical analyses of heavy equipment earthmoving operations.

- Sub-Objective III

Develop a cost estimation engine to forecast total bridge costs at the conceptual design stage including pre-bridge and post-bridge construction heavy equipment costs.

- Sub-Objective IV

Design a fully automated and integrated decision support system with gamma deterioration shock models to predict bridge deteriorations at the conceptual design stage.

- Sub-Objective V

Generate a near-optimum bridge linear schedule including heavy earthmoving operations based on a simulated annealing approach at the conceptual design stage.

Hence, this study presents a methodology for integrating BrIMS, comprising a fuzzy logic decision support system using quality functions and a multi-criteria decision-making approach, with fleet selection, cost estimating, and deterioration forecasting, and linear scheduling at the conceptual design stage. The study focuses on the methodology followed while considering interoperability standards and presents an integrated system foundation for future development to advanced design stages.

1.5 Development Methodology

In this research, the following processes; i) bridge type selection; ii) 3D CAD model; iii) technical analysis; and iv) maintenance and remediation are selected for the development and integration of cost estimation at the conceptual design stage.. Since the expert system comprised of bridge information modeling integrated with cost estimation and gamma shock models at the conceptual design stage, the development methodology includes the four main steps as follows:

1. Developing integrated databases for the selection of bridge type, bridge information modelling (BrIM), and preliminary cost estimation based on UNIFORMAT II - Standard Classification of Bridge Elements.
2. Creating and designing a BrIM model that will have built-in customization plug-ins that is capable of undertaking numerical sensitivity analyses in order to suit bridge stakeholders' requirements.

3. Designing and implementing an object-oriented integrated system that is capable of predicting bridge deteriorations by deploying stochastic gamma shock modelling and subsequently prioritizing MR&R solutions.
4. Developing a line of balance system that is compatible with interoperability standards and capable of efficiently retrieving required information from diverse subsystems (i.e. fleet selection module) in order to superimpose bridge construction operations into a near optimum line of balance.

Furthermore, repair costs have proven to exceed annual or semi-annual preventive maintenance costs; hence, the developed system integrates quality functions for maintenance, repair, and replacement (MR&R) alternatives with a Gaussian probabilistic matrix factorization at the conceptual design stage. The integrated approach presented herein is used to forecast bridge components deterioration and then to prioritize the maintenance, repair, and replacement alternatives, i.e., inspection, sampling, preventative, and maintenance operations. This integration technique is an approach that justifies ineffective spending by bridge stakeholders, since it minimizes subjectivity in bridge deterioration. Moreover, the integration not only contributes to the reliability of a particular bridge element but also to the reliability of the collected data and the probability of occurrence of deterioration benchmarks such as corrosion and elemental degradations.

1.5.1 Review of Literature

A review of the literature pursuant to bridge information modeling (BrIM), 3DCAD modeling, decision support systems, cost optimization, artificial intelligence, and preliminary cost estimates is presented in detail in Chapters 2. A review of the literature pertaining to bridge deterioration forecasting and linear scheduling at the conceptual design stage is presented in Chapters 6 and Chapter 7.

1.5.2 Professional Feedback

As part of research and development, technical feedback from engineers and experts in the field of bridge design and computer-integrated construction technologies has been recorded for future development purposes. Technical feedback has been obtained by conducting interviews with bridge experts representing organizations including, but not limited to, 1) Ministry of Transportation - Ontario (MTO) - Highway and Bridges; 2) Stantec Engineering Services; and 3) EXP Services Inc. A face to face straight-forward interview questionnaire is provided for each expert in order to identify and prioritize bridge design criteria. Interviewees' details cannot be released due to privacy and confidentiality reasons. Appendix I illustrates the bridge experts' interview questionnaire form pertaining to the seven main bridge "WHATs" criteria.

1.6 Thesis Organization

- Chapter 2 presents a comprehensive review of the literature on bridge information modeling (BrIM), cost estimation, and decision support for bridge type selection at the conceptual design stage.
- Chapter 3 describes the research and development methodologies and system components, architecture, and process flow diagrams.
- Chapter 4 Technical paper I illustrates the viability of integrating a fuzzy logic decision support system with bridge information modeling and cost estimation at the conceptual design stage of concrete box-girder bridges.
- Chapter 5 Technical paper II presents an integrated expert system for linear scheduling of heavy earthmoving operations.
- Chapter 6 Technical paper III proposes integrating fuzzy logic decision support with a bridge information management system (BrIMS) at the conceptual stage of bridge design.

- Chapter 7 Technical paper IV illustrates the process of integrating an expert system with BrIMS, cost estimation, and linear scheduling at the conceptual design stage of bridge projects.
- Chapter 8 presents the study conclusions, limitations, contributions, and recommendations for future work.
- Chapter 9 provides a list of references and corresponding data links utilized mainly for the review of literature and expert system development.

CHAPTER 2

BrIM COST ESTIMATION, AND DECISION SUPPORT

2.1 Introduction

The word “integration” in the context of Computer-Integrated Construction (CIC) has no explicit definition. However, researchers at the Centre for Integration Facility Engineering (CIFE) at Stanford have implicitly defined integration as the incessant sharing of a project database, knowledge, and objectives among its participants (Fischer, 1989). This definition of integration provoked another group of researchers in Finland to raise diverse questions pertaining to who integrates, what to integrate, how and when one should integrate, and why one would choose to integrate. Based on this set of questions, a framework was developed by Fischer et al. (1993) in order to define the different levels of integration.

BrIM is a new management technology that is developed to store information for a bridge project into a database in order to ease the access of this information among project participants and to be readily available for multi-party uses (Amy et al., 2008). According to Furst (2010), BrIM achieves significant improvements in 3D modeling techniques and a transformation from traditional vector-file-based analysis of bridge elements to dynamic real-time analyses besides facilitating the exchange of information among participants. In another perspective, existing 3D CAD solutions are not sufficient for utilizing BrIM models since technical improvements are a necessity for the effective exchanging of information among interoperable software (Shim et al. (2011). Furthermore, Gallaher et al. (2004) state that the absence of efficient interoperability among 3D modeling solutions could substantially refrain users from reaping remarkable benefits. Moreover, integrating a complete set of processes could significantly influence design alternatives at the conceptual design stage of bridges. In this thesis, however, integration is primarily understood as the interdisciplinary exchange of

project information among the BrIM model by utilizing an interoperable 3D CAD modeling solution.

2.2 Computer-Integrated Construction (CIC)

Presently, interoperability among disperse information databases of a bridge construction project is ineffective due to the dynamic nature of shared information technologies. Hence, technological advancements in interoperability and compatibility are crucial for more productive transfer of information among the different database applications. Computer-integrated construction (CIC) is a broad and strategic concept designed to optimize interoperability and to use diverse information technologies effectively. CIC is defined as a concept where a computer is used to develop a model of definitive design and construction aspects in a virtual environment and then convert it into reality (Caneparo, 2005). Brown et al. (1996) promoted computer-integrated construction through the deployment of a supporting system using distributed object technology. The system was developed to standardize and effectively link information among different objects in a computer integrated construction system. In another study, Jung and Gibson (1999) proposed a methodology to deploy computer-integrated construction techniques in real world applications. In their study, computer-integrated construction was defined as the integrated solution of computer system and business management throughout a construction project. As part of their study, crucial automated integration aspects of CIC pertaining to 3D modeling, engineering design, and management application were illustrated. According to Arayici and Aouad (2005), computer-integrated construction (CIC) is a promising technique with a potential of determining technical requirements of the developed integrated systems and capable of enhancing the productivity and efficiency of the construction industry. Boddy et al. (2007) believed that advancements in CIC studies related to virtual modeling were required to apply it to the construction industry. In their study, a business model along with proposed system

architecture was illustrated. In another study, Elbeltagi and Dawood (2011) developed a computer integrated construction model to assist stakeholders visualize the benefits of integrating project time control with information modelling technologies for repetitive construction projects. Ding et al. (2014) believed that the application of computer integrated construction technologies is capable of transforming a 3D CAD model into multi-dimensional models that may be utilized in the construction industry. In their study, an information model framework was proposed to facilitate the transfer of information among project participants to assist stakeholders in decision makings during the construction stage. In another study, Jeong et al. (2016) developed a computer integrated construction simulation framework that captures changes in productivity rates during the construction stage. The framework was developed to extract data from the information model and automatically predict variability in production in order to assist project stakeholders plan schedules that adapt to the dynamic nature of construction operations.

Based on this literature, this thesis defines the CIC concept as an evolving integration methodology that unifies diverse business applications of a construction project. Furthermore, the CIC technique facilitates interoperability, compatibility, and subsequent productivity of information systems, and enhances time and cost effectiveness in real-world construction projects.

2.2.1 CIC Objectives

The main objective of the computer-integrated construction concept is to enhance 3D CAD modeling and information management of construction projects through the innovative integration of computer systems and the evolving digital media (Messner, 2005). As part of developing the CIC concept, a list of target goals is summarized below:

- Support integration and interoperability among diverse applications;
- Deploy innovative tools and techniques to support process integration and innovation;
- Enhance 3D visualization and means of communication using project information; and
- Determine the best integrated project delivery approaches that support sharing information technologies.

2.2.2 CIC Prerequisites

Prior to implementation, computer-integrated construction requires the following list of prerequisites (Wagter, 1992):

- Compiling cost databases of earlier projects to be categorized and organized into interoperable database applications.
- Integrating diverse computer-integrated systems in order to automate the generation of cost estimates at the conceptual design stage.
- Converting 3D CAD models into a virtual environment for visualization.

In this thesis, these prerequisites are used as part of the development process of 3D CAD bridge information models and for conceptual cost estimation in order to achieve interoperable and compatible integrated modules to facilitate efficiency and productivity.

2.3 Bridge Information Modeling (BrIM)

Bridge Information Modeling (BrIM) is the process of developing and managing bridge data throughout the bridge life cycle. It includes a sophisticated three-dimensional, intuitive, object-oriented bridge modeling tool to enhance design productivity. The modeling tool is capable of producing a BrIM comprising geometry, structural analysis, and reporting (Peters, 2009). An advantage of BrIM is that it illustrates a bridge life cycle and also provides

material quantities and properties. With BrIM, working systems and assemblies as well as construction sequencing may be demonstrated at a relative scale (Shim et al., 2011).

2.3.1 Purpose of BrIM

The main advantages of applying a BrIM tool during the conceptual design stage are the significant capabilities illustrated in Figure 2.1.

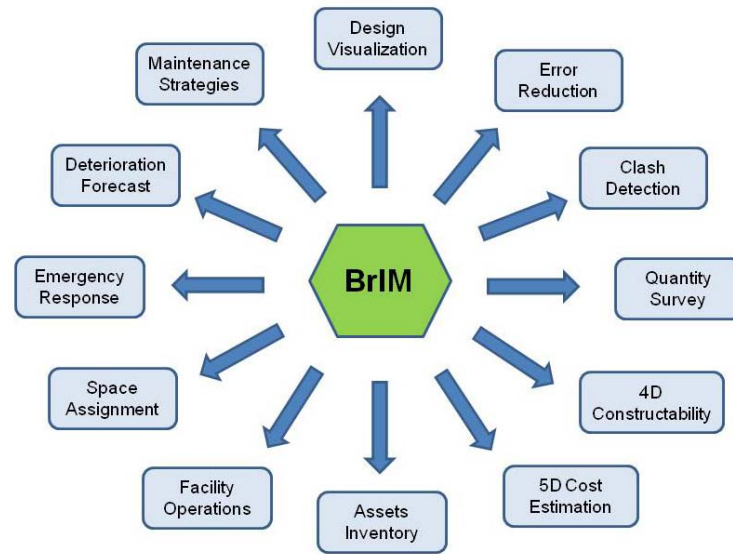


Figure 2.1 Bridge Information Modeling Features (Amy et al., 2008)

BrIM paves the way towards a working environment where owners, designers, and contractors become a single integrated team that makes important decisions for a better project's final results when compared to the traditional methods of delivery.

2.3.2 Benefits of BrIM

BrIM enhances cost estimation techniques, identifies construction conflicts, and improves elemental bridge sequencing at the conceptual design stages. The main advantages are less error-prone outcomes and subsequent cost and resources savings (Amy et al., 2008). BrIM promotes what-if scenarios, effective allocation of resources, and construction cost fine-

tuning. To owners and designers, BrIM assists in visualizing a bridge project and serves as a decision support mechanism. Moreover, BrIM houses bridge database resources in a single file that eases the allocation of information and enhances interoperability among diverse information technologies (Furst, 2010).

2.4 3D CAD Modeling

3D CAD modeling benefits the entire bridge project resulting in the development of best practices at the conceptual design stage. In one study, Heikkilä et al. (2003) presented the development of a new methodology for 3D design of concrete bridges in connection with 3D site measurements where modern technologies developed in the field of site measurements utilizing ground-based laser scanners were recalled. The developed design concept was tested through the implementation of real time computer-aided design/computer aided manufacturing (CAD/CAM) measurements utilizing a 3D robot tachometer as a device tool hand in hand with a Micro-Station. 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. 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 through an internet connection. Another study by Shirole et al. (2009) summarized research conducted to demonstrate the acceptance of integrated project delivery approach by 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 illustrate 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 afore-mentioned technologies are considered a major pitfall. At the end, the authors concluded that industry-wide standards must amalgamate to reinforce this widely-accepted integrated project delivery approach. In another study, the application of 3D BrIM to the design and construction of bridges was conducted by Shim et al. (2011). The main focus of their study was the enhancement of information modeling for bridges. In an attempt to enhance BrIM techniques, a construction project lifecycle management system specifically for bridges was developed. Their 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, Lee et al. (2012) investigated the application of 3D BrIM to 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 main parameters. In another study, McGuire et al. (2016) proposed a prototype that integrated 3D BrIM with bridge information management. The developed prototype was designed to extract bridge inspection information in order to facilitate the transfer of condition assessment data, foster interoperability, and automate bridge information management at the operation stage.

2.5 Summary

An overview of the significance of deploying BrIM modeling in the industry illustrated that integrated models enhance project time efficiency and provide less error-prone results at the conceptual design stage. On the other hand, earlier studies had focused on developing bridge information guidelines in an attempt to assist design engineers in detecting “before-hand” clashes, developing less error-prone models, and fostering operational efficiency during the construction phase of bridge projects. These studies; however, did not incorporate the influence of the developed computational tools and applications at the conceptual design stage. Based on this, BrIM’s crucial role is not only providing the user with a visualization of the project at the early conceptual design stage through analysis software but also allowing

the user to accurately define bridge elements and undertake complex numerical analyses.

In this thesis, the developed system is designed to enhance construction technologies and practices, in addition to providing an effective means of interoperability among project participants at the conceptual design stage.

2.6 Compensation Management System

The success of any construction project is evaluated based on the level of closeness between the actual and estimated costs. In practice, cost estimation at the conceptual design stage of a bridge project is known to be highly influenced by the adopted method of estimation besides the estimator's previous experience and availability of relative cost data. Over time, technological advancements have paved the way for "time-enhanced" cost estimation techniques and have resulted in less error-prone outcomes. The overall project cost is established at the conceptual design stage and maintained throughout its life cycle. Hence, the exchange of information during the design and quantity survey process has been proven to enhance the management of project cost. Effective integration between the project conceptual design phase and the post-design stages ensures control of project cost throughout entire life of the project. This necessitates the development of a compensation management system comprising the following three components: (1) direct cost (DC) and overhead (OH); (2) pain share; and (3) gain share. The pain and gain shares depend on whether the project goals have been achieved or not. The distribution of pain and gain shares is also dependent upon project participants' respective weighted percentage of contribution rather than that of project cost.

In summary, the implementation of infrastructure projects requires the development of the following financial provisions: (1) individual DC & OH; (2) shared profit/loss; and (3) project incentives (Pinto, 1998).

This chapter includes a comprehensive review of the literature on cost estimating besides the optimization of heavy earthmoving logistics. Finally, a comprehensive review of diverse cost estimate strategies and types based on degree of accuracy is included focusing on the types of estimates applicable at the conceptual design stage of construction projects in general and bridge projects in particular.

2.7 Cost Estimation

Cost estimation for construction projects is often defined diversely among estimation experts and decision makers. For instance, according to the American Association of Cost Estimation (AACE) an estimate is defined as: “An evaluation of all the costs of the elements of a project or effort as defined by an agreed-upon scope” (Westney, 1997). Furthermore, the Project Management Institute (PMI) considers cost estimating: “The development of an approximation (estimate) of costs of the resources needed to complete project activities.” (Pinto, 1998). In estimation standards, effective cost estimates pave the way towards the success of a project management strategy and subsequent control of budget, cost, and corresponding schedule. In a study conducted by Forrest and Lorenzoni (1997), a cost estimate was considered a strategic technique to forecast the execution mode of a construction project. In other words, their study presents a cost estimate as a break-down for completion of project milestones. In another study conducted by Uppal (1999), a cost estimation process was defined as the anticipation of costs for a definite scope of works necessary to successfully complete a project. In one study, Peurifoy and Oberlender (2002) concluded that since cost estimation is not a precise discipline, the construction industry is in dire need of knowledge experts, logic, and experienced personal judgment to achieve less error-prone decision making. Furthermore, An et al. (2007) proposed a case-based reasoning cost estimating model integrated with analytic hierarchy process. The proposed model was developed to minimize shortcomings of estimator previous experience on estimation attribute

weights. In another study, Makovsek (2014) studied the relationship between the cost estimation methodology and estimation accuracy. It was concluded that estimation accuracy is directly proportional to bidders' attitude and unit pricing changes. According to Kim et al. (2017), case-based reasoning estimates generate reliable estimates for life cycle assessment of concrete beam bridges in the early design stage. In their study, it was recommended to implement a decision support system in order to support life cycle cost assessments at the conceptual design stage of bridge projects.

As stated earlier, cost estimation is endorsed as a forecasting technique, a continuously developing state, and a strategic estimating technology for unforeseen construction costs. In order to gain a better understanding of cost estimation, further research studies that exist in the literature, pertaining to the diverse types and degrees of accuracy of cost estimates, are reviewed and summarized below.

2.7.1 Estimation Rationale

Cost estimation reasoning mainly entails determining the actual costs required to successfully construct a project in conformance with design drawings and with general and particular specifications. Hence, the availability of a project information database is of major significance for project stakeholders especially when it comes to the decisions related to funding. Furthermore, securing a strict and definitive project budget at the early stage of a project assists owners and stakeholders in cost-controlling the subsequent phases including the construction phase (Westney, 1997).

In summary, cost estimation reasoning is an essential element that must be considered at the early project stages for its significance in: 1) affording a capital cost evaluation; 2) setting the milestones for cost planning and control; 3) providing a breakdown of operation and

associated costs; 4) illustrating human resources and equipment necessities; and 5) contributing towards the development of a balanced cash flow; 6) providing overall system productivity and risk assessment; 7) engaging team work involvement; and 8) resolving data amalgamation and interoperability issues (Westney, 1997).

2.7.2 Cost Estimation Types

Hendrickson (2000) divides the types of estimates into three main categories in accordance with the degree of project definition; (1) design estimates, prepared for owners or project stakeholders to provide a preliminary estimate of construction costs at the conceptual stages and prior to investing in enormous design efforts; (2) bid estimates, prepared for owners or project stakeholders for bidding purposes; (3) control estimates, prepared for project stakeholders or construction managers for cost control and monitoring during construction. A study conducted by Peurifoy and Oberlender (2002) stated that a project passes through diverse estimation stages and most construction cost estimates are revised continuously throughout a project life cycle, starting with the conceptual estimate and extending into the later stages including execution phases.

Based on this, the selection of cost estimation type is highly influenced by the degree of project definition, which subsequently dictates the type of cost estimate for construction projects. In this thesis, cost estimates are considered to fall within approximate estimate category where such estimates are strictly and solely dependent upon the available project data at the conceptual design stage.

2.7.3 Estimate Accuracy

In principle, reliability of a cost estimate is highly dependent on its corresponding accuracy and agreement with the actual costs. For instance, Oberlender and Trost (2001) concluded in

their study that the degree of estimation accuracy is directly proportional to the percentage of agreements compared with the actual total costs. Furthermore, four major inputs that influence particular cost estimate accuracy are summarized as follows; (1) subjectivity; (2) methodology; (3) project definition; and (4) factors and assumptions. Technically, cost estimation passes through a series of steps to reach a certain level of accuracy. At first, an estimate is developed at an initial accuracy ranging between a minimum of -30% and a maximum of +50%. Such an estimate is referred to as a parametric estimate. This is refined at a later stage to an accuracy level ranging between a minimum of -15% and a maximum of +30% and then defined as a conceptual estimate. Towards the end, the estimate is refined to an accuracy level ranging between a minimum of -5% and a maximum of +15% and referred to as a definitive estimate (Rast and Peterson, 1999).

In summary, controlling the estimate accuracy is highly influenced by the degree of experience of the individual or group involved in preparing the estimate and the availability of project information at the early stage. Besides that, the source and type of cost data used and its relative accuracy may significantly influence the accuracy of a cost estimate.

In this thesis, a cost type analysis is undertaken where a comprehensive breakdown of cost data is conducted to verify hard and soft resource costs (i.e. manpower, heavy equipment, and operational man-hours). Moreover, the reliability and quality of cost data are considered the “pre-qualifications” for cost estimates when used for either budgetary or financial decision makings.

2.7.4 Conceptual Estimates

At the initial stage, very little or no reliable information about a construction project is available. Moreover, establishing the economic viability of a construction project is necessary

before moving on to the comprehensive design stage. Hence, a conceptual estimate is an essential requirement that must be developed at the conceptual design stage prior to undertaking extensive detailed designs.

Typically, conceptual estimates are developed by stakeholders and cost estimators at the early stages of a project in order to secure the necessary budget before exceeding with the design. Such estimates are, in few circumstances, used as base references depending on project's type, size, and completion time (Rast and Peterson, 1999). On the other hand, preliminary estimates are only developed where up to 40% of project definition and design has been achieved. Substantial experience and extensive judgment skills are the two main constituent requirements for achieving reliable estimates (Rast and Peterson, 1999). According to Peurifoy and Oberlender (2002), conceptual estimates and their applicability are adequately accurate for approximate estimates but not sufficiently reliable for bidding purposes. According to Bode (1998), cost-related parametric factors, assumptions, and cost indices are often used to enhance the conceptual estimate. Furthermore, recently developed technological applications comprising probability and statistics, Artificial Intelligence Techniques (AIT), and Relational Database Management Systems (RDBMS) have been employed for the same purpose. In addition, several studies conducted in 1989 by Bradley et al. (1989), Hegazy and Ayed (1989), and Yeh (1989) confirmed that an increase in accuracy for conceptual estimates of up to 20% is only possible if existing cost estimation applications are used in such types of estimates. In this thesis; however, the source of cost data is considered an important key for cost estimate accuracy. Hence, cost data type analysis is conducted in order to minimize contingency and achieve cost estimates with enhanced accuracy.

Therefore, this thesis contemplates the approximate estimate with more emphasis on the conceptual estimate, as it is considered the milestone and a reference base point for the latter.

2.7.4.1 Estimate Characteristics

Conceptual estimates are commonly characterized by imprecision. In most cases, the scarcity of data and lack of information at the conceptual design stages result in evaluating alternatives by means of previous experience in similar projects and engineering judgment. Furthermore, conceptual estimation is an art that engages a scientific approach based on recalling the costs of similar projects and adapting them to existing conditions (Peurifoy and Oberlender, 2002). Another main characteristic of such an estimate is that the validity of an estimate and its corresponding accuracy are considerably reliant on the level of definition and scope of work of the project. According to Peurifoy and Oberlender (2002), conceptual estimates are typically restricted against the availability of data resources and limited to the following inputs; 1) database; 2) time; and 3) cost. In addition, precision of available data is often restricted in details, time, and cost since conceptual estimates are mainly undertaken for funding purposes and to support feasibility studies, in addition to providing a screening of initial alternatives prior to proceeding with detailed design.

2.7.4.2 Estimate Preparation

Generally, the preparation of a conceptual cost estimate is initiated through a series of integrated processes to obtain the project's estimated cost. As part of developing the conceptual estimate, relevant information and corresponding assumptions are described to provide a better understanding of the outcomes. Based on the review of literature and survey of conceptual cost estimating guidelines, the following information is needed for conceptual estimate preparation; 1) cost estimates of similar projects; and 2) corresponding detailed general and particular specifications (Westney, 1997).

2.7.4.3 Estimate Work Breakdown Structure (WBS)

A cost estimate Work Breakdown Structure (WBS) is considered by most cost estimating professionals to be an essential project deliverable that breaks down the main elements of the cost estimate into smaller sub-elements to provide the necessary framework for cost estimate control and this paves the way towards a successful schedule. Unlike elemental classifications, traditional project classifications are based on functionality regardless of the actual design and detailed product specifications (Charette and Marshall, 1999). According to Charette and Marshall (1999), elemental classification has proven its dominancy over traditional classification techniques. Furthermore, a modified version of elemental classification was proposed by the National Institute of Standards and Technology (NIST) in mid-2011 to incorporate a major reformation of the American Society For Testing and Materials (ASTM) standard classification E2103; a directed standard classification for bridge-related projects, proved to maintain consistency and enhance acceptance among its beneficiaries (NIST, 2011). Furthermore, an important aspect of the proposed classification designed to incorporate sub-element classifications into the standard to enhance element classification throughout the entire life cycle of bridge projects is presented. The major difference between elemental classification estimates and traditional ones is the concept behind an element function as opposed to the methodology employed for product delivery classifications. Often, conceptual estimates are supported by elemental classifications through the use of a structured approach (NIST, 2011). In 1975, project stakeholders showed an interest in developing a common framework for estimators, paved the way towards the development of UNIFORMAT; for which a standard elemental classification, E1557, of building components was announced and released in 1980 (NIST, 2011). Following the deployment of the E1557 UNIFORMAT II standard for building projects, a bridge elemental classification, E2103, was developed and presented in 2010 where a wider family of classification standards was addressed.

In this thesis, the bridge elemental classification, E2103, is implemented as the foundation for a broad database of bridge construction costs.

2.7.4.4 Rationale

Bridges are one of the main constituents of a national infrastructure network. According to the American Association of State Highway and Transportation (AASHTO), the average age of a bridge in the USA was estimated to be 46 years in (NIST, 2011). Moreover, a survey conducted by the American Society of Civil Engineers (ASCE) in 2009 concluded that only 60% of necessary maintenance costs are spent to maintain aging bridges. Because of that, major amendments to the E2103 bridge classification to achieve reasonable consistency with the UNIFORMAT II Guidelines is a necessity as the original E2103 differed from UNIFORMAT II elemental classification in:

1. The WBS organizational chart, which subsequently restricted its usability.
2. The absence of alphanumeric designators for multi-level bridge classification which provide a basis for cross referencing of bridge cost databases.
3. The limitation of sub-elemental categorization since the primary focus of the UNIFORMAT II is on the elemental concept comprising the following three levels:
 - a) major group elements; b) group elements; and c) individual elements. (NIST, 2011).

Therefore, these major revisions to the proposed E2103 elemental bridge classification engage an enhanced mutual understanding among users and stakeholders within the bridge industry. Moreover, the proposed UNIFORMAT II framework significantly promotes the applicability of a distinct elemental classification for bridge project stakeholders at bridge level and network level (NIST, 2011).

In this thesis, the UNIFORMAT II Standard Classification of Bridge Elements Guidelines is deployed for an approximate estimate of construction costs at the conceptual design stage. As a result, bridge project stakeholders will maintain cost-effective solutions for construction of new bridges and forecast subsequent maintenance, repair, and replacement strategies.

2.7.5 Parametric Estimates

A parametric estimate is a numerical representation that provides a practical cost correlation among diverse project characteristics. Such estimates may be considered as enhanced cost estimation tools for preparation of approximate estimates when there is no or little information available, complemented by several methodologies while complying with a defined level of accuracy (Hendrickson, 2000). According to Hendrickson (2000), parametric estimates are typically developed during the feasibility stage and prior to starting the design stage, where an estimator often relies on previous estimates of similar projects. However, it is important to define a few basic parameters and obtain relevant database resources from a project similar to the one of interest. Furthermore, the deployment of a dynamic parameter as a base reference for the other related parameters is the dominant approach in parametric cost estimates (Melin, 1994). According to Ellsworth (1998), the basic straightforward method to obtain the most probable cost outcome of a project is to compare costs of an established similar project with the project of interest. In many cases, there is a lack of cost data for projects of similar size; therefore, parametric estimates subject to adjustment in size are precluded and “brand-new” estimates are to be developed from scratch. In a contradictory finding, Moselhi and Siqueira (1998) concluded that the reliance of a cost estimator on earlier estimates and diverse estimating methodologies in developing parametric estimates results in inconsistent and unreliable outcomes. On the other hand, Bajaj et al. (2002) stated that accuracy of parametric estimates is strictly dependent on the appropriateness and trustworthiness of historical data. During their study, the authors found that such estimates

are often used in construction industry applications in order to assist stakeholders in allocating funds for a particular project in a timely manner. According to Meyer and Burns (1999), accurate parametric estimates are developed in line with engineering parametric factors obtained from earlier projects, standard practices, and advanced construction technologies. Furthermore, the authors describe in detail such parameters as: 1) length; 2) bridge type; 3) foundation; 4) exterior; 5) usable space; and 6) system requirements.

In this thesis, parametric estimates are used to provide a cost correlation at the feasibility stage of the project. Such type of estimate is useful when little information is available for a bridge characteristic component and may be utilized as an estimation tool to assist in preparation of approximate estimates at the conceptual design stage.

2.7.6 Preliminary Estimates

Following the preparation of approximate cost estimates, architects/designers are typically instructed by project stakeholders to develop a preliminary cost estimate in line with the design plan. Stakeholders consider preliminary cost estimates to be estimates developed at the pre-design stage regardless of design type, accuracy, and purpose (Ostwald 1984). Furthermore, Sanders et al. (1992) believed that preliminary estimates are used for supporting the funding of decision-making processes regardless of their corresponding accuracy and, in many cases, such estimates are the sole means for accepting or dismissing a project. Uppal (1999), however, stated that preliminary estimates are a major necessity for effective strategic planning of long-term “capital cost” projects. Furthermore, Sanders et al. (1992) believed that preliminary estimates are used for supporting the funding of decision-making processes regardless of their corresponding accuracy and, in many cases, such estimates are the sole means for accepting or dismissing a project.

Typically, preliminary estimates are considered as advanced estimates where the project scope is approximately 40% defined (Vojinovic et al., 2000); however, in many cases, project drawings or specification are not made available at the initial stages so that the estimator is directed solely towards the outlined specifications. According to Vojinovic et al. (2000), preliminary estimates are typically utilized for evaluating total project costs at initial stages with insufficient information. On the other hand, another study conducted by Johnson and Kwong (2001) concluded that during initial design phases, extensive efforts are invested towards developing accurate cost estimates and such efforts are often fulfilled when overall project scope is defined.

In this thesis, the process of preparing approximate cost estimates in standard units at the conceptual design stages is developed based on R.S. Means Heavy Construction cost data with UNIFORMAT II being the benchmark for a work breakdown structure.

2.8 Heavy Equipment Selection

Equipment selection is a critical factor in construction projects. This is much more critical in bridge construction projects where heavy equipment fleets play a vital role in performing the work. In this type of project, the equipment fleet may represent the largest portion of the bidding price (Nunnally, 1977). Since equipment selection is highly influenced by complex factors, bridge stakeholders and engineers tend to rely upon their historical data and experience in similar projects to assist them in determining the optimum fleet. While this is a good approach at the conceptual stage of the project, it is not sufficient to build the equipment fleet benchmark due to the dynamic nature of construction projects. Other approaches such as expert systems could be useful only if integrated with a database of historical data.

Rational selection of equipment leads to profits. At the same time, miscalculating the proper size of fleet required for the project may result in losing the contract or suffering from high overhead costs (Tavakoli and Taye, 1989). Therefore, bridge stakeholders consider the selection of an equipment fleet as a vital factor for the success of any construction project (Marzouk and Moselhi, 2004).

To overcome this shortcoming, the developed system presented in this thesis is based on integrating heavy equipment manufacturer information for selected equipment with a comprehensive economic operation analysis for diverse earthwork operations.

2.8.1 Technological Advancement of Equipment

Technological advancement of construction equipment has followed major changes in global transportation that took place in the late nineteenth and early twentieth century (Schexnayder and David, 2002). Major developments came to supply the demands of new inventions in the construction process in general and equipment capability in particular.

In the late nineteenth century, construction in the United States was changing from canal building to railroad construction (Schexnayder and David, 2002). The need for new machines for huge earth excavation was inevitable. These demands introduced the world to an era of skyscrapers, bridges, dams, and other types of buildings. Many of these inventions in the equipment industry are utilized in the process of earthmoving (Nunnally, 1977). Earthmoving typically includes excavating, loading, hauling, backfilling, grading, and compacting of materials. The benefits earned from these inventions underlie improved productivity rates as newer-type equipment possesses more power and much more capacity. In general, innovation in the construction equipment industry is based on a demand-pull phenomenon fueled by market conditions (Arditi et al., 1997).

Besides the advancement in equipment, newly advanced technologies, such as hydraulic systems, tire advancements, and design capabilities directly influence productivity rates and overall construction downstream processes.

2.8.2 Previous Research Work

There have been numerous attempts to solve the challenge of equipment selection. Different methods and models have been proposed to optimize equipment selection for different types of operation. However, these models are proposed for specific types of construction work due to the many factors that contribute to equipment selection. Current models utilize the common models for equipment selection; 1) genetic algorithms; 2) simulation; 3) expert systems; 4) decision support systems; and 5) the analytic hierarchy processes, and the following techniques for determining overall equipment system productivity; 1) bunching theory; 2) productivity curves; and 3) simulation as summarized in Figure 2.2.

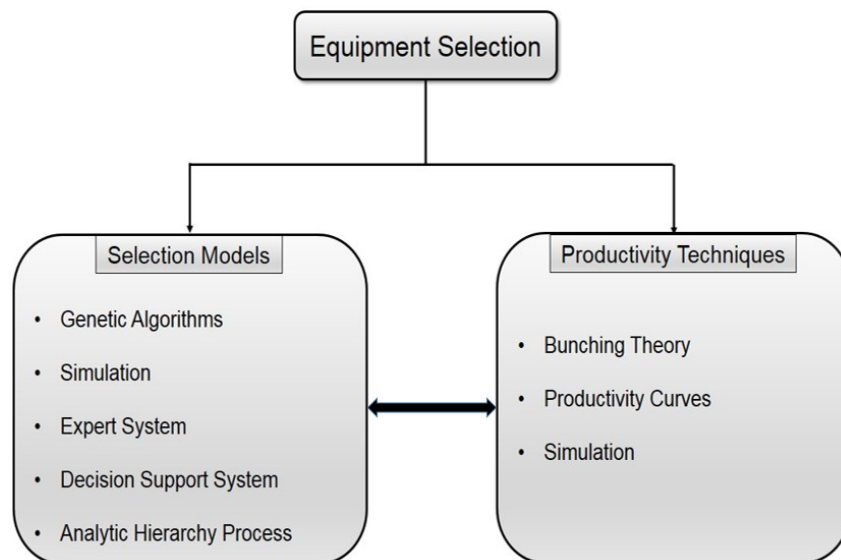


Figure 2.2 Diverse Techniques and Models for Equipment Selection

The majority of studies published in the literature focus on the optimization of equipment selection in heavy civil work, such as airports and highway bridges, based on diverse

complex factors; however, none of the studies are designed to include or perform economic operation analysis. One study however, conducted by Moselhi and Marzouk (2000) addresses cost estimation of heavy earthmoving operations. In their study, an equipment cost application system for time and cost estimation of heavy earthmoving operations was developed. The system was then verified by a numerical example with a detailed step-by-step description of the procedure to be followed. This study is of major significance at the design stage of a construction project and is limited to initial costs anticipated for earthmoving operations. Another study by Marzouk and Moselhi (2003) addressed cost applications without considering complex factors in heavy equipment operation analysis. In their study, an object-oriented simulation model for earthmoving operations was developed. The model was implemented in a Microsoft environment to enhance its component integration capabilities with the Visual Basic 6.0 code. The developed model consists of a simulation program, a database and cost application, and an optimization and reporting module. At the end, the study was verified with a numerical example by comparing the corresponding outputs of Caterpillar's software with the developed earthmoving simulation program. It was concluded that results were in good agreement with a difference of less than 8%. Also, it was found that the simulation program was more accountable than Caterpillar's software for uncertainties that arise during the execution of earthmoving operations. The main focus of their paper, however, was targeted towards the simulation program.

Diverse methods and models have been proposed to optimize equipment selection for different types of operation. These models have been proposed for specific types of construction work due to the many factors that contribute to equipment selection. Furthermore, researchers have focused on developing expert systems in an attempt to assist construction managers and contractors in selecting the fleet of equipment needed for their projects. These studies, however, do not incorporate equipment operation analysis and

associated costs. An expert system model to select the 'best' fleet of equipment needed in road construction and earthmoving operations based on resources collected from field practitioners such as planning engineers and equipment specialists was developed by Alkass and Harris (1988). The development of the expert system comprised four main stages. The first stage of the study was to identify tasks and job conditions. Following the identification of tasks and job conditions, equipment selection was commenced based on broad categories. After that, the equipment fleet was matched with the proper category. Towards the end, the selection of the equipment fleet was made while taking into consideration factors from earlier stages. A rule-based expert system model for selecting earthmoving equipment was developed by Amirkhanian and Baker (1992). The system was developed to interpret data pertaining to soil conditions, operator performance, and volume required for the earthmoving operations. Furthermore, a model for optimizing excavating and hauling operations and the utilization of equipment in opencast mining was developed by Haidar et al. (1999). Their model was based on a decision support system for the selection of opencast mine equipment. As part of developing the decision support system, a hybrid knowledge-based system and genetic algorithms were used to design the system. Other studies have addressed significant factors that influence operation analysis. For example, a fuzzy clustering model for estimating haulers' travel time, capable of being integrated with diverse simulation and estimation models, was developed by Marzouk and Moselhi (2004). The model exploits regression analysis and subtractive clustering and was implemented by means of Visual Basic for Applications (VBA) in a Microsoft environment. Results obtained from the developed model were in good agreement with the results obtained from Caterpillar's software. A model based on an analytical hierarchy process was developed by Shapira and Goldenberg (2005). The model was intended to provide solutions for two main issues as follows: (1) systemic evaluation of soft factors; and (2) weighing of soft benefits when compared to costs. Also, the developed model is capable of providing users with results to compare different alternatives

based on several criteria. Output results will be the selection of equipment based on highest score. Furthermore, Alshibani and Moselhi (2012) developed a simulation model based on a global positioning system that is capable of optimizing heavy equipment selection during the construction stage. In another study, Hummer et al. (2017) studied the viability of customizing fleet combinations to reduce equipment cost. As part of their study, a decision support model was developed to select optimum fleet while taking into account equipment availability and construction operations scheduling.

2.8.3 Equipment Economics

For construction projects, especially heavy civil work such as airports and highway bridge projects, equipment is understood to be one major resource that project managers and general contractors rely upon to perform the required work. Equipment may either be owned or it may be rented for a period of time. The economic analysis of construction equipment is mainly focused on determining owning and operating costs as well as the economic life for each type of equipment (Nunnally, 1977). According to Schaufelberger (1999), an equipment fleet may represent the largest investment in the long term for construction companies. Economic analysis of equipment must be obtained in order to properly determine an optimum fleet. This step is considered critical in order to evaluate rental options and to support decision makers. To properly complete the equipment's economic analysis, all costs associated with the selected equipment must be considered.

In this thesis, the Caterpillar[®] Performance Handbook (2011) issued to develop the owning and operating cost database. A description of equipment economic analysis components is illustrated in Figure 2.3.

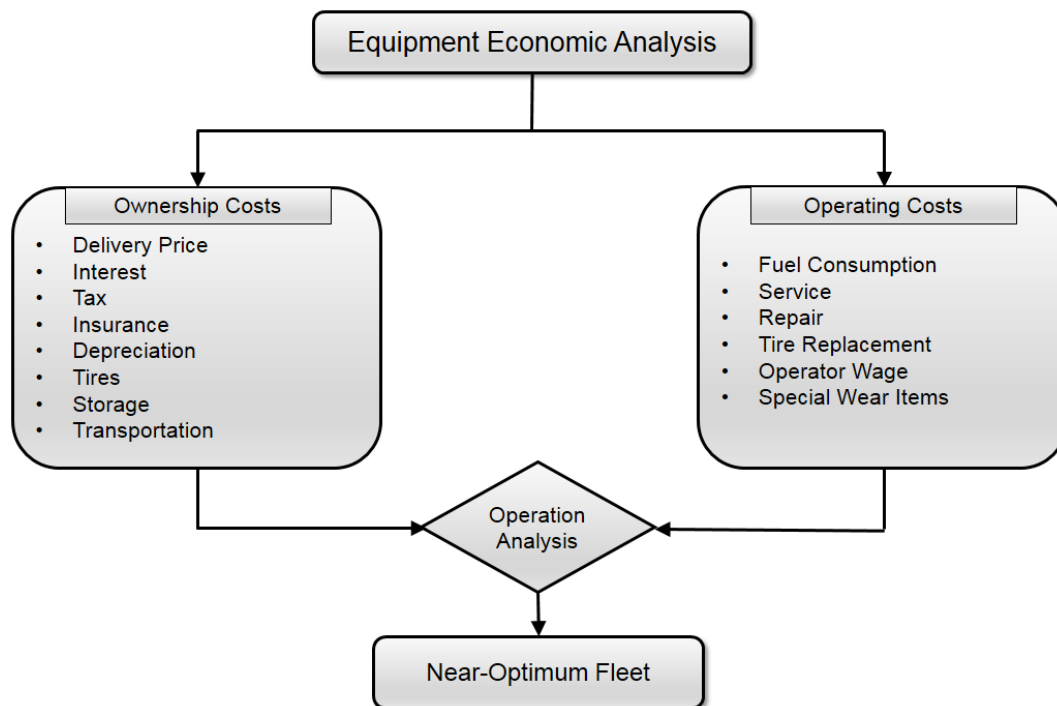


Figure 2.3 Equipment Economic Analysis

2.8.4 Ownership Costs

Ownership costs are a fixed type of costs that are incurred whether the equipment is used or not. These costs must be recovered by using a piece of equipment to perform construction projects that earn profits (Day and Benjamin, 1991). Ownership costs include; (1) purchase expense; (2) interest; (3) salvage value; (4) taxes; (5) insurance; (6) license fees; (7) depreciation; (8) storage; and (9) transportation. According to Lucko and Voster (2003), an equipment salvage value is the price for which a piece of used equipment can be sold in the market at a particular time. It is known that depreciation is the loss of equipment's value over time within the expected life. Diverse depreciation methods are used to estimate the loss in value at the end of any specific period.

2.8.5 Depreciation Calculation Methods

Diverse methods for calculating equipment depreciation value are available. However, only a few have been found to be accurate, efficient, and applicable in the construction industry (Schaufelberger, 1999). In this study, four depreciation methods are incorporated and made available to users to select from a dropdown menu as follows: 1) straight-line; 2) sum-of-the-years; 3) double declining balance; and 4) capital cost allowance. The double declining balance method depreciates equipment at a faster rate than the straight line method by considering 200% of the depreciation rate (Schaufelberger, 1999). This depreciation method is conservative in terms of calculating equipment depreciation when compared to the available methods. Furthermore, the main difference between straight line and sum-of-the-years is that the straight line method applies a constant rate of depreciation annually while the sum-of-the-years method applies a variable rate. However, the capital cost allowance (CCA) depreciation method is commonly used for the selection of heavy equipment in order to maintain consistency with tax liability for an equipment purchased within Canada along with its corresponding ownership costs (i.e. delivery price, tax, storage, transportation...etc).

2.8.6 Operating Costs

Operating costs are costs associated with operating the equipment and variable in terms of the total cost as they are a function of the number of operating hours (Halpin and Woodhead, 1998). These costs include; (1) fuel; (2) lubricants; (3) filters; (4) hydraulic fluids; (5) parts; (6) maintenance; (7) repairs reserve; (8) tires cost and repairs; (9) special wear items; and (10) operator wages. These costs are considered in the optimization process since they are common parameters to the owning and renting cost analysis that contribute to fleet selection at the conceptual design stage

2.8.6.1 Caterpillar® Methods to Calculate Ownership and Operating Costs

Since the prime objective of this thesis is to optimize costs of selected equipment, it is convenient to rely on manufacturer's data in this regard. Caterpillar recommends the following steps to be considered when calculating the ownership and operating costs of equipment; 1) the price of any equipment must always be obtained locally for a more reliable estimate; 2) the calculations must be based on a complete equipment fleet; 3) multiplier factors provided must work equally well in any currency; and 4) operating conditions must be defined in zones because of different standards of comparison.

2.8.7 Equipment Classification

Contractors tend to classify their fleet based on the equipment function or the type of operation that it can perform since they wish to facilitate the process of allocating resources for bridge projects. In general, a piece of equipment is classified based on its characteristics or the type of work in a construction project. Equipment classification based on function or characteristics includes; (1) power units; (2) tractors; (3) haulers; and (4) material-handling equipment; whereas equipment classification based on the type of work includes: (1) clearing and grubbing; (2) excavating; (3) loading; (4) hauling; (5) backfilling; (6) grading; and (7) compacting equipment (Day and Benjamin, 1991).

2.8.7.1 Factors Affecting Equipment Selection

Operational inefficiency is a result of structural or mechanical failure due to equipment overloading or stressing beyond its maximum capacity (Gransberg et al., 2006). The main consideration in any endeavor is to get the job done according to timeframe and cost limitations. In order to achieve this goal, proper calculation of productivity rates for a fleet while considering variable factors is required. According to Gransberg et al. (2006), the first factor to consider is matching the right equipment to the proper type of operation. Another

factor is the availability of the right equipment with proper service, maintenance, and repair reserves. Besides the previous factors, Gransberg et al. (2006) propose the following two factors to be considered when selecting proper equipment: (1) type and condition of the site work, which includes the distance to be traveled; and (2) desired productivity, which is a critical factor that affects equipment selection. Furthermore, Schaufelberger (1999) states the following two general factors to be considered in the process of selection of equipment fleet: (1) cost effectiveness, which involves considering the size of equipment in addition to the proper type; and (2) versatility, which involves selecting equipment that can perform multiple tasks at the site work.

2.8.7.2 Methods in Optimizing Equipment Productivity

The cost and productivity relationship between hauling and loading units is a basic challenge during planning (Gates and Scarpa, 1975). Peurifoy and Schexnayder (2002) propose the first method in optimizing bridge construction equipment productivity, which is based on simple assumptions and constraints. First, all physical constraints on the hauling system are determined and then are evaluated in order to determine the system's ultimate performance. These constraints are listed and are summarized as follows; (1) haul road rolling resistance; (2) haul road grades; (3) haul unit horsepower; (4) haul unit loaded and empty weight; (5) haul unit transmission characteristics; (6) haul unit loading time; (7) haul unit travel time; (8) haul unit delay time; and (9) altitude of the project site (Gransberg et al., 2006). Another method proposed by Phelps (1977) introduces the amount of time wasted into computations. However, both methods consider the equipment rim-pull.

2.8.7.3 Forces Affecting Motion of Equipment

Self-propelled equipment gets its power from the engine. However, there are certain parameters that need to be considered when conducting the economic operation analysis.

These parameters are: (1) total resistance force; (2) traction; (3) power; and (4) effects of altitude (Day & Benjamin, 1991). Prior to optimization, all of these factors are taken into consideration while conducting the economic operation analysis of equipment fleet. The total resistance force must be calculated in the operation analysis in order to determine if a piece of equipment produces an equivalent power to overcome this force; otherwise, the machine will not move. It is known that the total resistance varies based on the total weight of the equipment, that is, the machine weight and the weight of the material. However, this power is limited to the maximum power the equipment can produce or the maximum traction that can be developed between tires or tracks of the equipment and the surface (Nunnally, 1977). Traction is the maximum usable force that can be applied before a piece of equipment begins to slip. To determine the maximum traction force, the coefficient of traction, which is the degree of traction between the tires or the tracks and the ground must be known.

2.8.7.4 Effects of Altitude

When equipment operates at higher altitudes, the internal combustion engine loses power because air density decreases and affects the fuel-to-air ratio in the combustion chamber of the engine (Schaufelberger, 1999). To overcome this shortcoming, it is necessary to calculate the factor for derating equipment performance when operating at an altitude that exceeds 1,000 (ft.) above sea level. All of these concepts and equations are used to build the system as a first step in the operation analysis. There are several factors that affect the equipment selection process. In this thesis, these factors are defined as constraints. However, to better understand the whole concept, a thorough analysis that includes estimating the production rate for each piece of equipment using the developed system is required. In this thesis, the developed system contains all necessary data and equations, including types and properties of material to be dealt with, specifications of the project site, and specifications related to the selected

pieces of equipment. Appendix II illustrates the equipment specifications and mathematical formulations.

2.9 Summary

An overview of earlier research work pertaining to cost estimation and heavy equipment selection is presented. Diverse cost estimate types, characteristics, and their corresponding level of accuracy is illustrated. Since optimizing equipment selection in heavy earthwork operations is a critical key towards the success of a bridge project, it is important to note that a detailed methodology for the selection of heavy equipment must be deployed. The development of a fleet selection system based on cost optimization approaches enhances the accuracy of a preliminary cost estimate at the conceptual design stage provided that heavy equipment may represent up to 20% of the estimated cost.

In this thesis, a heavy equipment economic operation analysis along with a comprehensive owning and operating cost analysis are implemented and incorporated within the UNIFORMAT II cost estimate framework for preparation of approximate cost estimates at the conceptual design stage while utilizing standardized units of metrics and measures.

2.10 Decision Support System

Making decisions pertaining to the selection of bridge type and the preventative maintenance, repair, and rehabilitation alternatives with their associated costs is a major undertaking for bridge stakeholders. Presently, the majority of bridges in North America are beyond their anticipated lifespan and they are also not designed to accommodate the continuously increase in urban and suburban population, which is constantly adding to the traffic volume. Besides that, the majority of bridge stakeholders are often obliged to pay for annual or semi-annual preventive maintenance fees, which have been economically proven to be of no significance

in preventing or controlling a deteriorating bridge structure, rather than investing in early preventative maintenance. Moreover, many infrastructure asset managers tend to enforce a long-term plan where overall maintenance costs are held down to a level just above minimum standards for structural integrity, functionality, and safety. Based on this, it is clear that managing infrastructure assets in general and bridge projects at the project or network level is a multifaceted task that requires outstanding efforts. Therefore, the following sections summarize the readily-developed decision support strategies that attempt to overcome these obstacles and simplify the entire process.

A decision support system is a directional process that utilizes knowledge management by promoting the latest advancements in information technology and systems to support decision makings. Such systems are also known as expert systems since the decision making processes are based on a rule-base drawn from experienced professionals' knowledge. In many cases, a knowledge-based decision support system comprises numerical optimization modules to assist decision makers in cost variation alternatives. In one study, Zuk (1991) developed a knowledge-based decision support system in an attempt to support infrastructure assets managers in maintenance, replacement, and repair (MR&R) strategies pertaining to aging bridges. In another study conducted by Brito et al. (1997), a bridge management system comprising two integrated modules was presented. The first module, BRIDGE-1, was designed to maintain consistency among inspectors and inspection strategies, while, the second module, BRIDGE 2, was developed as a receiver database that allocates exported data from the first module and processes them to produce a decision pertaining to maintenance and repair techniques. At the end, the authors concluded that the proposed application is limited to detecting corrosion in concrete reinforcement bars to support bridge inspectors in subsequent decision making. Furthermore, Chassiakos et al. (2005) presented an expert system for planning maintenance operations of highway bridges. As part of developing the

expert system, data pertaining to maintenance operations were derived from skilled maintenance personnel and incorporated into the system. However, expert systems are not considered an effective stand-alone management tool and are limited in the degree of support they offer as the applicability of such systems is targeted towards a distinct field as opposed to generic applications with indefinite purposes. In another study, Rashidi and Lemas (2011) studied the viability of developing a decision support system that is capable of selecting the most suitable bridge remediation alternative based on a simple multi-attribute rating technique (SMART).

As part of their study, a methodology for monitoring and evaluating existing bridges condition was presented. Furthermore, Sun et al. (2015) developed a decision support system to optimize bridge maintenance and repair management costs. In their study, two modules were developed to monitor structural integrity and carbon emissions. It was concluded that maintenance costs that compromise structural integrity exceeded those due to carbon emissions, and hence; signified the necessity to develop an optimum maintenance, repair, and replacement plan that considered environmental impacts.

Presently, expert system strategies have been witnessed in diverse private and public infrastructure asset management organizations. For instance, the Province of Ontario employs a bridge management system, Ontario Bridge Management System (OBMS), encompassing an expert system that is specifically designed to help asset managers to select elemental treatment scenarios (Thompson et al., 2000). Moreover, in the province of Alberta, an expert system, Bridge Expert Analysis and Decision Support (BEADS), with an aim of supporting bridge management's decisions pertaining to MR&R, cost optimization, and performance evaluation was developed such that the proposed system is integrated within a broad-scope infrastructure management system (Hammad et al., 2007).

2.11 Fuzzy Logic Theory

Fuzzy logic theory is an evolutionary extension to Aristotle's logical propositional calculus where there is only one true value for any proposition. The concept of fuzzy sets is defined as a set where corresponding members possess a particular degree of membership. Fuzzy logic sets are developed in a manner that with the aid of a membership function in a real interval, elemental membership in a particular set may be progressively and logically determined. The concept of fuzzy logic sets was first introduced by Zadeh and Klaus in the year 1965 as an extension to the classical conventional set definition. According to Zadeh (1965), a set is designated as a fuzzy set when a membership function comprising real values is used to determine the extent an element belongs to a definitive set. Historically, the concept of fuzzy logic is deployed as a bridge management approach to present the subjective nature of condition assessments. Yao (1980) studied the viability of using fuzzy sets as an alternative approach to evaluating conditions of deteriorated structures. The intent of the proposal was to use a bridge expert's experience and intuition to construct a systematic decision support system. Hadlpriono (1988) proposed an algebraic approach based on fuzzy rules such that verbalized scorings of condition assessments are translated into graphical models resulting in overall bridge performance ratings. Furthermore, Tee et al. (1988) studied the viability of developing a numerical approach based on fuzzy set rules such that the degree of subjectivity involved in evaluating bridge deterioration was treated systematically and was incorporated into a systematic knowledge-based system. Liang et al. (2002) proposed grey and regression models for predicting the remaining service life of existing reinforced concrete bridges. In their study, the fuzzy logic concept was introduced as a methodology for evaluating the extent of deterioration of existing bridge structures. Zhao and Chen (2002) proposed a fuzzy logic system for bridge designers to help to predict bridge deteriorations based on factors incorporated at the initial design phase. Sasmal et al. (2006) recalled earlier studies using fuzzy logic theory and stated that those methodologies were either much too simple or too

complex so that key support requires considerable time. In another study, Jain and Bhattacharjee (2012) studied the applicability of fuzzy logic theory to visual evaluation of deteriorated bridges to minimize the degree of subjectivity in condition assessments. In their study, a fuzzy set methodology was developed based on the vertex method and defuzzification in order to determine elemental indices. Furthermore, Srinivas et al. (2016) developed a fuzzy logic decision support system for condition assessments and ratings based on existing bridge deterioration data in order to assist stakeholders plan for maintenance strategies systematically at the operation stage.

In summary, earlier research work overlooked key issues pertaining to membership functions and other parameters; such as, priority vectors and mappings, which are fundamental for bridge condition assessments.

In this thesis, a numerical methodology for forecasting deterioration predictions of bridges at the conceptual design stage is implemented based on fuzzy mathematics integrated with an eigen-vector technique and priority ratings.

2.12 Artificial Intelligence

Artificial Intelligence (AI) is a scientific and specialized approach to deduction, reasoning and problem solving. It is also referred to as the design of intelligent ‘agents’ such that an engineered system recognizes the problem encountered and processes input functions by deduction, reasoning and, finally, problem solving in an attempt to reach the best solution. The main goal of developing such intelligent systems is to train the system for 1) deduction, reasoning, and problem solving; 2) knowledge representation; 3) planning; 4) learning; 5) natural language processing; 6) perception; and 7) motion and manipulation. Common approaches of artificial intelligent agents include: 1) statistical methods; 2) computational

processes; and 3) traditional systems (Kawamura et al., 2003). Furthermore, intelligent agent tools include search and optimization engines and approaches based on numerical approximations and statistical technologies.

Intelligent agents are either logical or sub-logical agents such as neural networks. Tremendous research efforts have been expended to overcome the mysterious complications of neural networks. Kawamura et al. (2003) developed a knowledge based system in parallel with neural networks to perform the explicit function of assessing deteriorating bridge superstructures. In their study, the authors focused their efforts on incorporating the proposed expert system by a back propagation method. However, the system was found to create a tremendous number of inferences during its operation, which resulted in complex, inefficient, and unviable processes. In one study, Jinsong et al. (2007) proposed a probabilistic model based on neural networks to assess the reliability of long span bridges. In their study, sensitivity analyses pertaining to diverse failure modes were analyzed to validate the proposed model efficiency and accuracy. In another study, Callow et al. (2013) developed an artificial intelligence-based optimization model comprising case-based reasoning and a genetic algorithm to determine condition assessment ratings for bridge deterioration long-term predictions.

2.12.1 Intelligent Computational Agents

Presently, bridge design involves a large amount of subjectivity in the selection of bridge type, system, and material at the conceptual stages. Malekly et al. (2010) proposed a methodology of implementing quality functions, a client-based quality management system based on bridge users' relative importance perception on a set of defined competitors and the technique of preference by similarity to ideal solution (TOPSIS), a multi-criteria analytical approach used for the selection of the best bridge design alternative based on a specified list

of parameters. Their methodology takes a novel approach while overcoming interoperability issues among the databases. On the other hand, Otayek et al. (2012) studied the integration of an intelligent decision support system using Artificial Intelligence (AI) and Neural Networks (NN). The authors recommended further development in decision support systems to try to assist bridge designers in selecting bridge types at the conceptual phases.

In this thesis, the developed system includes an intelligent system comprising quality functions and TOPSIS along with design-related attributes for bridge type selection integrated with elemental cost estimation for bridges at the conceptual design stage. When compared to other simple weighted average methods, such as FAHP, and Neural Networks, TOPSIS provides both quantitative and qualitative study of the problem besides providing more accurate and faster decisions than FAHP (Fuzzy Analytic Hierarchy Process) and Neural Network. Moreover, TOPSIS prevents rank reversing and is better suited to the problem of preferred alternative selection pertaining to changes of alternatives and criteria, agility and number of criteria.

2.12.2 Simulated Annealing

Presently, many in the manufacturing industry are attempting to enhance production streams using simulation models, but the construction industry is in dire need for simulation models since they are worthwhile approaches for sequencing various earthmoving operational processes. Simulation models are powerful because they enable the user to predict earthmoving flows, minimize shortages of equipment resources, and test various what-if scenarios. Generally, simulation models are capable of supporting static operational environments; however, in logistics settings, dynamic approaches are a necessity to accurately define complex earthmoving processes. König et al. (2007) developed a simulation model to enhance the sequencing of civil engineering and ship building industry work

packages, based on a definite set of constraints. This approach, Simulation of Outfitting Processes in Shipbuilding and Civil Engineering (SIMoFIT), allow existing project and process conditional states to be readily defined and integrated by altering or even eliminating constraints. According to Beißert et al.'s (2007) continuation of König's work, the approach incessantly verified constraint requirements throughout the entire simulation process and only strictly valid executable schedules are simulated. Afterwards, a simulated annealing approach was defined and successfully integrated into the developed simulation approach in order to obtain optimized scheduling results. In their study, the entire simulation approach was incorporated in considerable detail. A case study was used to validate the simulated annealing approach and to illustrate its capabilities for optimizing linear scheduling of bridge earthmoving logistics. Furthermore, Hasancebi and Dogan (2010) studied the viability of implementing simulated annealing to optimize the design of bridge truss components. As part of their study, an optimization model was developed to customize truss components based on a definitive set of design code constraints. In another study, Marti et al. (2016) proposed a heuristic simulated annealing approach and a rule of acceptance technique for automating the design of bridge decks. In their study, the authors concluded that the heuristic approach provided optimum design and subsequently minimized bridge deck construction costs.

In this thesis, the simulated annealing approach is incorporated into the expert system as a scheduling forecasting technique at conceptual design stages that permits a scheduler balance the productivity rates and maintains work continuity at the conceptual design stage. When compared to other methods such as traditional genetic algorithms and tabu search, simulated annealing enhances operation schedules through task substitution where an optimized schedule is obtained by replacing a current solution with an improved solution. Besides that, the simulated annealing approach is capable of accepting rejected solutions to escape local minima as most simulation approaches have the pitfall of locking at a local minimum

resulting in time-consuming, error-prone solutions.

2.13 Linear Scheduling

2.13.1 Introduction

Linear scheduling is a technique utilized in heavy civil work such as airports and highway bridges projects and known to be a unique means of resource allocation for earthmoving operations with a linear curve display of the time-space interface (Hinze, 2008). According to Hinze (2008), implementation of linear scheduling is very appropriate for horizontal construction projects comprising concurrent and repetitive operations. Linear scheduling represents a particular earthmoving operation as a 2D linear production curve with station/location and time on the y- and x-axes respectively. Typically, production lines are shown as linear curves with constant slopes; however, in practical situations, a particular operation features inconsistent slopes due to dynamic production rates attributed to specified large quantity, level of work complexity, erratic weather conditions and job-related circumstances (Hinze, 2008).

2.13.2 Related Research Work

Most heavy earthmoving applications and computational studies focus on complex factors; however, none of the studies include or perform linear scheduling optimization comprising time and cost controls and tracking during post-operational stages. Typically, construction managers at major construction projects involving heavy earthmoving operations expect to successfully complete the complex task of a particular job while enhancing logistical productivity and efficiency throughout, but, as most scheduling optimization studies point out, achieving these goals requires directly and effectively planning, scheduling, and controlling integrated systems. For example, Halpin and Woodhead (1976) developed a model based on queuing theories, while others investigated the development of simulation and optimization models. According to Reda (1990), the four main objectives of planning and

scheduling heavy earthmoving logistics are as follows; (1) resource optimization; (2) resource balancing during both pre-and post-construction phases; (3) selection of the “best” equipment to suit the task while taking into consideration geographical constraints and equipment specifications; and (4) successfully completing a project through time-cost optimization interrelated analogies. Considerable work has been conducted to develop models for managing, controlling, and scheduling earthmoving operations. These studies are of major significance; however, their proposed systems have major shortfalls in regards to their capability in providing effective interaction within the bridge equipment fleet, simultaneous evaluation of providing reliable scheduling estimates of combined loading-hauling operation travel times, and providing dynamic real-time configuration scenarios during post-operational stages. Other studies focus more on linear scheduling of bridge earthmoving operations.

According to Hinze (2008), few resources in the literature have focused on the linear scheduling method and have reflected information on current trends in scheduling, such as short-interval scheduling, computer scheduling, and linear scheduling. In one study, Tang et al. (2014) proposed a multi-objective optimization model comprising linear scheduling and a constraint-based programming to control scheduling during railway construction stages. In another study, Su and Lucko (2016) investigated the effect of multiple crew theory with discontinuous functions on linear schedules. In their study, a new approach to productivity scheduling methods was proposed based on what-if scenarios for multiple crews in linear construction projects. Typically, scheduling forecasts at early planning stages are highly influenced by the subjective nature of the scheduler and the availability of information resulting in deterministic linear schedules. Past research has focused on linear scheduling during operational phases rather than during early design stages. Since scheduling uncertainty is not addressed, this causes major conflicts. As stated earlier, related research work has

shown that the linear scheduling method may be used as an alternative tool for scheduling phased repetitive construction operations, providing a visualization of scheduling information, not available with traditional scheduling methods, such as GANTT charts, in terms of relating operation and production rates with time- and space-related constraints. However, it is important to note that, typically, all operations are considered to be critical in linear scheduling and work continuity must be maintained consistently throughout a project in order to achieve efficiency in heavy earthmoving projects. Also, none of the studies have addressed the major shortfall of determining effective near-optimum linear scheduling solutions for heavy earthmoving operations.

In this thesis, the goal is to design, implement, and enhance earlier relative work on optimizing linear schedules in heavy earthmoving operations as follows; 1) unifying the process of optimizing fleet productivity rates while taking into account temporal variability; 2) satisfying time- and space-related constraints; and 3) modeling an integrated stochastic simulated approach for optimizing linear schedules. Furthermore, linear scheduling is deployed as a strategic scheduling forecasting technique at conceptual design stages that permits a scheduler to balance the productivity rates and to maintain work continuity while refraining from idle production resources.

2.13.3 Constraint-Based Simulation

Modeling linear scheduling simulations as constraint satisfaction problems is a thoughtful pattern capable of solving diverse scheduling conflicts. According to Rossi et al. (2006), constraint-based simulation problems are typically defined by a set of variables and corresponding constraints such that constraint parameters specified for a defined set of variables must be satisfied for one operation prior to proceeding to the next one.

2.14 Summary

An overview of earlier research work pertaining to decision support systems and artificial intelligence is presented. Diverse fuzzy logic concepts and intelligent computational agents are illustrated. Besides that, research work related to the application of stochastic linear scheduling technique for heavy earthmoving operations is recalled. In addition, the simulation annealing approach for optimizing deterministic and stochastic linear scheduling is presented. Furthermore, optimizing linear scheduling for repetitive construction operations is a critical key towards the success of a project. Hence, developing a methodology for optimizing linear schedules that includes overall bridge components in addition to earthmoving operations is a necessity.

In this thesis, a line of balance system comprising a comprehensive bridge earthmoving linear scheduling module is implemented and incorporated within the fuzzy logic decision support system. Furthermore, the developed system is capable of generating a near-optimum line of balance at the conceptual design stage by utilizing the constraint-based simulated annealing approach for bridge construction operations.

CHAPTER 3

RESEARCH METHODOLOGY AND DEVELOPMENT

3.1 Introduction

This chapter presents the research methodology and development process of integrating an expert system with a bridge information management system (BrIMS) and cost estimation for bridges at the conceptual design stage. The developed system is designed to accommodate future improvements and advancements that would enhance its capabilities. Overcoming system constraints and fulfilling user requirements are also key goals in the development strategy. Hence, an actual case study of a bridge project is used to evaluate the developed system's degree of accuracy and relative efficiency in numerical computations and estimations.

All four phases of the development methodology are explored in detail using the case study. In order to achieve the set objectives, a defined research methodology process is performed as shown in Figure 3.1.

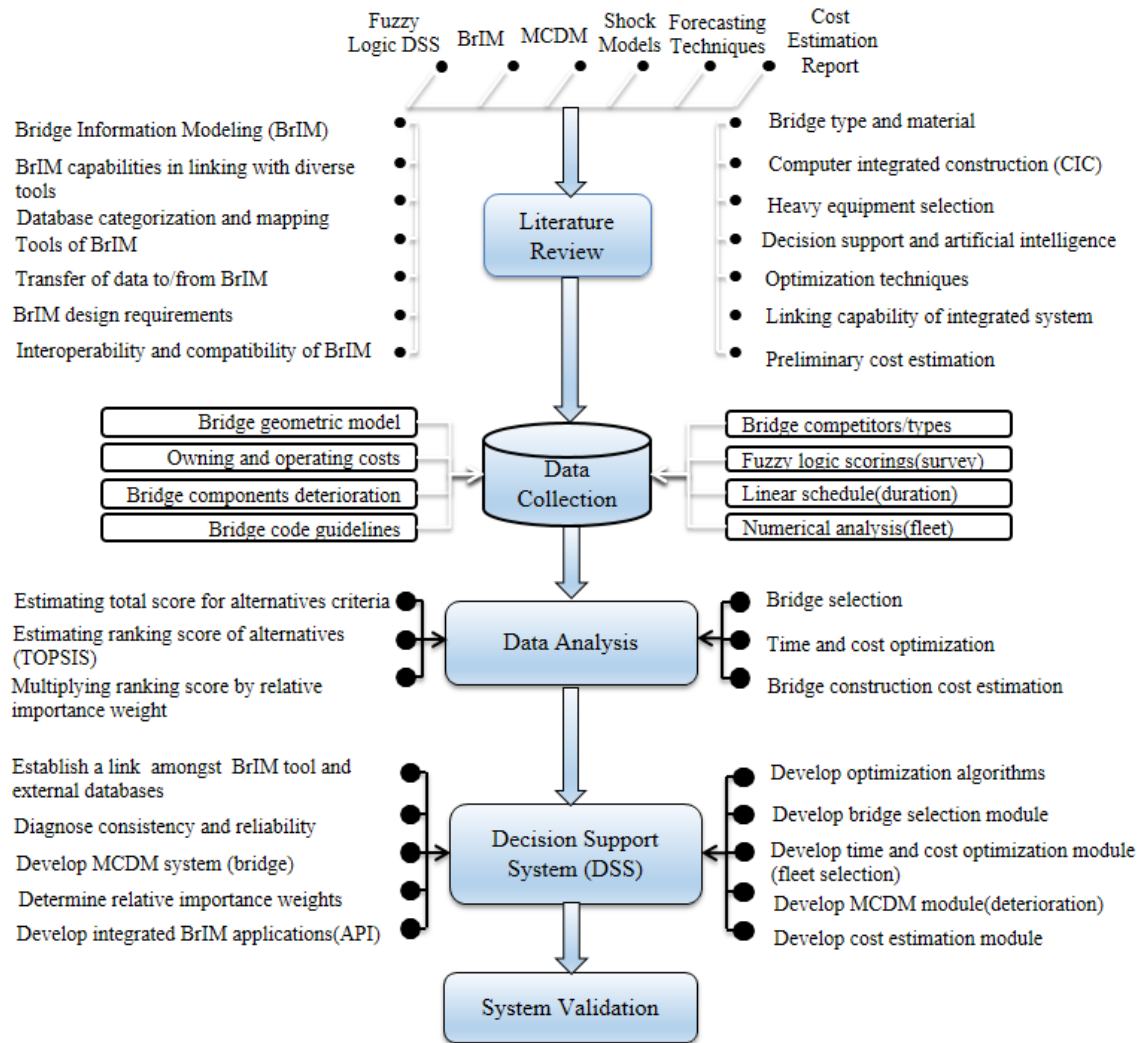


Figure 3.1 Research Methodology Process

3.2 Data Collection

Data pertaining to bridge cost estimation utilized in the development of the expert system are based on R.S. Means heavy construction cost data for the year 2012. In this thesis, construction cost data for the year 2012 had been implemented; however, the developed system databases may be updated to a later version of construction cost data at user discretion. Data pertaining to bridge earthmoving logistics are obtained from the heavy equipment manufacturer, Caterpillar®, pursuant to the types and specifications of equipment. Due to the variety and wide range of equipment types, data refinement is important to ensure there shall be no conflict during the system development. The most important step in

analyzing equipment operations is to understand the characteristics of the materials to be transferred, which in turn affects the type of equipment required to successfully complete the project. Therefore, diverse materials properties are extracted from the Caterpillar® Performance Handbook for the year 2011 and stored in the database incorporated into the developed system. Also, mathematical formulas for the operational analysis are incorporated into a set of modules to conclude the data collection phase. Some of these data are tabulated in order to enhance the system's capability of interfacing with the information that has to be entered by the user. In this thesis, Caterpillar® performance handbook for the year 2011 had been implemented; however, system databases may be updated to a later version of the performance handbook at user discretion. Furthermore, the database of information incorporated into the system includes a variety of equipment capacity, power, and maximum allowable weight which enables the developed system to be applied to various construction projects regardless of the volume and types of material involved. Multiple adjustments are made to allow the synchronization of the bridge construction cost database with expert system modules.

3.3 System Architecture and Components

The developed system is designed in a hierarchical modular format comprising the following five main modules: i) 'CONCEPTUAL BRIDGE DESIGN'; ii) 'FLEET SELECTION'; iii) 'PRELIMINARY COST ESTIMATION'; iv) 'DETERIORATION FORECAST'; and v) 'BRIDGE LINE OF BALANCE.' The developed system is implemented in an object-oriented .NET framework and undertaken by following these six main steps: 1) data collection of bridge-user-driven parameters; 2) implementation of a decision support system that assists the user in making decisions about bridge design alternatives; 3) development of complex quality functions to evaluate bridge users' relative perceptions of bridge components; 4) deployment of a numerical model to evaluate bridge component ratings; 5) development of a

mean deterioration resistance regression fit where component rankings are determined; and 6) optimize and prioritize maintenance, repair, and replacement (MR&R) alternatives. In order to synchronize bridge information, a schematic view of the developed system's architecture process illustrating interrelations among the 3D BrIM solutions with preliminary cost estimation is presented in Figure 3.2.

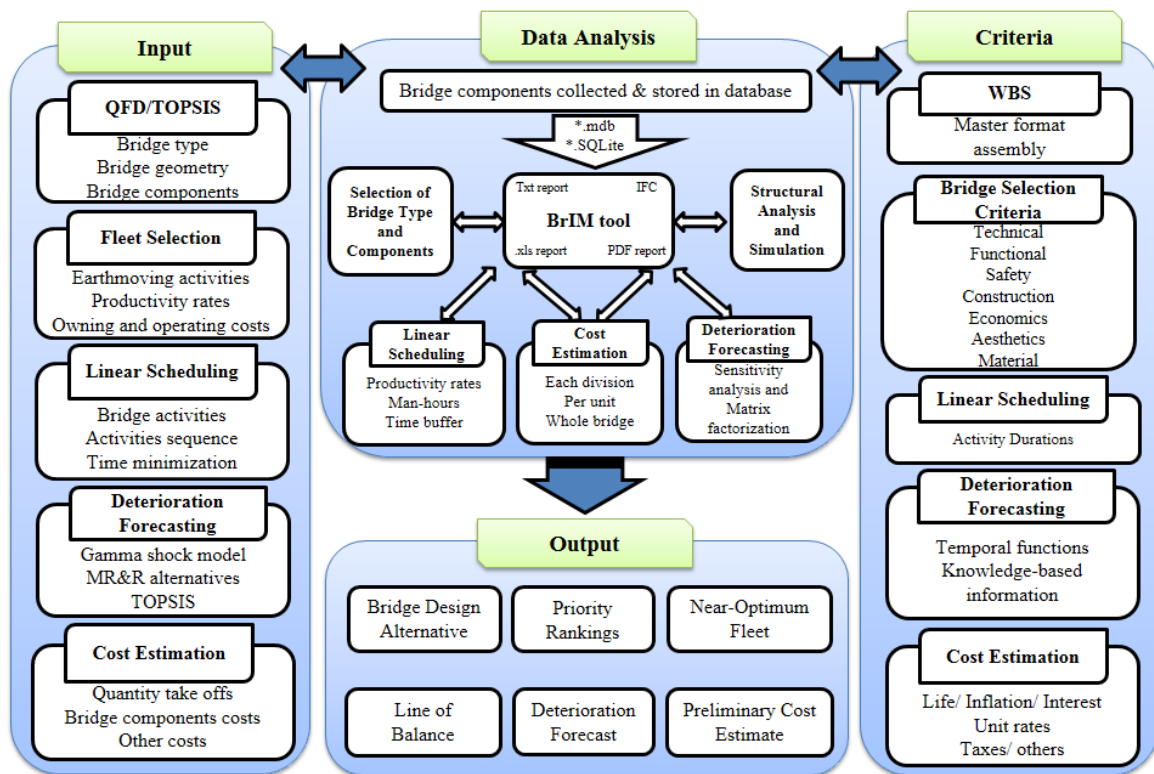


Figure 3.2 System Architecture

Based on afore-mentioned, system requirements and components are defined and categorized accordingly. The most important thing for an integrated development methodology is a system that facilitates the effective integration of information and contributes towards less error prone outcomes. In addition, fostering proper share of project information among the developed system components is illustrated in Figure 3.3.

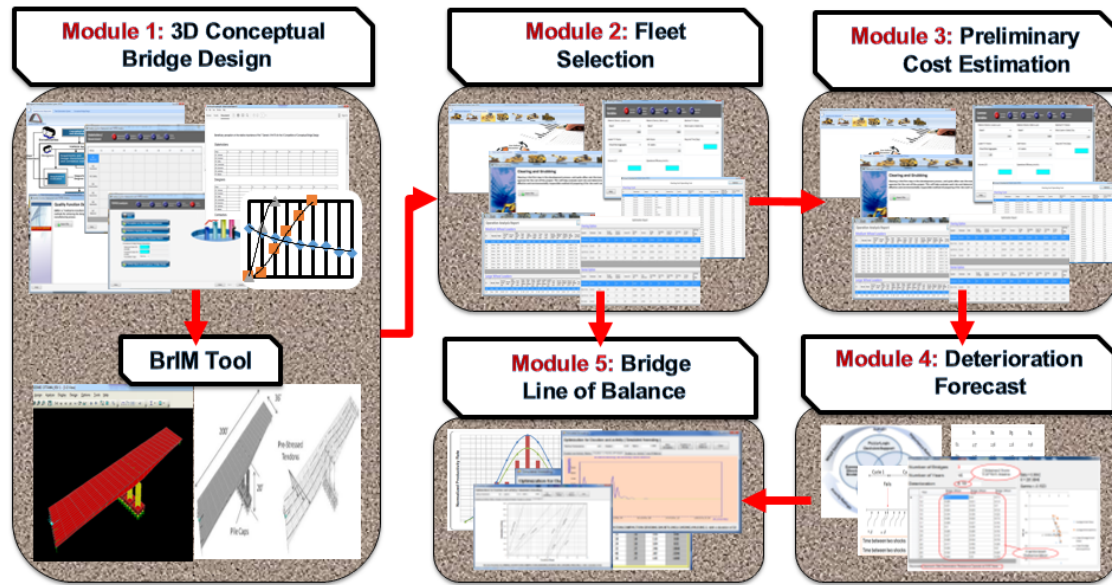


Figure 3.3 System Components

As illustrated in Figure 3.3, the system comprised of five main system components developed in a modular and sub-modular formats as follows: 1) 3D conceptual bridge design which includes the BrIM tool; 2) fleet selection; 3) preliminary cost estimation; 4) deterioration forecast; and 5) bridge line of balance. Furthermore, the expert system is developed in such a way where the user may proceed directly from “Module 2: Fleet Selection” to “Module 5: Bridge Line of Balance” to determine a bridge linear schedule as shown in Figure 3.3.

3.4 System Integration

The proposed methodology includes the development of a BrIMS based on a strategic framework that is capable of integrating a fuzzy logic decision support system with bridge linear scheduling, deterioration forecasting, and cost estimation through the deployment of complex quality functions derived from bridge-user-driven parameters and symmetrical triangular fuzzy numbers (STFN's) to assist bridge stakeholders and designers in the selection of bridge type and to determine the construction costs at conceptual design stage.

Based on this, the developed system requirements and components are defined and categorized accordingly. The intensive review of the literature presented in Chapter 2 help defining the corresponding system's components. The most important outcome during the development of an integrated methodology is a system that facilitates the effective integration of information and contributes towards less error prone results as well as fostering proper sharing of project information among participants via a user-friendly interrelated tool that is available upon request. The implementation of the developed integrated system is undertaken by the following five main phases is illustrated in Section 7.5.2.

3.5 System Modules

A proper handling of the modeling data will results in less error-prone outcomes that tend to be caused by duplication or amalgamation of inconsistent bridge database resources. To overcome the subjective nature of bridge type selection, the developed system includes a unique aspect of BrIMS by incorporating bridge types and associated components into a multi-criteria decision making (MCDM) approach to derive priority ratings among competitive alternatives. The developed integrated system consists of five major modules as follows:

3.5.1 Module 1: Conceptual Bridge Design

In this thesis, the methodology of Malekly et al. (2010) is adopted and integrated into a novel approach, while overcoming interoperability issues among the diverse databases. First, bridge users are identified along with the seven main (WHATs) criteria as follows: 1) technical, which is defined by design-related parameters such as bridge span; 2) functional, which is defined by practicality such as number of lanes and width; 3) safety, which is defined by protective measures against risk such as lane barriers; 4) construction, which is defined by the obstacles that hinder construction such as traffic diversions; 5) economics, which is defined

by the funds required to construct the bridge; 6) aesthetics, which is defined by architectural concept and design; and 7) material, which is defined by the type of material used to construct the bridge. The (WHATs) criteria are developed based on earlier research work, bridge design guidelines, and practitioners' recommendations to minimize the degree of subjectivity involved in the selection of bridge design, type, and material. There are generally four main bridge users, i) shareholders; b) designers c) contractors; and d) public. Generally, the main focus is on the ultimate user who could be identified through public feedback and research. Bridge users' perception on the WHATs criteria are used to calculate criterion weights. The best approach for obtaining users' perceptions on the seven WHATs is either by face to face straight-forward interviews or public feedback. For instance, an interview component for the "technical" WHAT are: "What is (user) score from 1 to 10 on the fuzzy-logic scoring system for a bridge (Technical) criterion?" Secondly, relative importance ratings of user needs are determined. Typically, user needs (WHATs) are of variable degrees of importance.. The final average set of ratings is determined based on users' perceptions on the WHATs' relative importance. Then, bridge type competitors are identified for users' competitive analysis. Bridge users' perceptions on the relative importance ratings for bridge competitors on each WHAT are obtained. Useful ways of conducting this kind of comparison analysis are public feedback and individual face to face straight-forward interviews. Corresponding scores from public feedback including WHATs criteria and bridge competitors are recorded and transformed into a digital format to be inputted into the conceptual bridge design module for analysis in measure, crisp and fuzzy forms. As part of developing the module, responses from interviewees are collected and analyzed to assess their influence on the seven WHATs criterion weights. The results showed that the number of interviewees was of little or no influence on criterion weights. However, if a WHATs criteria on is eliminated, the weighting process is affected and data sensitivity analyses would then be required to quantify its degree of accuracy.

Following bridge users' assessment of WHATs criteria on bridge competitors, relative importance perception ratings in crisp and fuzzy forms is obtained. Furthermore, the probability distribution and corresponding measure of entropy of WHATs criteria are determined. Afterwards, a user competitive matrix is established where parametric weights are assigned for TOPSIS analysis. Then, a set of bridge design parameters comprising; (i) technical span; (ii) functional span; and (iii) foundation type are required. Afterwards, the development of a TOPSIS matrix is undertaken followed by normalized decision and weighted matrices. Next, the determination of the positive and negative ideal solutions is performed and set as the reference datum. At the end, separations from positive and negative ideal solutions are obtained followed by a TOPSIS relative closeness to ideal solution decision matrix with priority ratings.

Following the determination of the bridge competitors' priority ratings, the user is directed to input technical and functional spans and the foundation type. Then, the developed system is capable of proposing bridge substructure and superstructure material and profile. The user is then provided with a set of three curves that serve as guidelines for the recommended bridge type, system, and material for BrIM model's implementation. Moreover, logarithmic and polynomial functions for three set of results are developed in order to provide the user with a 'virtual' numerical measure of the nominated bridge design alternative. Once the user is provided with a TOPSIS matrix for bridge type selection, geometrical parameters of the bridge model are inputted into the BrIM tool for preliminary load application and design analysis. In this thesis, SAP2000 is the selected BrIM tool and later substituted by CSiBridge since it includes a dedicated bridge designer module that complies with AASHTO LRFD-09 and CALTRANS seismic design requirements. Also, its user-friendly interface permits the user to customize seismic design code requirements and model complex bridge structures.

The tool features an Eigen-value buckling procedure based on a subspace Eigen-solver through an accelerated iteration algorithm.

Towards the end, bridge vehicular moving load, transverse load bearing, and basic dynamic analyses are conducted. Bridge design reports illustrating required bridge girder sections with corresponding load and moment resistance capacities are readily displayed for the preliminary design. Afterwards, the user is guided to the next module where relevant data pertaining to fleet selection is required. Figure 3.4 summarizes the conceptual bridge design module process flowchart.

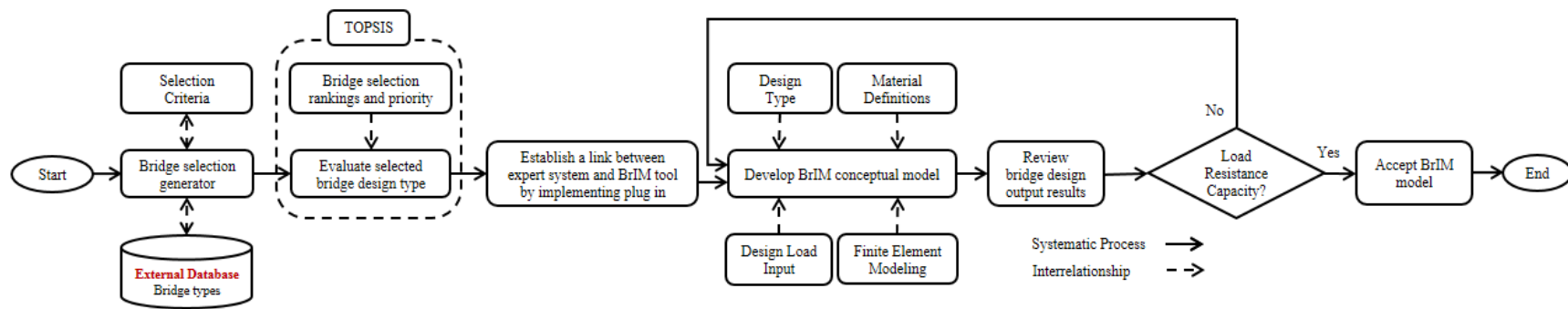


Figure 3.4 Conceptual Bridge Design Module Process Flowchart

As illustrated in Figure 3.4, the conceptual bridge design module comprises the establishment of a DLL-invoked API link to facilitate the interoperable transfer of information between the expert system and BrIM tool, CSiBridge. The link is developed as a plug-in algorithm that is hard-coded and incorporated within CSiBridge to enable the user exchange information among the developed system modules. The plug-in is developed within an object-oriented .NET framework while utilizing SQLite database, which is capable of enhancing interoperability among database applications. Within CSiBridge, an add-on file is designed as a neutral file format accompanied with an extensible markup language (XML) schema. The XML file is defined and located within CSiBridge in order to facilitate the transfer of information between the conceptual bridge design module and the decision support system automatically by using the developed plug-in.

The detailed systematic process for the development methodology of the conceptual bridge design module is presented in Chapter 4 – Technical Paper I.

3.5.2 Module 2: Fleet Selection

Once conceptual bridge design is developed, the total quantity of earth to be removed for the bridge construction is automatically extracted from CSiBridge and imported into to the fleet selection module. Most importantly, the total quantity of earth to be removed is dependent upon the selected bridge type, system, and components in addition to the customized BrIM model based on the span and foundation type recommendations obtained from Module 1. Following the user's input of all necessary scope of work-related parameters, the developed fleet selection module is designed to efficiently undertake operational analysis mathematical formulations. After that, output data is stored and recalled for owning and operating cost computations, which

would be further analyzed for optimization. Furthermore, since heavy equipment selection for bridge earthmoving operations is an essential component, operation analysis for selected types of equipment based on comprehensive owning and operating costs is performed for major operations of earthwork. The developed system module is integrated and implemented within the integrated system as shown in Figure 3.5.

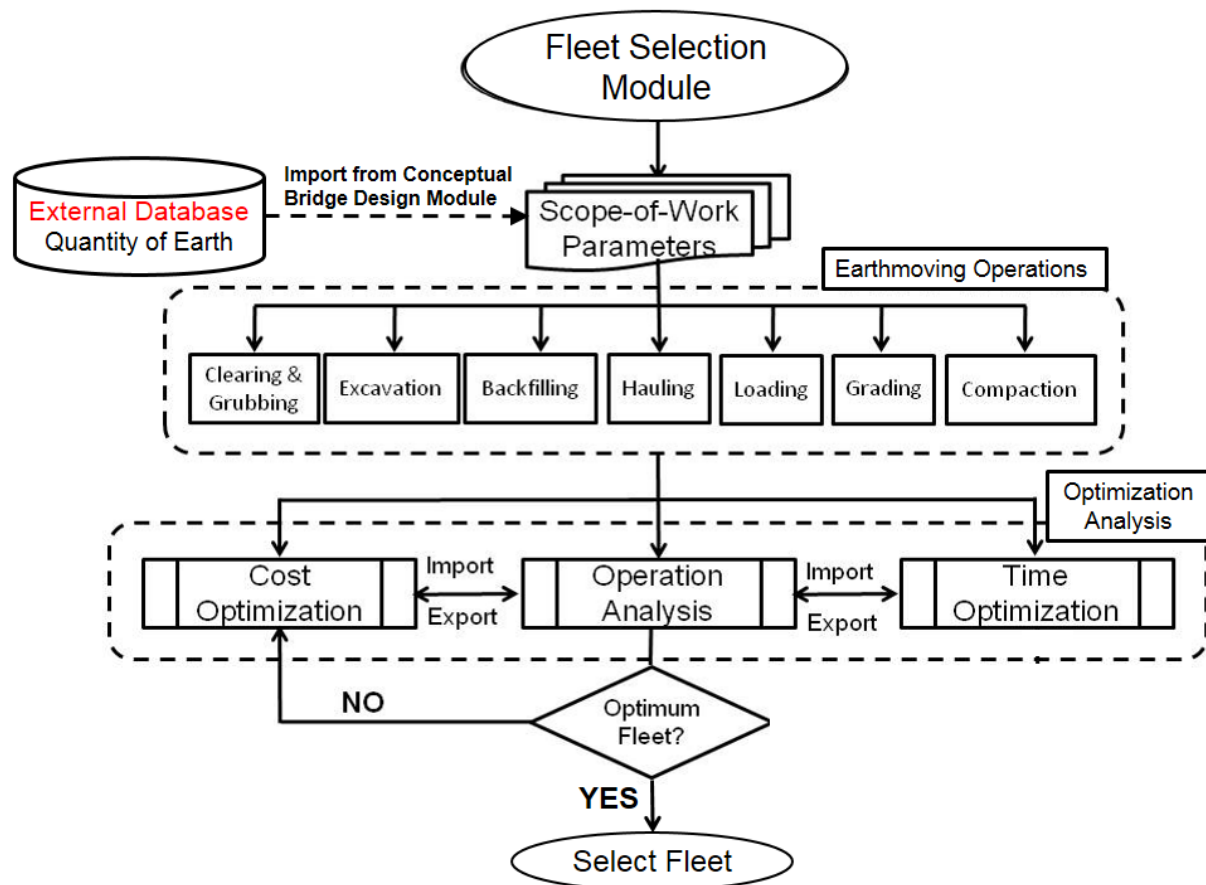


Figure 3.5 Fleet Selection Module Components

As illustrated in Figure 3.5, the economical optimization of equipment fleet operating on diverse types of soils proves the workability of the system. The main purpose of the developed module is to facilitate the interface between operational analyses, user input data, and cost minimization functions. The fleet selection module comprises seven bridge earthmoving operations that are

organized by operation names where every operation has four sub-modules. The sub-modules are as follows; (1) an operation analysis sub-module that comprises equipment operation analysis; (2) an economic analysis sub-module that includes all owning and operating cost-related parameters and calculations; (3) a cost minimization sub-module that displays near-optimum results; and (4) a report sub-module, which contains professional output reports that summarize results extracted from the cost minimization sub-module. Figure 3.6 summarizes the fleet selection module process flow chart.

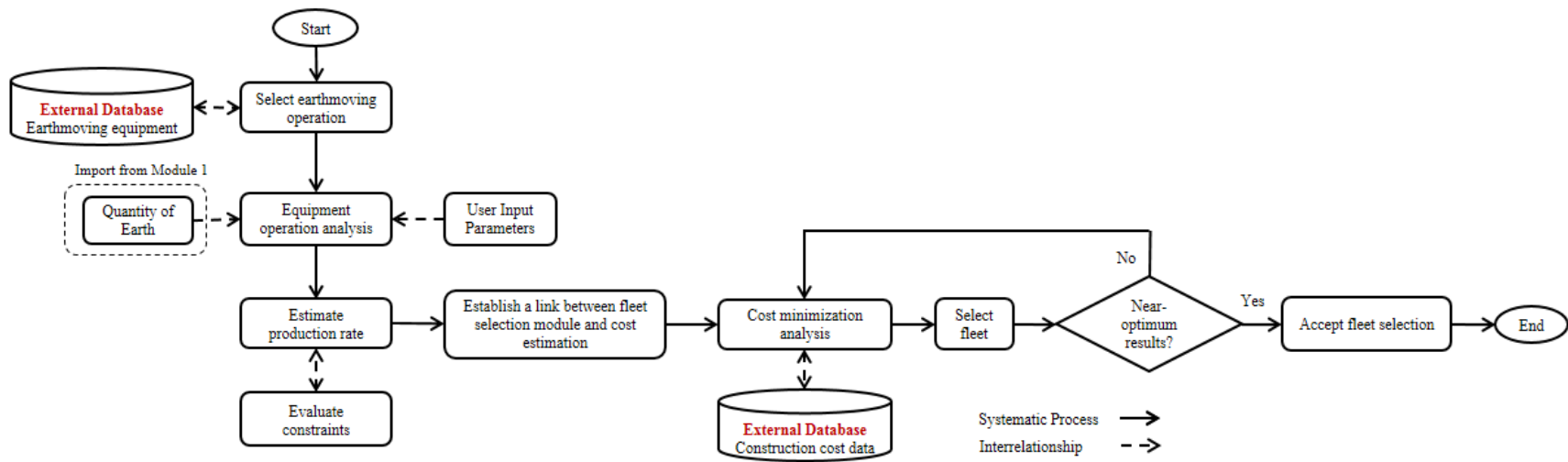


Figure 3.6 Fleet Selection Module Process Flowchart

As illustrated in Figure 3.6, the developed module is designed to automatically extract the quantity of earth from Module 1. Then, the user selects the required earthmoving operation(i.e., clearing and grubbing, excavation, loading, hauling, backfilling, grading, and compacting) from a user-friendly gateway. At this time, the user enters job-specific data required to execute the equipment operation analysis. It is important to note that the data required for the economic operation analysis vary from one earthwork operation to another; however, (1) material density; (2) fill factors; (3) safe factors; (4) time constraints; (5) amount of work; and (6) operational efficiency is a common list of data variables among all seven earthmoving operations. The quantity of earth to be undertaken is measured in terms of volume of earth material in loose cubic yards (LCY) and automatically extracted from 'Module 1: Conceptual Bridge Design, which in turn is used by the economic operation analysis in order to obtain the near-optimum fleet. The user is then directed to validate the input data and to ensure all constraints are satisfied. If any constraint set by the developed module is not satisfied, an error message pop ups to notify the user that a few pieces of equipment will not be considered in the optimization process. After reviewing all of the earthmoving operations numerical analyses, the user is guided to the owning and operating cost sub-module for fleet cost-related analyses. Cost data pertaining to heavy earthmoving equipment is necessary for optimizing selection. It is, after all, about minimizing equipment comprehensive owning and operating costs while taking into consideration factors and constraints that govern the selection process. The developed fleet selection module includes 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, operating costs include; (a) fuel; (b) service; (c) tire replacement; (d) emergency reserves; (e) wages; and (f) wear items. The Caterpillar® Performance Handbook (2011) is used to obtain data pertaining to heavy equipment ownership and rental costs, whereas, bridge construction unit costs are obtained from the R.S.

Means for heavy construction cost data handbook. Once completed, cost minimization approach is performed for selected fleet based on a list of requirements and constraints represented as linear relationships. All constraints obtained from the operation analysis are represented in a mathematical form and incorporated into the cost minimization sub-module. After inputting all necessary information, the developed module is capable of determining the near-optimum fleet. The results include the required number of equipment, equipment productivity (LCY/hr), and corresponding unit cost (\$/LCY).

A detailed systematic process for the development methodology of the fleet selection module is presented in Sections 3.6 through 3.11.

3.5.3 Module 3: Preliminary Cost Estimation

Once fleet selection is completed, equipment owning and operating costs are automatically extracted and stored into the cost estimation database. Furthermore, bridge design-related parameters are recalled from the BrIM tool, CSiBridge, and incorporated into the cost estimation database. First, main bridge components are identified and organized into a UNIFORMAT II work breakdown structure (WBS). Second, 'Level I – Major Group Elements' are categorized as follows: (1) substructure; (2) superstructure; (3) protection; and (4) site work. Then, 'Level 2 – Group Elements' are identified as follows: a) piers; b) short span assemblies; c) structure protection; and d) site preparation. Afterwards, 'Level 3 – Individual Elements', such as; foundations, columns, and flexural members; 'Level 4 – Sub-Elements' such as; steel piling, parapet wall, and asphalt, and 'Level 5 – Field Requirements' such as; reinforcement, concrete placement, and finishing's are identified and categorized accordingly. Furthermore, miscellaneous costs such as: 1) site overheads; 2) mobilization/demobilization; 3) contingency;

4) overhead and profit; and 5) tax are also incorporated into the cost estimation module. Then, bridge components quantities, unit costs, and miscellaneous costs entered by the user are used to generate a preliminary cost estimate. Figure 3.7 presents the preliminary cost estimation module process flowchart.

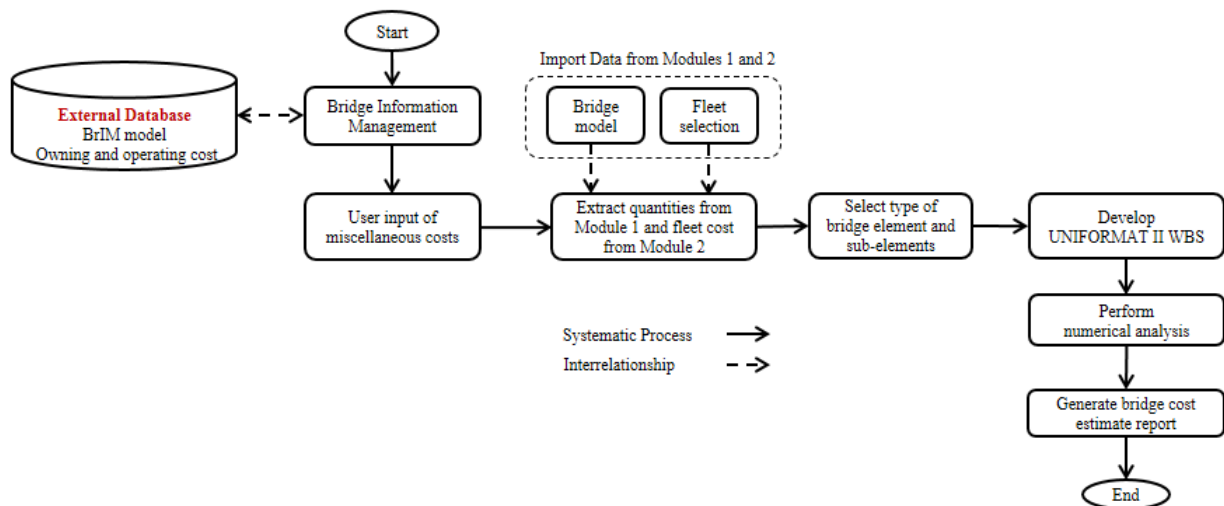


Figure 3.7 Preliminary Cost Estimation Module Process Flowchart

As illustrated in Figure 3.7, the following list summarizes the systematic process for developing the integrated preliminary cost estimation module; 1) data collection, where diverse data pertaining to the bridge information model are collected and stored in a well-designed database server comprising multiple main- and sub-databases along with equipment owning and operating costs; 2) user input, where miscellaneous costs are inputted by the user based on actual site conditions; 3) import data, where data pertaining to bridge design quantities and fleet selection costs are automatically extracted from Modules 1 and 2 respectively and imported into the preliminary cost estimation module; 4) bridge components, where the user is provided with the option to select and/or modify the type and specification of bridge element and corresponding sub-elements; 5) elemental classification, where bridge elements and sub-elements are

categorized into a UNIFORMAT II WBS; and 6) numerical analysis; where systematic procedures for estimating bridge cost estimate at the conceptual design stage are undertaken.

A detailed systematic process for the development methodology of the preliminary cost estimation module is presented in Section 3.5.

3.5.4 Module 4: Deterioration Forecast

Once bridge cost estimation is completed, the user inputs importance ratings on bridge components. Following bridge user's assessment on the importance of bridge components on bridge design alternatives, importance perception ratings are determined. Afterwards, a bridge users' competitive matrix is developed, where the probability distribution and corresponding measure of entropy of bridge components is determined. Once completed, the user proceeds with inputting a set of improvement goals that represent the user's required improvement in performance of bridge components. Following the input of goals, QFD and TOPSIS analyses are undertaken in order to develop priority rankings of bridge components. Afterwards, the user is guided to the HOWs scoring input form, which represents bridge users' importance ratings on bridge maintenance, repair, and replacement alternatives (MR&R) based on the output of QFD and TOPSIS analyses on bridge components. Following bridge user's assessment on the importance of bridge components on MR&R alternatives, importance perception ratings are obtained. Afterwards, a bridge users' competitive matrix is developed, where the probability distribution and corresponding measure of entropy along with competitive ranking of bridge components is determined. Afterwards, the user inputs the year digit and corresponding mean deterioration percentages such that a regression analysis along with the quality of fit methodology is deployed. Once completed, the developed system provide the user a

recommendation statement to reconsider the performance of a bridge component in order to enhance its deterioration resistance capacity, which represents a component's remaining service life. Figure 3.8 summarizes the deterioration forecast module process flowchart.

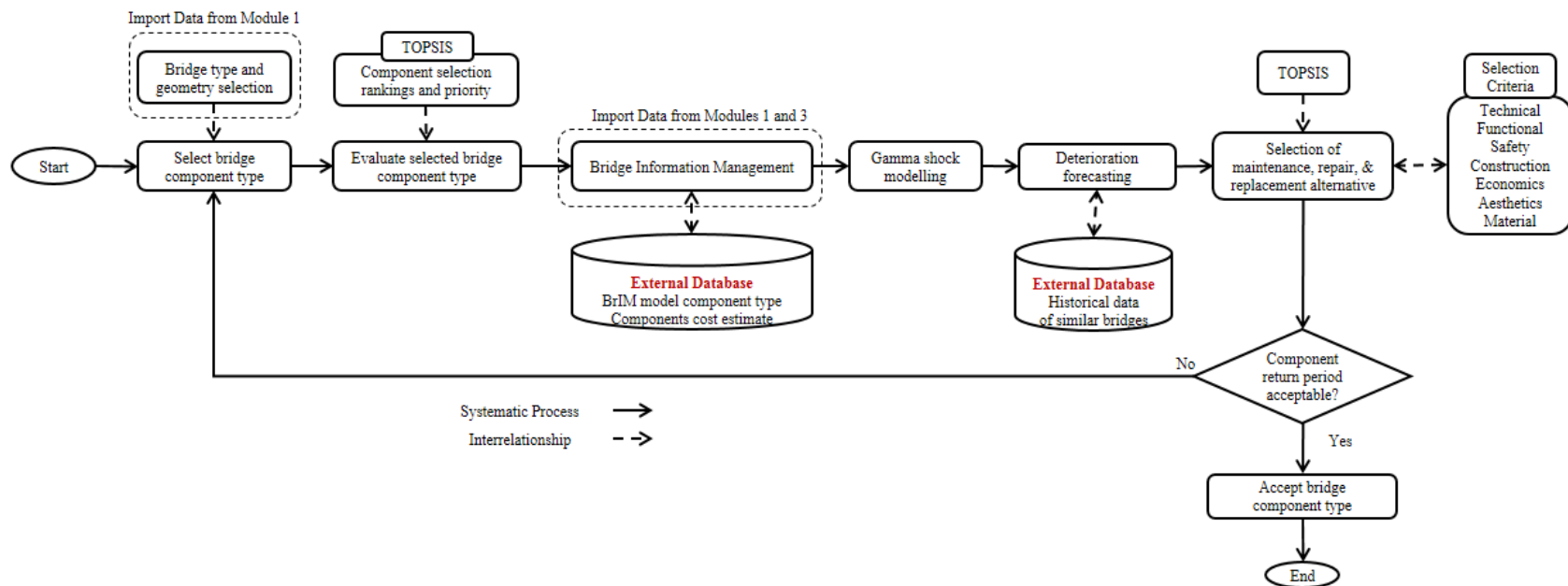


Figure 3.8 Deterioration Forecast Module Process Flowchart

As illustrated in Figure 3.8, the developed module is implemented in an object-oriented .NET framework and undertaken by completing the following five main steps: 1) data collection of bridge type and geometric selection imported from Module 1; 2) implementation of a decision support system that assists the user in making MR&R decisions; 3) development of complex quality functions to evaluate bridge users relative perception of bridge components; 4) deployment of a numerical model to evaluate bridge MR&R ratings; and 5) prioritizing maintenance, repair, and replacement (MR&R) alternatives. In this thesis, the MR&R alternatives are defined as cost representatives of a bridge component. For instance, a maintenance ‘M15’ alternative represents ‘15%’ of a bridge component’s estimated cost.

The flow of geometric information for diverse bridge types and resistance deterioration predictions begins at fuzzy logic scorings and ends at the forecasting of bridge component deterioration based on its cost recovery period. Throughout the process, the deployment of the technique of preference by similarity to ideal solution (TOPSIS), a multi-criteria analytical approach utilized for the selection of the MR&R alternative based on a specified list of parameters is undertaken. The MR&R are identified based on performance condition assessments of bridges in operational stages and grouped into three main categories as follows; Category (I) is a ‘Maintenance’ category that includes the maintenance of a bridge component for an expected extent ranging between 15% to 45% and comprising the decisions; ‘Maintenance: S₁.M15’, ‘Maintenance: S₂.M30’, and ‘Maintenance: S₃.M45’; Category (II) is a ‘Repair’ category that includes the repair of a bridge component for an expected extent of deterioration ranging between 45% to 75% and comprising the decision; ‘Repair: S₄.REPA45’, ‘Repair: S₅.REPA60’, and ‘Repair: S₆.REPA75’; Category (III) is a ‘Replacement’ category that includes the replacement of a bridge component for an expected extent of deterioration ranging

between 75% to 100% and comprising the decisions; ‘Replacement: S₇.REPL75’, ‘Replacement: S₈.REPL90’, and ‘Replacement: S₉.REPL100’.

A detailed systematic process for the development methodology of the deterioration forecast module is presented in Chapter 6 – Technical Paper III.

3.5.5 Module 5: Bridge Line of Balance

Once bridge components’ deterioration forecast is completed, the user is guided towards the bridge line of balance module. First, fleet productivity rates and expected durations obtained from the fleet selection module are automatically extracted and imported into the developed module. The rates are then organized so that a statistical normal distribution can be fitted accordingly followed by the stochastic linear scheduling process. Afterwards, a line of balance is established throughout a simulated annealing approach accompanied by a global minimization objective function where time and space buffer conflicts are automatically detected. Then, the developed module enables the user to modify operations durations to resolve conflicts and determine a near-optimum linear schedule. In order to effectively shape a linear schedule, a normal distribution function is fitted into the histograms and subsequently normalized to calculate expected duration.

Typically, productivity rates are not fixed and are subject to daily and, potentially, hourly fluctuations due to unanticipated occurrences. Hence, it is uncommon to represent a line of balance as a straight line; however, in many cases owners, designers, and construction managers prefer such a representation for indicative purposes at the conceptual design stage. In this thesis, the developed module enables the user to modify the start duration of a particular construction

operation in order to avoid scheduling conflicts between two consecutive operations. Furthermore, the user is provided with the option of entering the time buffer as deemed necessary to determine a near-optimum linear schedule. Figure 3.9 summarized the bridge line of balance module process flowchart.

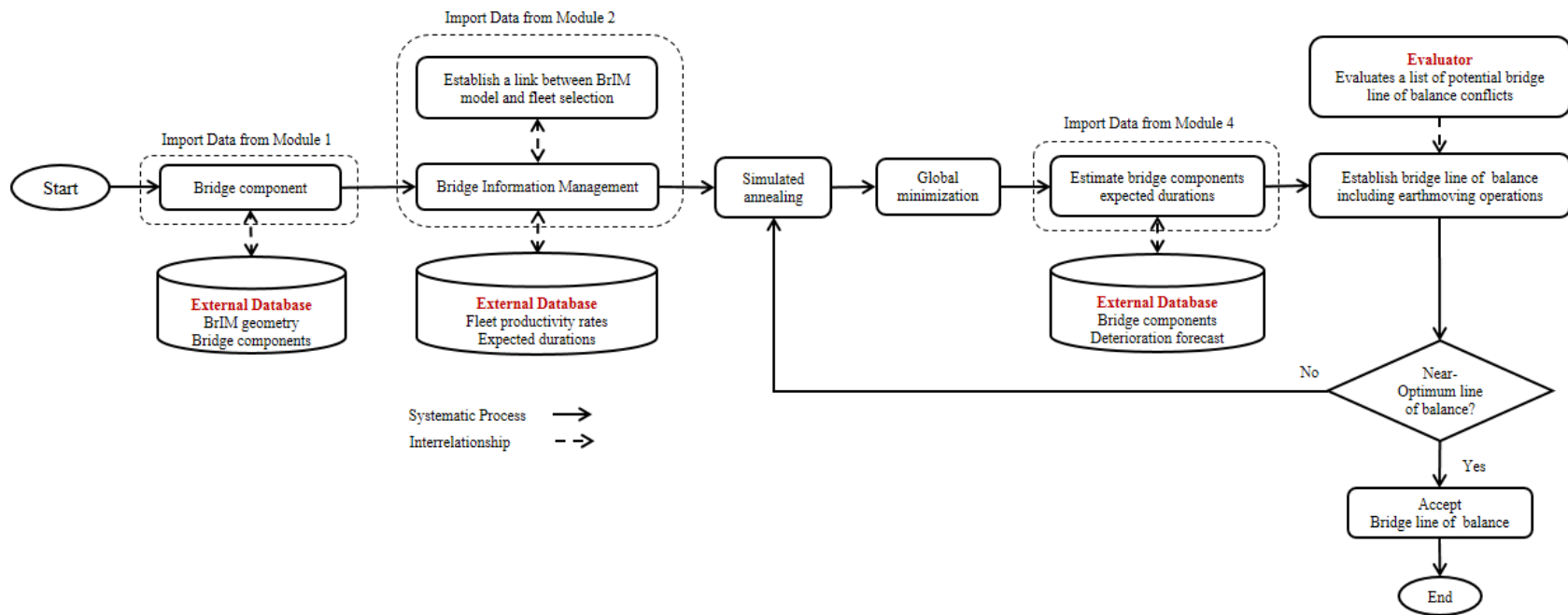


Figure 3.9 Bridge Line of Balance Module Process Flowchart

As illustrated in Figure 3.9, the bridge line of balance module development methodology is divided into the following four main phases: (1) categorization of bridge components; (2) integration of BrIM model and fleet selection module; (3) determination of bridge construction operations expected durations; and (4) deployment of the global integration platform. The first phase imports data from databases of Module 1 pertaining to the selection of bridge component types. These will be necessary for determination of bridge components expected durations. The second phase includes defining the correlated system modules that fit into the bridge information management system (BrIMS) in order to import data from databases of Module 2 pertaining to productivity rates and corresponding expected durations from Module 2. The third phase imports deterioration forecast data from relevant databases of Module 4 in order to determine bridge components' expected durations. The fourth phase is the physical deployment of the system modules to be integrated into the developed expert system. Finally, the last phase is the development of the integrated global platform to determine the bridge line of balance at the conceptual design stage.

A detailed systematic process for the development methodology of the bridge line of balance module is presented in Chapter 7– Technical Paper IV.

3.6 System Databases

Proper integration among interdependent databases and corresponding sub-databases constitutes a reliable information system (Elmasri and Navathe, 2007). Based on this statement, the main framework of the developed system databases is implemented following these two stages; 1) data collection and conceptual modeling; and 2) data categorization and mapping.

3.6.1 Data Collection and Conceptual Modeling

The first step in developing the system database includes problem identification and definition of user needs. After that, a conceptual model of the database is developed. A representation of the relationships among the following five main entities: 1) project; 2) group; 3) element; 4) sub-element; and 5) items illustrated in an Entity-Relationship Diagram (ERD). An ERD is a systematic approach describing data resources as entities or components connected by relationships representing interrelations among them. Relationships among the entities may be one-to-one, one-to-many, or many-to-many (Elmasri and Navathe, 2007). The diverse types of relationships among entities are identified in the ERD as illustrated in Figure 3.10.

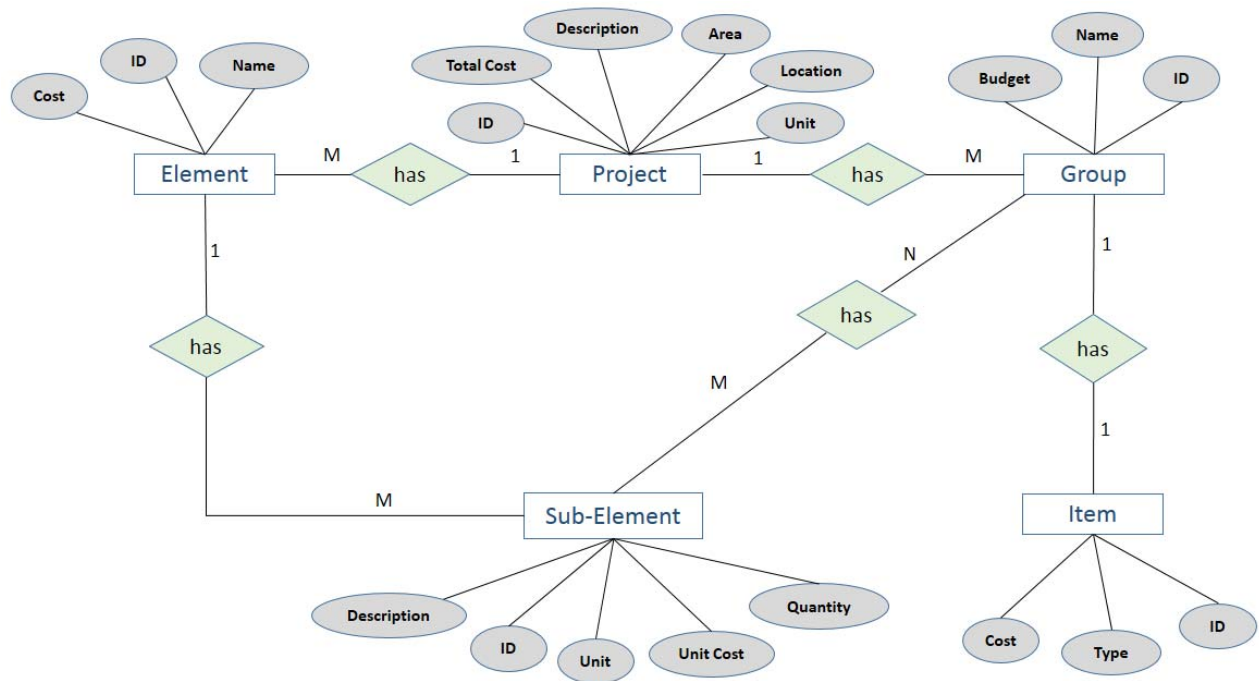


Figure 3.10 Entity Relationship Diagram for Preliminary Cost Estimation Module

As illustrated in Figure 3.10, the entity relationship diagram of the preliminary cost estimation module database is designed such that **entities** are derivatives of domain complexities that logically explain the conceptual model in terms of realistic aspects and are represented by

rectangular shapes; **relationships** represent the interactions among entities that exist in the following diverse types: a) one-to-one (1:1); b) one-to-many (1:M); and c) many-to-many (M:N) and are represented by the diamond shapes; and **attributes** are entities' characteristic properties that exist as: 1) single; 2) composite; or 3) multi-valued are represented by oval shapes (Elmasri and Navathe, 2007). In this process, the following five main entities are defined: 1) project; which includes the following composite attributes: a) ID; b) description; c) area; d) location; e) unit; and f) total cost, 2) group; which includes the following composite attributes: a) ID; b) name; and c) budget, 3) element; which includes the following attributes: a) ID; b) name; and c) cost. 4) sub-element; which includes the following attributes: a) ID; b) description; c) unit; d) quantity; and e) unit cost, and 5) item; which includes the following attributes: a) ID; b) type; and d) cost. Each of these entities has composite attributes including multiple attributes. The three diverse relationships defined for the entities are: 1) cardinality, where the relationship of one database library is of critical aspect to the other; 2) optionality, where the relationship of one database library is among alternatives of choice to the other; and 3) relationship, where the relationship of one database entity is categorized as one-to-one, one-to-many, many-to-many, or many-to-one with respect to the other (Elmasri and Navathe, 2007). Based on this, the relationship among entities is either a one-to-one, one-to-many, or many-to-many. It is important to highlight the relationship between the group and item entities which is a one to one bi-directional relationship. In other words, are cord in the 'group' table is associated with a single record in the 'item' table and vice versa.

3.6.2 Data Categorization and Mapping

The data categorization and mapping phase is an important step towards converting the conceptual schema to a physical design by mapping the data model and implementing the design. The database mapping procedure transforms components of the conceptual schema into interdependent relations. In this thesis, the relationships among the entities are categorized as follows: 1) one-to-one; 2) one-to-many; and 3) many-to-many relationships. The data model mapping process for the entity relationship diagram of the system's database is presented in Figure 3.11.

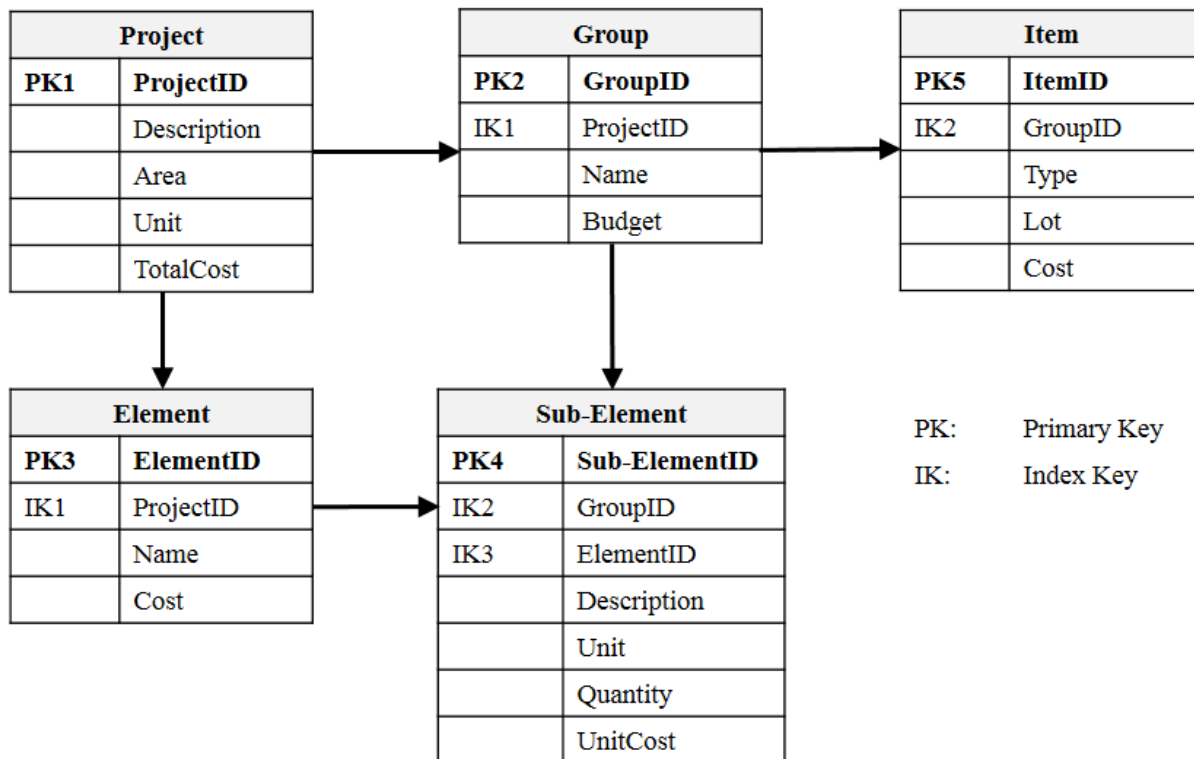


Figure 3.11 Preliminary Cost Estimation Module's Data Model Mapping

As illustrated in Figure 3.11, individual entities are transformed into a relation that includes attributes, index keys, and their primary entity. For instance, the 'Sub-Element' entity is

transformed into a relation that includes its attributes, index keys that point to ‘Group ID’ and ‘Element ID’ entities, and its primary entity. Furthermore, a sub-class is designed for each class and the many-to-many relationships.

Once the mapping process is completed, the database implementation phase is undertaken. This phase is the most significant as this is where the actual modeling work is performed, where database mapping entity relationships are implemented and associated attributes are represented by a table for each attribute. Once the necessary tables are developed, internal database schemas are accomplished by relating all the tables together as presented in Figure 3.12.

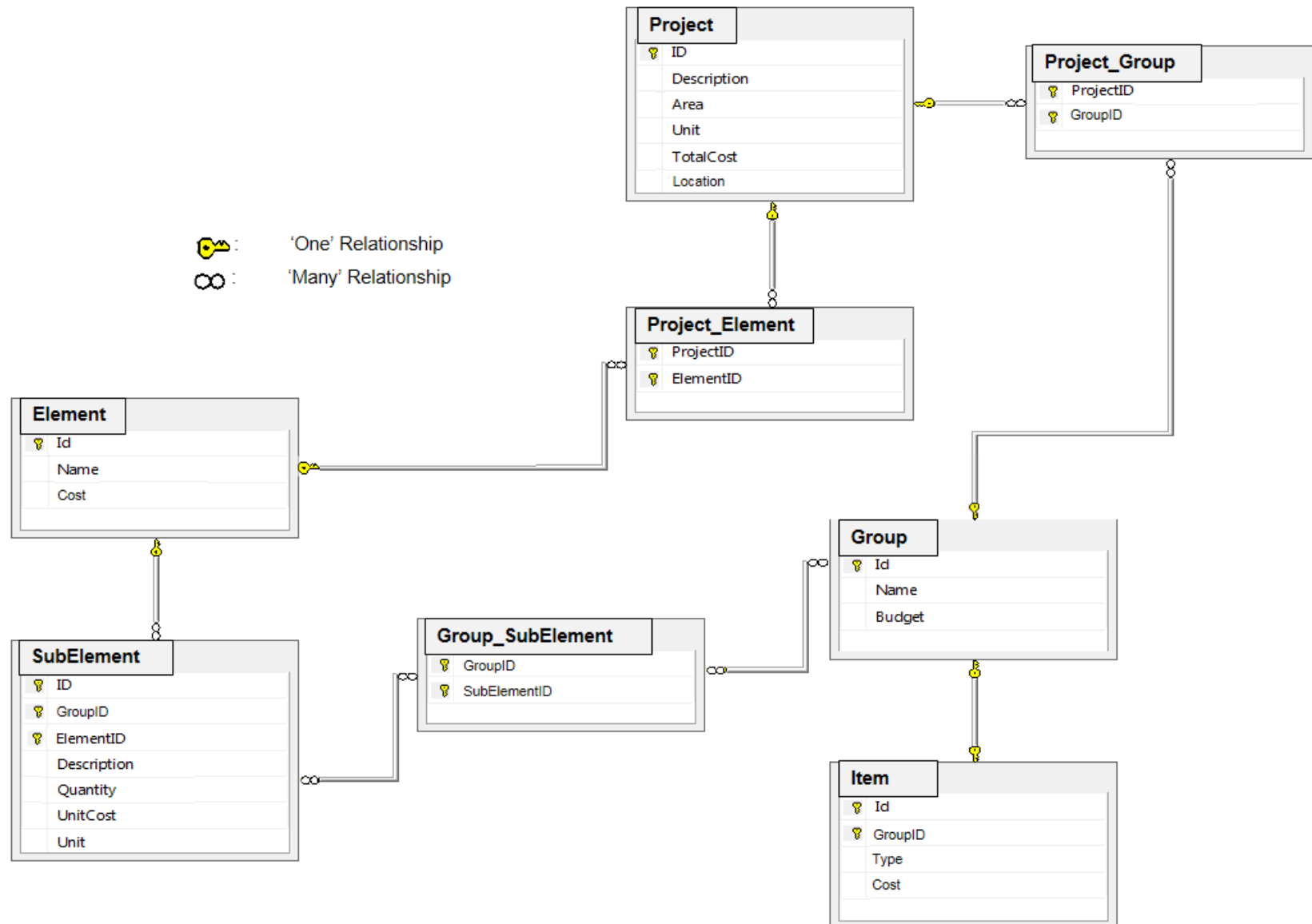


Figure 3.12 Physical Relationships of the Preliminary Cost Estimation Module Database

At the end, user data input is required for equipment specifications and corresponding cost data. This database is then managed by the global integrated preliminary cost estimation module. As part of developing system databases, an algorithm is developed by utilizing 'C#' and implemented in a classical .NET framework accompanied with an extensible markup language (XML) syntax index schema. The syntax index is hard-coded and incorporated into the developed system in order to facilitate the interoperable transfer of information between the system databases. Appendix III illustrates the XML-Algorithm for Converting System Databases into Digital Table Formats.

3.6.3 Cost Estimation

As defined in Chapter 2, preliminary estimates are considered advanced estimates where the project scope is up to 40% defined (Vojinovic et al., 2000); however, in many cases, project's drawings and/or specifications are not available at the initial stage and the estimator is directed solely towards the standard guideline specifications obtained from previous projects. Hence, direct costs, including project material, heavy equipment, and workers, may be determined, but also the indirect costs, including contingency, project overhead and profit, and sales tax. First, the external data interchange interface calls out the functions of the project information data; such as bridge component type and geometric parameters as extracted from the developed BrIM model. Then, a quantity take-off process will be undertaken for each work division of the selected work breakdown structure. In the developed system, the user is provided an option to customize and update and/or modify the cost database at any time throughout the estimation process such that total direct construction costs are automatically extracted upon call functions. Afterwards, the

user is directed to input corresponding percentages of overhead and profit, contingency, and sales tax.

3.7 System Framework

In this thesis, one of the main framework components of the development methodology is to analyze the following five main factors that influence equipment selection; 1) horsepower; 2) technical specification; 3) operation analysis; 4) productivity rate; and 5) equipment cost. The idea is to obtain a wide understanding of how equipment selection is affected by these factors. Since the influences of these factors are numerous and complicated, it is important to study them comprehensively and to identify their impact on equipment selection. Equipment horsepower and technical specifications are recalled from the Caterpillar Performance Handbook[®] for the year 2011 and stored in the fleet selection module database. Moreover, equipment operation analyses including owning and operating costs of the equipment selection are performed. Furthermore, a comprehensive review of the literature related to calculating equipment productivity rate and its corresponding costs is undertaken. It is important to note that the equations used to determine equipment cost are extracted from diverse sources in the field of construction equipment management; such as R.S. Means for heavy construction cost data and ZIEGLER Caterpillar[®] rental for the year 2012.

3.7.1 Data Collection

One important step prior to developing the system is to understand the characteristics of the developed system, which in turn reflects the “type” of estimate required to successfully implement a cost-effective conceptual design. Therefore, diverse database sources pertaining to

bridge users' interview questionnaires, including scope of work-related parameters, unit cost parameters extracted from R.S. Means for heavy construction cost data of the year 2012, are incorporated into a set of tables and stored in the developed system relative databases. For instance, data pertaining to bridge users' surveys and unit cost parameters are stored in the conceptual bridge design and preliminary cost estimation modules respectively. The selection of these sources of cost data is strictly based upon their popular use by the construction industry especially during the conceptual design stage of projects. Interviewing bridge users is a key of the development mechanism. Therefore, a finite set of diverse bridge types is defined and classified where bridge users' feedback to parametric-related queries for the different bridge types are transformed into a digital format for analysis.

3.7.1.1 Equipment Selection Factors

Factors that influence the selection of equipment are numerous and complicated. The first part of this research analyzes those factors and identifies their impact on equipment selection. As mentioned earlier, it is not possible to identify all factors for one simple reason; the nature of construction projects. Meanwhile, operation analysis, which is the core of this research, is carried out. In fact, operation analysis and ownership and operating costs of the equipment fleet are inseparable. During this stage, a literature review was completed to calculate the productivity of each type of equipment and its associated costs. The equations used were extracted from different sources in the field of construction equipment; such as the Caterpillar[®] performance handbook and construction equipment guide.

3.7.1.2 Equipment Operational Analysis

Economic operation analysis of selected types of equipment is considered essential for developing the optimization system. In this thesis, the developed system is designed to enable users to determine a near-optimum fleet for various types of earthwork based on their economic operation analysis. The analysis is performed for the following seven major operations of earthworks; (a) clearing and grubbing, (b) excavating, (c) loading, (d) hauling, (e) backfilling, (f) grading, and (g) compacting. The operation analysis is conducted while taking into consideration the variable factors affecting the productivity of equipment. Figure 3.13 summarizes the conceptual operation analysis system.

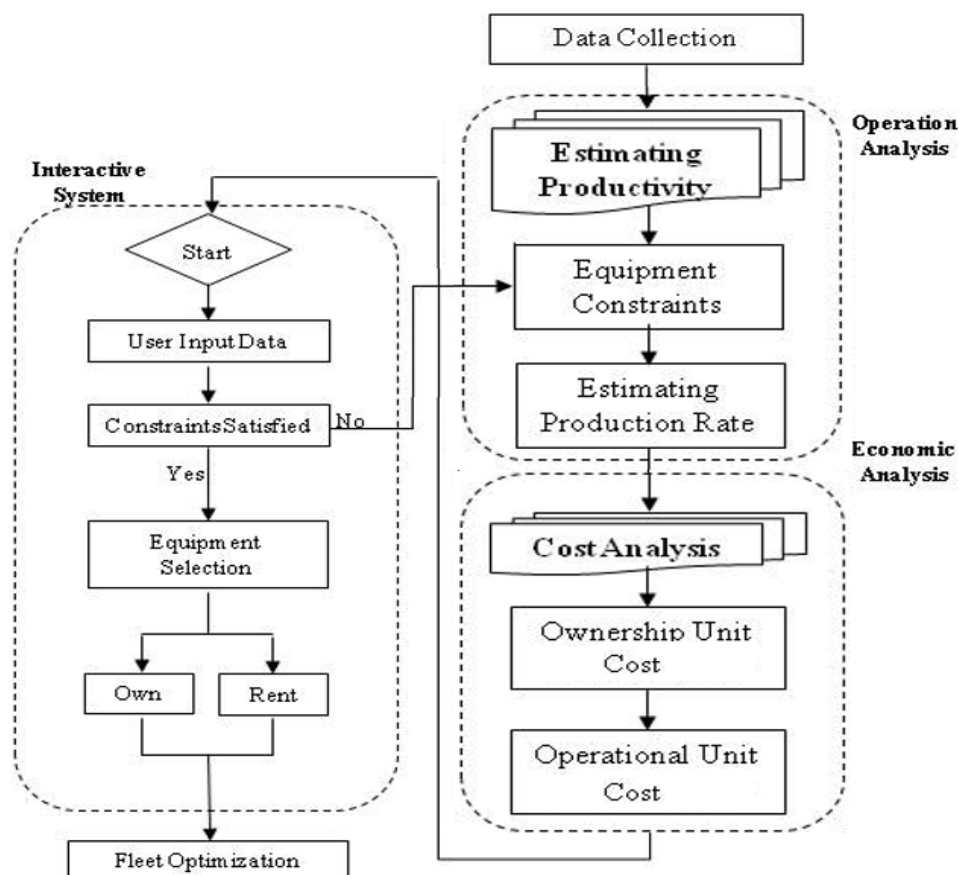


Figure 3.13 Conceptual Operation Analysis System

3.7.1.3 Equipment Specifications

Since the developed system does not rely on historical data or experts' knowledge, performing an operation analysis based on manufacturer's data is crucial. Equipment specification data necessary to carry out the analysis is obtained from the Caterpillar® Performance Handbook of the year 2011. Also, data pertaining to operation analysis is extracted and inserted into a SQLite database, which is considered as an innovative adoption of a database server application based on a Windows system without the "actual" requirement of a server for enhanced performance and data-recall efficiency. The SQLite database application was found to resolve interoperability issues among the "sub-database" applications within the developed system. By modifying user platform, bandwidth, and average file size specifications, it is possible to accurately reflect expected or planned environments. Table 3.1 summarizes SQLite average iteration response times for equipment operation analysis.

Table 3.1 SQLite Average Iteration Response Times for Equipment Operation Analysis

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

As illustrated in Table 3.1, Test No. 1 includes an equipment operation analysis with 90% of iterations completed within a 0.5-sec average response time. Similarly, Tests No. 2 and 3 include an equipment operation analysis with 95% and 99% iterations completed within 1-sec and 2-sec

average response times respectively. The type of equipment and number of numerical iterations required per operation underlie the differences between the test applications. Furthermore, it is important to note that the database of information possesses a variety of equipment capacity, power, and maximum allowable weight, which enables the developed system to be applied to any construction project regardless of the volume of materials involved. The types of equipment selected in this thesis are illustrated in Table 3.2.

Table 3.2 Types of Selected Equipment

Type of Equipment	Number of Equipment	Type of Operation
Excavators	55	Excavation
Scrapers	6	Excavation, Loading
Dozers	32	Clearing, Excavation, and Backfilling
Loaders	50	Clearing, Excavation, Backfilling, and Loading
Haulers	19	Hauling
Graders	13	Grading
Compactors	13	Compaction

After identifying the required types of equipment, data pertaining to the operation analysis are extracted from the fleet selection module database and inserted into the SQLite database. Some of these data are converted into tables instead of charts in order to give the system the ability to interface the database with information entered by users. Afterwards, a database server containing all equipment specifications is created. It must be noted that the selected pieces of equipment are carefully reviewed to ensure that the fleet possesses a variety of capacities, power, and maximum allowable weight in order to allow the system to be applied for any project regardless the volume of materials involved. In hauling, for instance, different types of haulers may be selected. For the system to provide accurate results, it evaluates all possible scenarios for

equipment selections. The evaluations include equipment capacity, total resistance, and available rim-pull/drawbar pull force. The same procedure issued for all other types of equipment. Performance charts are essential when it comes to calculating the speed of a piece of equipment. Since the developed system deals with actual values only, it is necessary to convert these charts into digital databases. The idea is to assist users in selecting the distance traveled and total resistance of a piece of equipment from a table instead of reading these values from performance charts.

3.7.1.4 Cost Data

Data related to the costs of owning and renting equipment are necessary for optimizing the equipment selection. It is, after all, about minimizing the cost while taking into consideration factors and constraints that govern the selection. As indicated earlier, the developed system considers two options, owning or renting the equipment. The common cost for both options is the operational cost. The data pertaining to ownership and operating costs are obtained from the Caterpillar® Performance Handbook of the year 2011 and worldwide Caterpillar® parts suppliers and agents, such as Ziegler, Altorfer, and Wyoming Caterpillar rentals. Rental costs are obtained from the R.S. Means cost data for heavy constructions catalogue. Following the completion of data collection, operation analysis for the selected pieces of equipment may be carried out starting with the fundamentals of earthmoving.

3.8 Fundamentals of Earthmoving

The most important step in analyzing construction operations is to understand the characteristics of the materials to be moved. Soil types and properties affect the type of equipment required to successfully complete a construction project. For this research, data pertaining to material properties are obtained from the Caterpillar® Performance Handbook of the year 2011.

3.9 Nature of Earthwork Material

Materials encountered in earthwork operations vary in their types and properties. For instance, rock materials vary from a light type that can be ripped, to a hard type that can only be removed by drilling and blasting. A visit to the site must be done in order to collect samples for testing purposes. In this thesis, data pertaining to material properties are obtained from several sources (i.e., Caterpillar® performance handbook, and construction equipment guide). In fact, these data are based on previous tests done on similar projects. The developed system depends on these data so that it can provide the near-optimum solutions. There are three measures commonly used in earthmoving processes. These measures refer to the state of the material during the operating process and can be classified into the following categories; (1) bank, (2) loose, and (3) compacted.

The material is measured in Bank Cubic Yards (BCY) when it lies in its natural state and is measured in Loose Cubic Yards (LCY) after it has been disturbed. If the material has been compacted, the measure is Compacted Cubic Yards (CCY). The density values are essential for calculating the percent swell, shrinkage factor, and load factor. Using these factors, an equipment database containing characteristic data is automatically updated. The idea is to develop a system that performs operation analysis and that is capable of being transformed into an interactive form.

3.9.1 Forces Affecting Motion of Equipment

Traction is the maximum usable force that may be applied before a piece of equipment begins to slip. In order to determine the traction force, the coefficient of traction, which is the degree of traction between the tires or the tracks and the ground must be known.

3.9.2 Equipment Power

There are two types of equipment power. The first is the rim-pull, which is the power applied to a wheeled piece of equipment, and the second is the drawbar pull, which is the power available to move a crawler piece of equipment (Day and Benjamin, 1991). For a piece of equipment to move a load, it must generate a force (rim-pull/drawbar pull) that is greater than the total resistance. All these concepts and equations are used to build the developed system as a first step in the operational analysis. As mentioned in Chapter 2, there are several factors that affect the equipment selection process. In the developed system, these factors are defined as constraints. However, to better understand the whole concept, a complete analysis that includes estimating the production rate for each piece of equipment using the developed system is required. The system contains all necessary data and equations, including types and properties of material, description of the project site, and specifications related to the selected pieces of equipment.

3.10 Estimating Equipment Productivity

Equipment productivity is a key factor that enables contractors to make a decision regarding project scheduling, fleet selection, and total costs. Most contractors rely on previous projects data to obtain the productivity of selected equipment (Tavakoli, 1985). In this thesis, the estimation of

productivity rates is performed for each type of equipment individually as illustrated in Figure 3.14.

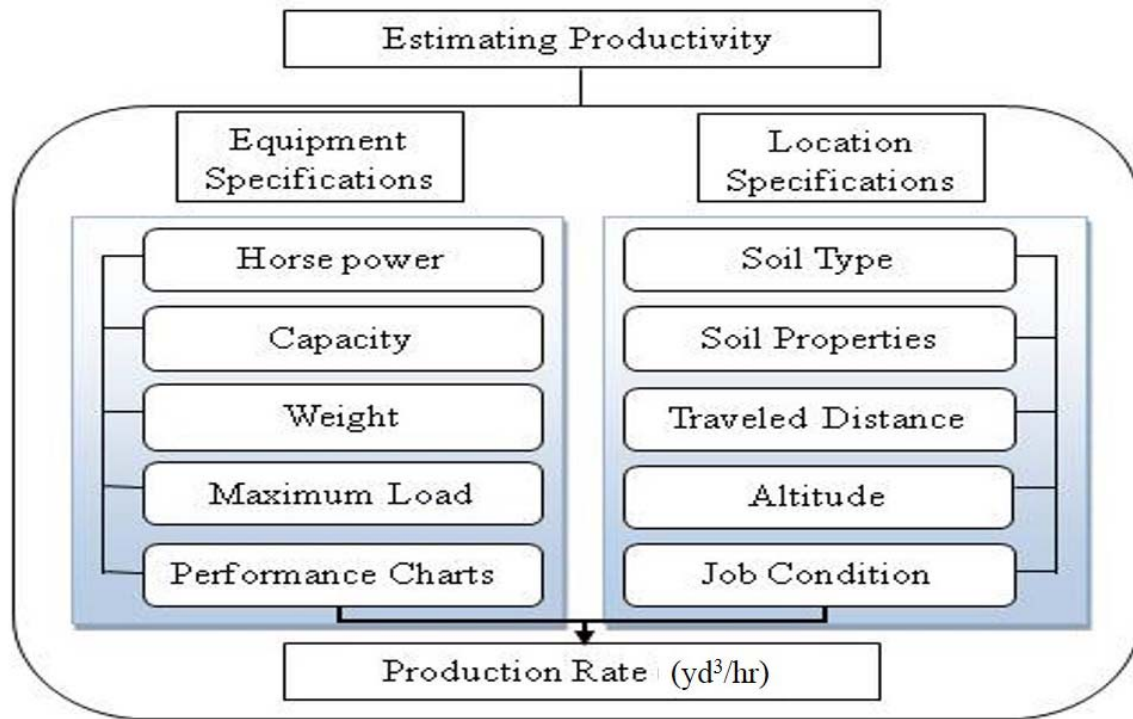


Figure 3.14 Methodology for Estimating Equipment Productivity

3.10.1 Estimating Excavator Productivity

There are several types of equipment that can perform excavation work. However, the most commonly used equipment among contractors is power digging equipment, which includes hydraulic excavators (Schaufelberger, 1999). This thesis includes the two main types of excavators, backhoes and front shovels; however, the selection of equipment is limited to one major manufacturer, Caterpillar®. The Caterpillar® Performance Handbook of the year 2011 is used to extract the necessary data and specifications. Excavators are carefully selected to ensure that the system has sufficient data to rely upon for optimization. It is important to determine the

heaped capacity which represents the maximum bucket capacity of an equipment that varies based on the soil type. Operational efficiency of an equipment is typically represented by a ratio factor or a percentage value. Finally, results obtained from the previous equations are implemented into the developed system as a major step towards accomplishing the operation analysis.

3.10.2 Estimating Dozer Productivity

Dozers are slow-speed machines but have great power to perform difficult tasks. Typically, dozers are used in different types of earthwork such as excavating, clearing and grubbing, backfilling, and spreading materials, and in towing operations. There are number of attachments that enable dozers to perform more complex and difficult tasks. In this thesis, dozers are selected to expand alternatives so that the developed system can evaluate for fleet selection optimization.

The following two methods are commonly used to calculate the productivity of a dozer:

- On-the-job Estimating: This method involves calculating the volume of earth that can be moved during each operating cycle. It is important to note that in order to determine the volume of earthwork, the width of blade must be determined while all other values may be obtained from the site or assumed based on available data from previous projects.
- Off-the-job Estimating: This method obtains the maximum productivity of a dozer from production curves provided by the manufacturer. Because the maximum production is based on certain conditions, contractors must correct its value by applying correction factors.

Correction factors are classified into five groups: (1) job condition; (2) material type; (3) job efficiency; (4) material weight; and (5) blade type. The semi-U type of blade is assumed to be the type of blade used in the selected dozers. The reason for selecting this type of blade is its strength and its ability to be used in heavy earthwork and in different types of earthwork operations. When comparing both methods, the on-the-job estimating method is considered the better option when the intent is to maximize equipment productivity. On the other hand, the second method is based on actual experiments that are conducted by the manufacturer based on certain conditions. These conditions can be corrected to match the new project using Equation 3.8. Therefore, the off-the-job estimating methodology issued in this study in order to allow users determines a near-optimum fleet selection based on off-site conditions. The maximum production of a dozer is indirectly proportional to travel distance. Furthermore, it is inferred that when comparing dozer productions rates for similar travel distances, the dozer of maximum flywheel power becomes less productive in higher proportion when compared to the dozer of minimum flywheel power. Hence, it is recommended to utilize the dozer of minimum flywheel power where travel distance is between 500 to 600 ft and the dozer of maximum flywheel power for a travel distance up to 100 ft. In this thesis, haulers of maximum flywheel power are automatically disqualified for terrains of grades exceeding 10%.

3.10.3 Estimating Scraper Productivity

Scrapers can perform different types of earthwork such as excavating, hauling, and backfilling. However, they are not as effective as backhoes or front shovels in excavating operations or as efficient as trucks in hauling (Eldin and Mayfield, 2005). A scraper consists of a tractor and a

bowl. The capacities of a scraper range from 9 cubic yard to over 50 cubic yard. Certain scrapers can cut a path over 12 feet wide and can haul materials up to 2 miles (Key, 1987). Selecting the proper scraper is very complicated and involves a great number of factors. Eldin and Mayfield (2005) developed a spreadsheet application to identify the most economical choice of scrapers for a specific project.

The productivity of a scraper is governed by the scraper type. Since the near-optimum fleet that the developed system shall determine is based on the type of earthwork operation rather than on the equipment alone, the choices of scrapers are limited to self-loading scrapers. It is important to note that the difference in scraper distribution of weight between front and rear wheels while loaded and empty significantly influences the cycle time and corresponding productivity. Furthermore, the weight distribution for scraper of maximum flywheel power tends to equalize when loaded. Hence, it is recommended to utilize the scraper for normal terrains when loaded and for rough terrains when empty. In this thesis, scrapers of maximum flywheel power are automatically disqualified for terrains with grades exceeding 10%. In order for the user to be able to select the proper value of total resistance, the effective grade is calculated. Once determined, the user is then directed to scraper retarder charts to obtain the travel time of a scraper while empty and loaded.

3.10.4 Estimating Loaders Productivity

The loader is a self-propelled type of equipment. It is used to load and dump material into trucks. Although the loader can be used in excavating, backfilling, and hauling operations, its capacity for hauling is limited to a distance less than 500 feet (Schaufelberger, 1999). Selected loaders vary from a small to a large loader and from a tracked to a wheeled loader. This variety enables

the developed system to select from a wide range of loaders. There are particular constraints that must be checked when conducting the operation analysis for loaders. The first constraint is the maximum weight a particular loader can handle per cycle. The second constraint is the load weight, which should always be less or equal to than the maximum weight. After that, the cycle time is estimated. In this thesis, the fixed time is assumed to be 0.5 minute for wheeled loaders and 0.3 minute for crawler loaders, based on the Caterpillar[®] Performance Handbook of the year 2011. For the travel time, the performance chart for each loader is tabulated. The travel time is calculated for the equipment while loaded and empty.

3.10.5 Estimating Haulers Productivity

A hauler is used to haul materials and is widely used in most phases of construction. Haulers vary in their size, capacity, and machine power. Also, haulers can be in a form of regular-size trucks (on-highway trucks) or gigantic trucks (off-highway trucks), which are typically used in heavy construction that involves huge rocks or hard materials. It is important to note that the difference in hauler distribution of weight between front, center, and rear wheels while loaded and empty significantly influences the cycle time and corresponding productivity. Furthermore, the weight distribution for hauler tends to be ‘rear-driven’ when loaded and ‘front-driven’ when empty. Hence, it is recommended to utilize the hauler for downhill grades when loaded and for normal and/or uphill grades when empty. In this thesis, haulers of maximum flywheel power are automatically disqualified for terrains with grades exceeding 10%. In order to calculate hauler productivity, several constraints should be considered and inputted into the developed system. A brief definition of the constraints is provided below:

- Maximum Load is the load that the truck is capable of carrying safely without exceeding the load weight constraint set by the manufacturer. The load weight is the sum of the weight of the empty truck and the weight of the load.

Most importantly, in the event that the maximum load exceeds the allowable load weight, the equipment with load weight less or equal to the maximum load is automatically disqualified. Furthermore, an error message will appear to notify the user that the disqualified equipment shall not be considered in the optimization process.

- Maximum Rim pull is the measure of the force to move the truck when it is loaded. The maximum rim-pull value is compared against the total resistance. The total resistance, however, should always be less than the maximum rim-pull; otherwise, the wheels will slip.

Cycle Time is the sum of the fixed and travel times. The fixed time equals the sum of the loading, dumping, and spotting times. For the loading time, a table is created to contain all the data for all sixteen selected loaders. On the other hand, the travel time has more complex procedures due to the fact that the hauling road has diverse grades. In order to overcome this shortcoming, the developed system is designed to allow the user to input the data required to estimate the travel time.

The user is required to input the following data pertaining to: 1) number of segments; 2) distance of each segment; and 3) grade; prior to estimating the travel time a particular hauler is required to

complete a cycle. Once user input data are defined, the developed system estimates the travel time based on these entries. In the event the maximum speed exceeds the rated speed, the developed system shall select the rated speed instead. Moreover, the travel time is estimated when the hauler is loaded and empty. The final step is now to balance the hauling and loading system. The balancing methodology is based on the queue theory, as stated earlier in Chapter 2; where at the queue or idle state, the hauler waits until the loader is available (Kim and Gibson Jr., 2003).

3.10.6 Estimating Graders Productivity

A grader is typically used to spread materials and for other types of tasks; such as grading, backfilling, scarifying, and maintaining the haul road (Schaufelberger, 1999). Afterwards, the average grading speed and moldboard length, which is the length of the moveable blade mounted to the grader, are determined. The effective grading width and the number of passes required are entered by the user. The method used for grader operation analysis is based on the Looping Method, which is typically used for linear grader operations.

3.10.7 Estimating Compactors Productivity

Compactors are used to compact and stabilize the surface. It is essential to study the soil compaction and stabilization in order to optimize the moisture content. In this thesis, two alternatives are considered when calculating productivity. The first alternative is based on stabilizing the surface while the second alternative is based on adding water to a dry soil and then using compactors for soil compaction. The required moisture content is calculated by subtracting the natural moisture content from the optimum moisture content. According to Schaufelberger (1999), there are three methods of stabilization used in construction projects:

- Lime Stabilization;
- Cement Stabilization; and
- Asphalt Stabilization

After considering these options, compactors are selected. The selection of compactors takes into consideration the variety of compactors that can perform several tasks. The effective compaction width is the dump width less the thickness of the lift. The average compactor speed is assumed based on manufacturer's data. The number of passes is to be entered by the user. After determining the productivity for each type of equipment, the first step towards developing the system is accomplished. Meanwhile, the next step is to conduct the subsequent cost and time analysis for each type of equipment.

3.11 Cost and Time Analysis

Cost analysis of construction projects is a vital key for project success. A comprehensive owning and operating cost analysis is implemented as a stand-alone module that is capable of being linked to any optimization module. The cost data consists of ownership, rental, and operating costs. For the ownership and operating costs, the Caterpillar[®] Performance Handbook estimating model is used. For rental costs, R.S. Means cost data is used.

3.12 Near-Optimum System

The development of the near-optimum system comprises the following three main phases; (1) data collection; (2) operational analysis; and (3) cost optimization.. As part of data collection, a database of equipment specifications and scope-of-work-related parameters is created. Then, a

set of equipment operational analysis formulations as specified in the Caterpillar[®] Performance Handbook of the year 2011 is utilized to assist in estimating equipment productivity based on project duration and specified scope of work while satisfying all equipment-related constraints. Following the equipment operational analysis, an economic analysis based on comprehensive renting, owning, and operating costs is conducted for all equipment based on their corresponding production rates obtained from the previous phase. After that, an equipment fleet is selected based on a linear cost optimization approach. A final near-optimum report providing equipment ownership and/or rental options is then presented to the user.

3.12.1 Data Collection

One important step in analyzing equipment operations is to understand the characteristics of the materials to be moved, which in turn affects the type of equipment required to successfully complete the project. Therefore, diverse material properties are extracted from Caterpillar[®] Performance Handbook of the year 2011 and are inherited into the developed system. Also, mathematical formulations relevant to the operation analysis are incorporated into a set of modules to conclude the data collection phase. Some of these data are tabulated in order to enhance the developed system and capability of interfacing the data with the information that has to be entered by the user. Furthermore, the database of information incorporated into the modules possesses a variety of equipment capacity, power, and maximum allowable weight, which enables the developed system to be applied for any construction project regardless of the volume and types of materials involved.

3.12.2 Cost Optimization Process

In general, optimization is the process of maximizing or minimizing the objective function while taking into consideration the prevailing constraints (Belegundu and Chandrupatla, 2002). To optimize equipment selection, one must understand all related constraints. Failure to do so may lead to erroneous results in the final output.

In this thesis, the decision support system developed is intended to minimize cost and obtain the required fleet for a particular operation. Linear programming (or linear optimization) is the methodology used for determining a near-optimum fleet. A near-optimum fleet is defined as a set of selected equipment that has the lowest combined ownership and operating costs. However, since owning and operating costs are inversely proportional to equipment operation analysis, the near-optimum fleet is selected based on performance and economic efficiency. For example, if a particular equipment fleet has the maximum productivity rate, it is going to yield the least owning and operating costs and vice versa. The near-optimum fleet is obtained by using the cost minimization approach in a given mathematical function for a list of requirements and constraints represented as linear relationships. All constraints obtained from the operation analysis are represented in a mathematical form and incorporated into the optimization module. The constraints, however, limit the degree to which the objective function can be pursued (Anderson et al., 2008). It is important to note that the developed system accounts for a time-cost tradeoff that occurs during the selection process. In other words, the developed system is designed to extract the project duration entered by the user in order to compare it with the required time based on the volume of earth material extracted from the conceptual bridge design module and corresponding productivity rates. For example, if the project duration data inputted by the user is

less than the required time obtained from system calculations, the system will select an optimum fleet with much higher costs and vice versa. Following the setup of the optimization process, a major obstacle is encountered when developing the hauling-loading system. The goal is not only to optimize the hauler selection but to also optimize the hauling-loading system as a whole.

3.13 Integration Platform

Decision making pertaining to the selection of bridge type necessitates the deployment of an integrated platform comprising the following: 1) expert system; 2) BrIM; 3) and cost estimation. In this thesis, the developed system includes a knowledge-based support system that extracts information from the 3D BrIM tool, CSiBridge, via a DLL-invoked API method that automatically recalls the parametric enriched object-oriented model. For instance, the developed system provides the user with an option to develop an information module by utilizing the fuzzy logic scoring system in order to determine the bridge type based on the deployment of the QFD and TOPSIS processes; otherwise, the application automatically extracts data from the developed BrIM model and presents nominations and recommendations of selected bridge type based on technical and functional spans and geotechnical attributes. The developed system is designed to extract all necessary information from the assigned model by exporting CSiBridge input databases via the Industry Foundation Classes (IFC) file format, which reduces loss of information during file transmission. After that, the developed system is objectively developed for bridges such that capturing of data displayed in the calling software is conducted by utilizing CSiBridge objects. Finally, bridge element attributes are recalled and organized via a DLL-invoked programming language and incorporated into the SQLite database server for utilization by the cost estimation module.

3.14 Interoperability

Following QFD and TOPSIS, bridge sub- and super-structure geometric parameters (i.e., bridge span, bridge girder cross-sectional area, bent size, pile caps, etc.) and subsequent coordinates are extracted from the SQLite database. The developed data interface is a unique implementation in the BrIM model and was found to foster system efficiency while resolving database interoperability issues. This mechanism will be designed and managed by the developed system, prohibiting third party data interruption. However, a few cost items, such as traffic signs, road markings, electrical, drainage works, landscape, and ecology are a necessity and must be entered by the user as they are variable costs and may not be predetermined. It is important to note that the output IFC files are extracted for cost estimation use via a dynamic link library (.dll) file, which contains a library of call functions and programming language codes and diverse database resources that can be easily accessed by any Windows-based program. Moreover, this platform is designed to reduce the running times of the applications and to resolve interoperability matters among the developed modules (i.e., decision support, 3D model, and cost estimation). The cost estimation module obtains elemental costs by extracting information from the 3D model objects in the database. For instance, a bridge cross-sectional area is extracted via IFC file formats by implementing a DLL-invoked call function and then incorporated into the SQLite database server for multiplication by its corresponding parametric unit cost from the R.S. Means heavy construction cost data catalogue to determine overall bridge costs at the conceptual design stage. The cost estimation module is developed in an object-oriented .NET framework using a SQLite database, which has the ability to resolve interoperability issues among internal database applications.

3.15 Summary

In this chapter, the development of an integrated system that assists stakeholders to plan for bridge construction projects at the conceptual design stage by integrating BrIM with cost data resources and user-defined input is presented. Comparative analyses of diverse bridge types is conducted by utilizing a fuzzy logic decision support system based on quality functions deployment (QFD) and the technique of order preference by similarity to ideal solution (TOPSIS). In this thesis, QFD is utilized for development of WHATs criteria weights while TOPSIS is utilized for prioritizing rankings due to their advantages in the trade-off processes that usually occur between criteria where a less preferred result in one criterion can be compensated for by a preferred result in another criterion. In other words, design attributes that negatively affect the selection of a particular bridge type alternative are offset by the positive contribution of other attributes. As a result, competitive priority ratings of bridge type alternatives are produced rather than completely including or excluding alternative solutions.

Furthermore, the development of a decision support system that includes a detailed operation analyses for the following seven heavy earthmoving operations; 1) clearing and grubbing; 2) excavating; 3) loading; 4) hauling; 5) backfilling; 6) grading; and 7) compacting has been presented. These are the operations that are mainly encountered in the construction of bridge projects based on their corresponding numerical analyses and theoretical background as specified in the Caterpillar[®] Performance Handbook of the year 2011 and in the literature, as opposed to traditional random off-site methodologies. Moreover, the developed system is capable of calculating comprehensive ownership and operating costs that are often neglected by most construction managers who attempt to provide cost estimates in a timely manner. Furthermore, a

complex integration platform for hauling-loading operation analysis and the subsequent optimization of fleet ownership and operating costs is also implemented. The developed system is also capable of automatically generating a bridge line of balance based on stochastic scheduling techniques. Thus, a meta-heuristic simulated approach utilizing a metropolis algorithm is implemented to assist in generating near-optimum line of balances. Furthermore, the developed system is designed to operate as a complete decision support tool that is capable of providing bridge cost estimates including equipment costs by utilizing linear cost and time minimization approaches regardless of the complexity of bridge projects.

In summary, the research methodology and development of the expert system is described. The system components, modules, and sub-modules processes are developed and integrated into the following five main modules; 1) conceptual bridge design, fleet selection, preliminary cost estimation, deterioration forecast, and bridge line of balance. A detailed step-by-step flow of the data processes of the modules and their tasks has been illustrated. The developed system is an estimation tool that may be utilized to estimate preliminary costs for a bridge project by providing universally accepted metrics of cost to evaluate the success of a bridge project. The actual accuracy of the developed system is highly dependent on technical and functional constraints as well as user-defined input. The developed system is anticipated to be of novelty to BrIMS integrated technologies and possess a great advantage over the diverse cost estimation algorithms, prototypes, and systems presently used in the bridge construction industry.

CHAPTER 4

TECHNICAL PAPER I

Integrating a fuzzy-logic decision support system with bridge information modelling and cost estimation at conceptual design stage of concrete box-girder bridges

Nizar Markiz, Ahmad Jade

(Published in International Journal of Sustainable Built Environment, Elsevier, 2014, 3, 135-152)

Abstract: Integrating 3D bridge information modeling (BrIM) with construction technologies had inspired many researchers for the past decade. In this study, research objectives are intended to demonstrate the viability of integrating a 3D computer-aided design (3D-CAD) model with a structural analysis application and bridge cost estimation framework without compromising interoperability matters. An integrated model that relates a fuzzy logic decision support system with cost estimation for concrete box-girder bridges is presented. Model development methodology comprises an integrated preliminary cost estimation system (IPCES), and complex quality functions and deployment of a multi-criteria decision making (MCDM) approach. An actual case project is used to validate and illustrate model corresponding estimating capabilities. The proposed model is engineered to enhance existing techniques implemented by bridge stakeholders and designers to prepare cost estimates at the conceptual design stage by taking into consideration a box-girder bridge project site preparations, substructure, and superstructure. The proposed model is anticipated to be of major significance to designers and its contribution resides into the integration of BrIM technologies with cost estimation approaches.

Keywords—decision support; complex quality functions; bridge information model; cost estimation

4.1 Brief Background

Bridge information modeling (BrIM) is an approach similar to building information modeling (BIM) and may be comprehended as an innovative approach to inform downstream processes of infrastructure projects. As part of developing this research incentive, it was understood that integrating a fuzzy-logic decision support system with BrIM and preliminary cost estimation of concrete box-girder bridges is possible only if objectives were kept simple, focused, and organized. Therefore, basic BrIM processes were researched, recalled, and analyzed. According to Bentley bridge solutions (Peters, 2009), the eight processes of BrIM are: (1) bridge type selection; (2) 3D-CAD model; (3) technical analysis; (4) planning for construction; (5) production; (6) phases of construction; (7) maintenance; and (8) remediation. In this study, the first two processes (i.e. bridge type selection, and 3D-CAD model) were selected for development and integration with cost estimation of concrete box-girder bridges at conceptual design stage.

4.2 Problem Statement

In the past, several attempts had been witnessed in efforts to developing computational tools for supporting various aspects of bridge design; however, these aspects were tackled independently from impediments arising due to availability of multiple data resources. Nowadays, few industries have moved forward in terms of incorporating integrated design with industrial processes in parallel with “broadly-accepted” interoperability standards. Although the deployment of object-oriented programming (OOP) approaches 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 benefits of utilizing such technologies in cost estimation at the conceptual design stage of bridge projects. For example, incorporating a fuzzy logic decision support system for bridge type selection assists the user in determining the economical bridge type for a given site conditions. This paper presents results pertaining to the integration of an information model as a technology that incorporates a fuzzy logic decision support system with a cost estimation system at the conceptual design stage of bridges.

4.3 Motivation and Objectives

Research motivations presented in this study underlie the deployment of an integrated preliminary cost estimation system (IPCES) with 3D BrIM for concrete box-girder bridge projects. The main objective of this paper; however, is geared towards the development of the fuzzy logic decision support system, multi-criteria decision making approach, technique of order preference by similarity to ideal solution (TOPSIS), and bridge conceptual design in order to obtain preliminary cost estimates. The subject matter presented hereby mainly emphasizes on the methodology followed to achieve the abovementioned objective while taking into consideration interoperability concerns. According to Shim et al. (2011), existing 3D-CAD solutions are not sufficient for utilizing information models of bridges since technical improvements are a necessity for the effective exchanging of information among interoperable software. In their study, a neutral file format accompanied with an extensible markup language (XML) schema is

deployed via a coded-link to enhance interoperability. Furthermore, Gallaher et al. (2004) clearly state that the absence of efficient interoperability among 3D modeling solutions could substantially refrain users from reaping remarkable benefits. Up to date, there is a lack in the literature on the effect of integrating a fuzzy logic decision support system and a multi-criteria decision making approach with BrIM and cost estimation at the conceptual design stage of bridges. Moreover, it is important to note that integrating a complete set of processes could significantly influence design alternatives and consequent notable cost savings at the initial design stage of bridges.

4.4 Review of The Literature

The majority of BrIM applications and computational studies focus on myriad complex factors; however, authors of this study noticed that none of the studies are to include or perform cost estimation comprising all direct and indirect costs associated with bridge substructure and superstructure. For example, Peters (2009) presents two major complex bridge construction projects that are conducted by utilizing BrIM technologies. Problem statements pertaining to execution processes are comprehensively defined for the Sutong Bridge in China and Stonecutters Bridge in Hong Kong. The aim of the study is to emphasize on the significance of incorporating BrIM into a complete set of bridge design processes. For instance, design factors ranging from bearing capacity to typhoon and seismic analyses of the bridge sub- and superstructure are considered. Moreover, it is shown that myriad factors evolving from a construction perspective are 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”. In another study, the application of 3D BrIM to the design and construction of bridges is conducted by Shim et al. (2011). The main goal of their study is geared towards the enhancement of information modeling for bridges. In an attempt to enhance BrIM techniques for civil infrastructure projects, a construction project lifecycle management system specifically for bridges is developed. As part of the system development, an architectural framework is established and comprised the actual bridge information model as well as architectural design layers. Furthermore, in order to enhance the interoperability of the 3D information model with other solutions, the architectural framework is established in an XML file format. 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, Lee et al. (2012), investigated the application of 3D BrIM to design and construction of concrete box-girder bridges. A construction project life-cycle management system is proposed in order to integrate all design and construction main parameters. The objective of their study is to deploy prefabricated bridge construction techniques throughout the entire development process of the 3D BrIM. As part of developing the model, main design parameters and relationships among them are subsequently defined. The system encompassed multi-layered information for the users (i.e. designers, contractors and owners). Bill of material for the fabrication of five different types of concrete box-girder segments is then defined and implemented into the information model, which is then utilized to optimize geometry control and reduce time and cost overflows during construction. At the end, the developed system is comprehended by the authors as a design guideline for prefabricated concrete box-girder bridge projects. On the other hand, Kivimäki and Heikkilä (2009) develop a prototype system capable of integrating 5D product models with 3D

on-site surveying of bridges via an internet connection. The proposed system is implemented in a Microsoft environment utilizing 'C#' programming attributes. As part of developing the bridge model, diverse applications such as; surveying instrumentation, total station, and the TEKLA 3D structural analysis are utilized. The main objective of the study is geared towards enhancing correspondence sessions among team players of a bridge construction project and found to be of major significance at the construction initial stage since it is capable of enhancing cost effectiveness of a bridge surveying session. In another study, Heikkilä et al. (2003) present the development of a new methodology for 3D design of concrete bridges in connection with 3D site measurements where modern technologies developed in the field of site measurements utilizing ground-based laser scanners are recalled. The developed 3D design concept is intended to be utilized during the construction phase of bridges. Therefore, a 3D bridge design guideline is proposed while taking into consideration 3D site geometric control measurements as well as construction and post-construction requirements. Towards the end, the developed design concept is tested via the implementation of real time computer-aided design/computer aided manufacturing (CAD/CAM) measurements utilizing a 3D robot tachometer as a device tool hand in hand with a Micro-Station. However, it is found that the developed 3D design concept is restricted in terms of measured point clouds and direct tolerance comparisons, which limits direct deviation controls and deteriorates accuracy requirements. In summary, earlier studies have focused on developing bridge information guidelines in an attempt to assist design engineers in detecting “before-hand” clashes, developing less error-prone models, and fostering operational efficiency during the construction phase of bridge projects. These studies; however, do not incorporate cost estimation modules based on their corresponding integrated approaches nor they

have included the influence of the developed computational tools and applications on overall project costs. For instance, Kivimäki and Heikkilä (2010) present results and findings of the Finnish bridge cluster consortium (5D-Bridge). One of the main findings is the development of the national bridge information modeling draft guideline in Finland. Another study by Shirole et al. (2009) summarize research conducted to demonstrate the acceptance of integrated project delivery approach by utilizing bridge information modeling among stakeholders in design and construction. Integration and deployment of earlier advancements in BrIM technologies are illustrated. Dataflow diagrams and computer-aided design as well as engineering software amalgamations for steel and concrete alternatives of a bridge design are demonstrated to illustrate design and verification via XML-coded extensions. Their study includes most of the 3D-CAD software integrations utilized to enhance BrIM at its maximum; however, a major lack of interoperability and compatibility among the afore-mentioned technologies is considered a major pitfall. At the end, the authors conclude that industry-wide standards must amalgamate to reinforce this widely-accepted integrated project delivery approach.

As discussed above, the majority of earlier studies do not consider cost estimation applications for bridge projects. In contrast, most of the studies consider numerous important factors for enhancing bridge information modeling techniques; however, none of them has specifically viewed a bridge project as a task or process that needs to be completed following critical budget constraints. Therefore, the proposed IPCES tool incorporates an economical estimation tool, which provides universally accepted metrics of cost to evaluate the success of a bridge project by utilizing a fuzzy logic decision support system based on complex quality functions and TOPSIS, a multi-criteria decision-making approach. Authors of this study decide to employ TOPSIS due

to its advantage in trade-off processes that usually occurs between criteria, where an un-preferred result in one criterion can be negotiated by a preferred result in another criterion. In other words, design attributes that negatively affect the selection of a particular bridge type alternative are offset by the positive contribution of other attributes. As a result, competitive priority ratings of bridge type alternatives are achieved rather than completely including or excluding alternative solutions.

4.5 Model Overview

In an attempt to synchronize complex bridge information, a schematic view of the model process illustrating interrelations among the 3D-CAD solutions with the developed Integrated Preliminary Cost Estimation System (IPCES) is presented in Figure 4.1. A proper harmony and handling of modeling data will result in less error-prone outcomes due to duplication or amalgamation of inconsistent bridge database resources. The flow of geometric and architecture informatics for concrete box-girder bridges starting by the substructure, and reaching at the superstructure will be presented in more details.

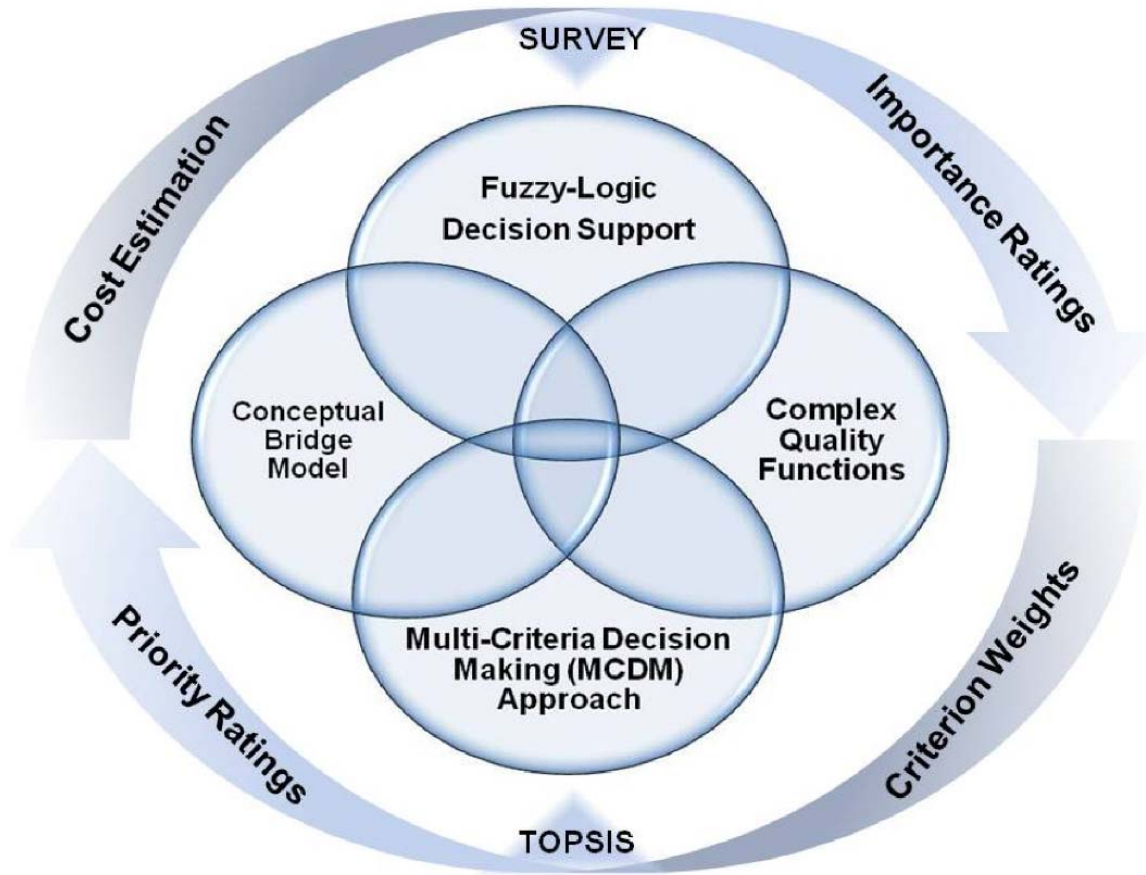


Figure 4.1 Integrated Preliminary Cost Estimation System (IPCES) Process

4.6 Research Methodology

Given the abovementioned objectives, a reliable determination of overall project costs necessitates the development of a thorough, reliable, and user-friendly cost estimation system to assist designers in making cost effective decisions between myriad established and innovative design alternatives. Towards that goal, a wider insight into the integration between a fuzzy logic decision support system and TOPSIS with BrIM and cost estimation is innovatively and subjectively created and deployed as illustrated in Figure 4.2. It is important to note that the 3D-

CAD structural analysis program (SAP2000) deployed in this study is an exemplar of a particular application commonly used in the industry.

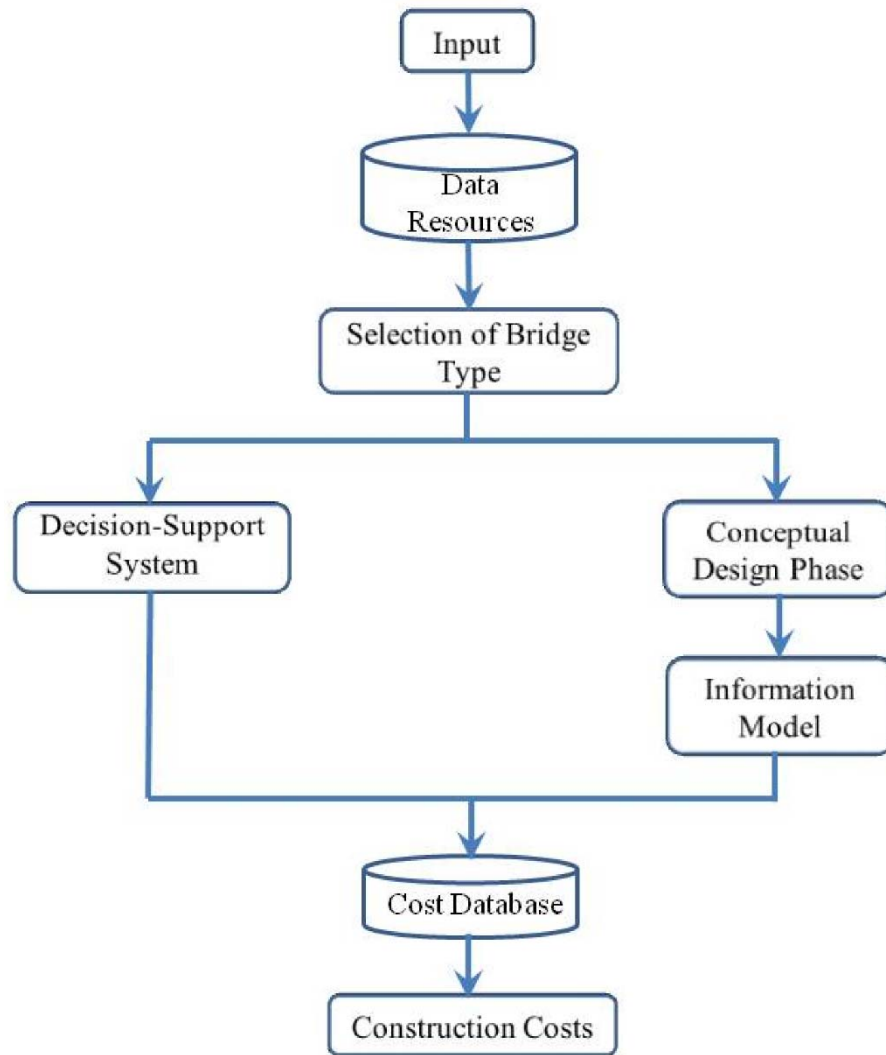


Figure 4.2 Model Development Flowchart

The cost estimation module is developed in an object-oriented .NET framework while utilizing SQLite [6] database, which has the ability to resolve interoperability issues among internal database applications. Model development process consists of five main steps: 1) Collect data

related to the different modules and organize them into a database server. 2) Create complex quality functions that analyze bridge beneficiaries/users relative perception on multiple evaluation criteria and incorporate them towards the development of a fuzzy logic decision support system that assists the user in selecting bridge type. 3) Conduct TOPSIS to evaluate bridge type scorings and provide results on the analysis. 4) Create a conceptual bridge design (BrIM) model where geometric parameters of a concrete box-girder bridge are defined for structural loading analysis. 5) Develop systematic procedures for overall cost estimation. Two main modules are then categorized according to the actual conceptual bridge design process. The modules are as follows: 1) a selection module of bridge design type, which comprises an automated quality function deployment (QFD) technique. A QFD is a client-based quality management system based on product beneficiaries/users relative importance perception on a set of defined competitors. Following QFD is TOPSIS; an analytical strategy utilized for the selection of the best bridge design alternative based on a specified list of parameters; 2) a cost estimation module, which contains a comprehensive database of costing factors that is automatically linked to the BrIM built-in database connected to a report sub-module that displays instantaneous output reports of preliminary cost estimating.

4.6.1 Data Collection

The most important step prior to developing the proposed model is to understand the characteristics of IPCES, which in turn reflects the “type” of estimate required to successfully implement a cost effective conceptual design. Therefore, diverse database sources pertaining to bridge beneficiaries’ surveys, including scope of work related parameters, and unit cost parameters are extracted from R.S. Means for Heavy Construction Cost Data Handbook [16] and

incorporated into a set of modules. The selection of the aforementioned resources of cost data is strictly based upon their popular deployment among the industry especially during the conceptual design stage of bridge projects. Surveying bridge users and beneficiaries is the ignition point of the development mechanism. Therefore, a finite set of diverse bridge types is defined and classified where bridge beneficiaries' survey responses to parametric related queries for the diverse bridge types are converted from a survey transcript into a digital format for analysis. This process shall be discussed in further details in the following sections. In this study, an SQLite (Hipp, 2013) database server application is utilized as the main database platform for its capabilities in enhancing general performance and data recall response time efficiency.

4.6.2 Fuzzy Logic Decision Support

Presently, bridge design is mainly influenced by the scale of subjectivity involved in the selection of bridge type, system, and material at conceptual stages. Otayek et al. (2012) have 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 recommend continuous and further development in decision support systems in an attempt to assist bridge designers in selecting bridge type at conceptual phases. On the other hand, Malekly et al. (2010) have proposed a methodology of implementing QFD and TOPSIS for bridge selection. Their methodology is integrated in a novel oriented approach while overcoming interoperability issues among the disperse databases. Therefore, authors of this study propose an integration prototype of a decision support system and design related attributes for bridge type selection with elemental cost estimation for concrete box-girder bridges at the conceptual design stage. Conceptual bridge design is found to be significantly influenced by each the following seven main (WHATs)

criterion: (1) technical ‘W₁’; (2) functional ‘W₂’; (3) safety ‘W₃’; (4) construction ‘W₄’; (5) economics ‘W₅’; (6) aesthetics ‘W₆’; and (7) material ‘W₇’. Selection of the WHATs criteria is based on earlier studies on critical factors that bridge designers rely upon and authors’ perception on bridge criterion importance and evaluation in selection of bridge type. A 9-point symmetrical triangular fuzzy logic numbers (STFN) ranging from one to nine, with one being very low and nine being very important, is adopted for assisting the user in predicting bridge beneficiaries perception pursuant to the seven main criteria listed above. The scoring system comprises crisp and fuzzy measures when uncertainty arises as illustrated in Figure 4.3.

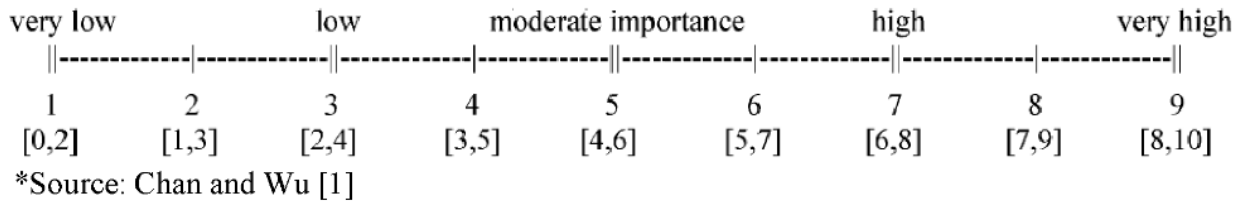


Figure 4.3 Fuzzy-Logic Scoring System

On the other hand, bridge beneficiaries are identified in this study and classified as follows: (i) stakeholders/government; (ii) designers/engineers; (iii) contractors/builders; and (iv) public/residents. Also, the following nine common bridge types “competitors” are identified and incorporated into the database platform for QFD analyses: (1) beam bridges ‘C₁’; (2) truss bridges ‘C₂’; (3) cantilever bridges ‘C₃’; (4) arch bridges ‘C₄’; (5) tied-arch bridges ‘C₅’; (6) suspension bridges ‘C₆’; (7) cable-stayed bridges ‘C₇’; (8) movable bridges ‘C₈’; and (9) double-decked bridges ‘C₉’. The adopted QFD analytical technology utilized for selection of bridge type is presented in Figure 4.4.

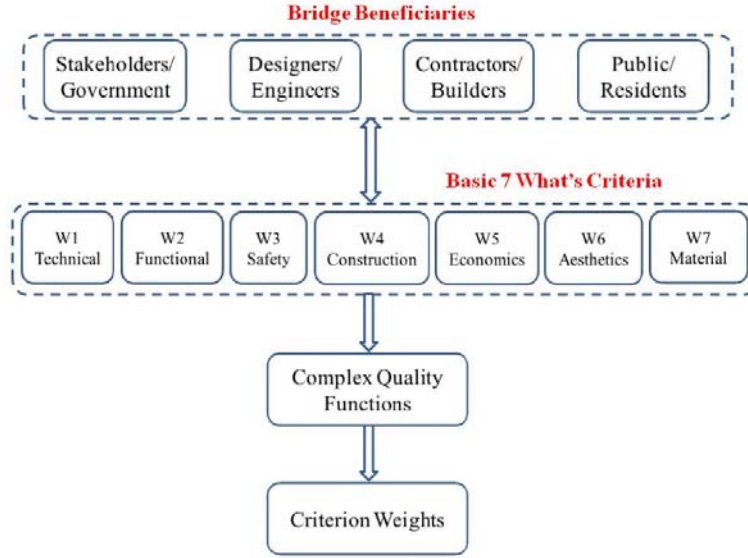


Figure 4.4 Quality Function Deployment Chart

Upon completion of beneficiaries' scorings on the seven WHATs, perception on relative importance ratings of the seven WHATs is determined. In this study, Chan and Wu [1] mathematical expressions are deployed due to their efficiency, systematic characteristics, and ease of use in competitive analysis of bridge type selection. Crisp and STFV measure forms of relative importance ratings are obtained in accordance with equations (4.1) and (4.2) derived by Chan and Wu (2005):

$$g_{mk} = \frac{(g_{m1} + g_{m2} + g_{m3} + g_{m4} + g_{m5} + g_{m6} + g_{m7} + g_{m8} + g_{m9})}{9} \quad (4.1)$$

$$\tilde{g}_{mk} = \frac{(\tilde{g}_{m1} + \tilde{g}_{m2} + \tilde{g}_{m3} + \tilde{g}_{m4} + \tilde{g}_{m5} + \tilde{g}_{m6} + \tilde{g}_{m7} + \tilde{g}_{m8} + \tilde{g}_{m9})}{9} \quad (4.2)$$

Where; g_{mk} is a bridge beneficiary relative importance perception on a WHATs criterion in 'crisp' form; k is a bridge beneficiary; W_m is a WHATs criterion; $\tilde{g}_{mk}$ is a bridge beneficiary relative importance perception on a WHATs criterion in 'fuzzy' form. In other words, g_{mk} is the

average “integer” crisp scoring value of a bridge beneficiary on the relative importance of each of the WHATs criteria and $\tilde{g}_{mk}$ is the average “integer” fuzzy scoring value of a bridge beneficiary on the relative importance of each of the WHATs criterion. Following the determination of relative importance ratings, bridge beneficiaries’ competitive comparison matrix analysis is developed as per Chan and Wu (2005) equations (4.3) and (4.4):

$$X = [x_{mk}]_{7 \times 9} \quad (4.3)$$

$$x_{mlk} = \frac{(x_{m11} + x_{m12} + x_{m13} + x_{m14})}{4} \quad (4.4)$$

Where; X is the bridge beneficiaries’ comparison matrix; x_{mk} is a bridge beneficiary assessment on W_m ; and x_{mlk} is a bridge beneficiary assessment of a bridge competitor on W_m . Afterwards, the probability distribution of each W_m on bridge competitors is calculated using Chan and Wu (2005) equation (4.5):

$$p_{mk} = \frac{x_{mk}}{x_m} \quad (4.5)$$

Where; p_{mk} is the probability distribution of W_m on bridge competitors; x_{mk} is a bridge beneficiary assessment on W_m ‘result obtained from equation (4.4)’; and x_m is the total of bridge beneficiary assessment of all bridge competitors on each of W_m . Following the determination of probability distribution of W_m , its measure of entropy, which is a quantification

of the expected value of a system with uncertainty in random variables, may be obtained using Chan and Wu (2005) equations (4.6) and (4.7):

$$E(W_m) = -\phi_9 \sum_{l=1}^9 p_{mk} \ln(p_{mk}) \quad (4.6)$$

$$\phi_9 = \frac{1}{\ln(9)} \quad (4.7)$$

Where; $E(W_m)$ is the measure of entropy by a discrete probability distribution for W_m ; ϕ_9 is the normalization factor that guarantees $0 \leq E(p_1, p_2, \dots, p_L) \leq 1$; p_{mk} is the probability distribution of W_m for the diverse bridge competitors.

Higher entropy or $(p_1, p_2, \dots, p_L)$ implies smaller variances and lesser information in a probability distribution p_L . At the end, it is possible to determine bridge competitors' priority ratings on each of the seven W_m using Chan and Wu (2005) equation (4.8):

$$e_m = \frac{E(W_m)}{\sum_{m=1}^7 E(W_m)} \quad (4.8)$$

Where; e_m is the criterion weight of W_m which is exported to TOPSIS and further discussed in Section 4.6.3. This complex quality function deployment mechanism of assigning priorities to competing alternatives is directly related to information theory concept of entropy.

4.6.3 TOPSIS

Upon determination of the seven WHATs, a multi-criteria decision making approach, TOPSIS, is undertaken. This approach takes into account the following criteria: (i) qualitative benefit; (ii) quantitative benefit; and (iii) cost criteria. As part of TOPSIS analysis, the following two most contradicting alternatives are surmised: (a) ideal alternative in which the maximum gain from each of the criteria values is taken; and (b) negative ideal alternative in which the maximum loss from each of the criteria values is taken. Towards the end, TOPSIS opts in for the alternative that converges to the ideal solution and opts out from the negative ideal alternative. Prior to undertaking the multi-criteria decision making approach, a TOPSIS matrix is developed using equation (4.10) below:

$$X = (x_{ij}) \quad (4.10)$$

Where; X is the bridge beneficiaries comparison matrix; and x_{ij} is an “m x n” matrix with ‘m’ criteria and ‘n’ bridge competitors that display the score of bridge beneficiary ‘i’ on criterion ‘j’. TOPSIS analysis comprises the following consecutive five steps: (i) normalized decision matrix; (ii) weighted normalized decision matrix; (iii) ideal and negative ideal solutions; (iv) bridge competitors’ separation measures; and (v) relative closeness to ideal solution as shown in Figure 4.5.

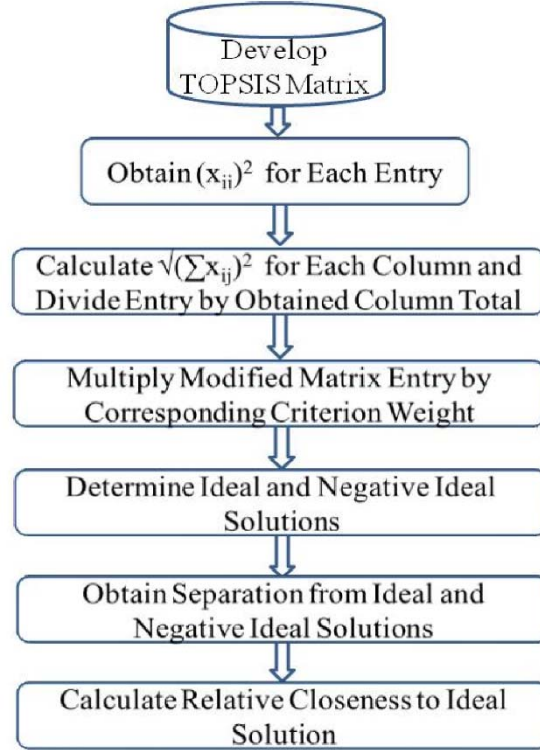


Figure 4.5 Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) Process Flow

In this study, Hwang et al. (1993) mathematical expressions are deployed based on their direct applicability to ranking bridge type alternatives and proven reliability. Generating the normalized decision matrix is intended to convert various parametric dimensions into non-dimensional parameters to allow for contrasting among criteria using Hwang et al. (1993) equation (4.11) below:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum x_{ij}^2}} \quad (4.11)$$

Where; r_{ij} is the normalized scoring value of bridge beneficiaries on bridge competitors' criteria. Afterwards, the creation of a weighted decision matrix is obtained by multiplying the criterion weights determined from equation (4.8) by its corresponding column of the normalized decision matrix obtained from equation (4.11) through the employment of Hwang et al. (1993) equation (4.12):

$$v_{ij} = w_i r_{ij} \quad (4.12)$$

Where; v_{ij} is the weighted normalized element of the TOPSIS matrix; and w_i is the WHATs criterion weight value. Afterwards, the ideal and negative ideal solutions are determined using Hwang et. al. (1993) equations (4.13) and (4.14) respectively:

$$A^* = \{v_1^*, \dots, v_j^*\} \quad (4.13)$$

$$A' = \{v_1', \dots, v_j'\} \quad (4.14)$$

Where; A^* is the positive ideal solution; where $v_j^* = \{\max v_{ij}\}$ if $j \in J$; minimum v_{ij} if $j \in J'$; A' is the negative ideal solution where $v_j' = \{\min v_{ij}\}$ if $j \in J$; maximum v_{ij} if $j \in J'$; where J is the set of beneficial attributes or criteria; and J' is the set of negative attributes or criteria. Afterwards, bridge competitors' separation measures from ideal and negative ideal solutions are calculated by using Hwang et al. (1993) equations (4.15) and (4.16) respectively:

$$S_i^* = \left[\sum (v_j^* - v_{ij})^2 \right]^{1/2} \quad (4.15)$$

$$S_i' = \left[\sum (v_j' - v_{ij})^2 \right]^{1/2} \quad (4.16)$$

Where; S_i^* is the separation from the positive ideal solution; S_i' is the separation from the negative ideal solution; and i is the number of bridge competitors. Finally, relative closeness to ideal solution is calculated by using equation (4.17) as follows:

$$C_i^* = \frac{S_i'}{(S_i^* + S_i')} \quad ; \quad 0 < C_i^* < 1 \quad (4.17)$$

Where; C_i^* is the relative closeness to positive ideal solution. The recommended bridge competitor or alternative is the one with a corresponding C_i^* closest to the value of unity “1”. As part of developing the fuzzy logic decision support system, further studies are undertaken to reach a unified reinforced concrete bridge classification in terms of technicality, functionality, and foundation type as illustrated in Tables 4.1 through 4.3.

Table 4.1 Bridge Material Type Based on Technical Span

Span (ft)	Bridge Material
0 to 330	Reinforced Concrete Beam
330 to 650	Reinforced Concrete Beam / Steel
650 to 880	Steel

Table 4.2 Reinforced Concrete Bridge System Based on Functional Span

Span (ft)	Bridge System
0 to 130	Reinforced Concrete Beam
130 to 200	Reinforced Concrete Beam / Arch
200-	Arch

Table 4.3 Reinforced Concrete Bridge Foundation Material Based on Geotechnical Recommendations

Span (ft)	Bridge System
Shallow	Pile (Including Timber)
Deep	Reinforced Concrete / Steel

Following bridge design type classifications, the tabulated data presented above are transformed to graphical formats where technical and functional spans as well as foundation type recommendations obtained from a geotechnical expert report or accredited soil investigation laboratories may be incorporated based on user discretion. The developed model or system shall be capable of assisting the user with design recommendations of the ‘best’ bridge type and system provided the circumstances given.

4.6.4 Conceptual Bridge Design

Once the user is provided with a TOPSIS matrix for bridge type selection, geometrical parameters of the bridge model are incorporated into the BrIM tool for preliminary load application and design analyses. In this study, SAP2000 is selected as a 3D-CAD structural

analysis tool since it encompasses a dedicated bridge designer module and complies with AASHTO LRFD-09 and CALTRANS seismic design requirements. Also, its user friendly interface permits the user to “easily” model complex bridge structures. The tool features a 4-noded shell element, known for reliability in modeling finite shell elements, and an Eigen-value buckling procedure based on subspace Eigen-solver through an accelerated iteration algorithm. As part of developing the model, earlier studies pursuant to finite shell element meshing are recalled. A study by Dabbas (2002) concludes that shell elements size and aspect ratio could significantly affect design results. It is also found that elements with a square shape reflect accurate outcomes. Therefore, in this study, finite shell elements comprising an aspect ratio of nearly equal to unity are employed.

Following the creation of the 3D BrIM, bridge vehicular moving load analysis is conducted. Bridge design reports illustrating required bridge girder sections with corresponding load and moment resistance capacities are readily displayed for preliminary cost estimating, which shall be discussed in further detail in the Section 4.6.5.

4.6.5 Preliminary Cost Estimation

Comprehensive data pertaining to concrete box-girder bridges costs are necessary for reaching at accurate preliminary estimates. It is after all about determining corresponding costs while taking into consideration factors and constraints that govern the estimation process. As part of developing IPCES, bridge structural elements are automatically extracted from the developed BrIM and organized into the database platform as per the following categories: 1) substructure; which includes foundations construction material and reinforcement steel; 2) superstructure;

which includes bridge bearings, box-girders, reinforcement and post-tensioning steel; and 3) finishing; which include water proofing system and parapet walls. Afterwards, the aforementioned items unit quantities are directly extracted by the cost estimation engine to obtain a preliminary cost estimate supported by universally accepted metrics of costs. Cost data resources pertaining bridge construction unit costs are obtained from R.S. Means for Heavy Construction Cost Data Handbook (2012). Bridge construction rudiments are identified and organized in Table 4.4.

Table 4.4 Cost Estimation Output Report Categories and Elements

Preliminaries	Substructure	Superstructure	Railing & Barriers	Miscellaneous
Site Overheads	Material	Bearing	Traffic	Strip Seal
Mobilization/	Reinforcing	Girders	Barrier	Retaining Walls
Demobilization	Steel	Waterproofing	Pedestrian Railing	Noise Wall
Temporary		Reinforcing Steel	Bicycle Railing	Detour Bridge
Fencing		Post-Tensioning		Road Pavements
Environmental		teel		Curbs & Footways
Barriers				Paved areas
Site Clearance				Traffic Signs
Dewatering				Road Markings & Lighting
Temporary				Columns & Brackets
Shoring				Electrical work
Earthmoving				Communications
Operations				Drainage Work
Granular Sub-base				Landscape & Ecology
				Testing & Commissioning

4.7 Integration Platform

Decision making pertaining to the selection of bridge type necessitates the deployment of an integrated platform comprising: 1) expert system; 2) BrIM; 3) and cost estimation. In this study, the developed model includes a knowledge-based support system that extracts information from the 3D structural analysis program, SAP2000, via a Dynamic Link Library (DLL)-invoked

application programming interface (API) method that automatically recalls the parametric enriched object-oriented model. For instance, the developed model provides the user with an option to develop an information module by utilizing the fuzzy logic scoring system in order to determine the bridge type based on the deployment of the afore-mentioned processes (i.e. QFD & TOPSIS); otherwise, the application automatically extracts data from the developed BrIM model and presents results pertaining to nominations and recommendations to selected bridge type based on technical and functional spans besides geotechnical attributes as summarized in Tables 6.1 through 6.3. The application is designed to extract all necessary information from the assigned model by exporting SAP2000 input databases via Industry Foundation Classes (IFC) file formats which reduce loss of information during file transmission. After that, the application is objectively developed for concrete box-girder bridges such that capturing of data displayed in the calling software is conducted by utilizing SAP2000 objects. After all, bridge elements attributes are recalled and organized via a DLL-invoked programming language and incorporated into the SQLite database server for utilization by the cost estimation module.

4.8 Interoperability

Following QFD and TOPSIS, bridge sub- and super-structure geometric parameters (i.e. bridge span, bridge girder cross-sectional area, bent size, pile caps, etc) and subsequent coordinates are extracted from the SQLite database. The proposed data interface is a unique implementation in BrIM model and found to foster system efficiency besides resolving database interoperability issues. This mechanism is designed and managed by the developed model such that third party data interruption is prohibited. However, few cost items, such as; traffic signs, road markings, electrical, drainage works, landscape, and ecology are a necessity and must be entered by the

user as they are variable costs and may not be predetermined. It is important to note that the output IFC files are extracted for cost estimation utilization via a dynamic link library (DLL) (.dll) file, which contains a library of call functions and other information such as: a programming language codes and diverse database resources that can be easily accessed by any windows program. Moreover, the platform herein is developed in such a way that corresponding applications running time is reduced and interoperability matters among the developed modules (i.e. decision-support, 3D model, and cost estimation) are resolved. The cost estimation module utilizes extracted information of the 3D model objects that is stored in the database server for obtaining elemental costs. For instance, a box-girder bridge cross-sectional area is extracted via IFC file formats by implementing a DLL-invoked call functions and incorporated into the SQLite database server subsequently for numerical multiplication by its corresponding parametric unit cost obtained from R.S. Means for Heavy Construction Cost Data Handbook (2012) in order to determine overall bridge costs at the conceptual design stage.

4.9 Model Development

The model is developed through an object-oriented programming (OOP) approach utilizing ‘C#’ and implemented in a classical .NET framework. The main purpose of the model is to facilitate the interface between bridge design at the conceptual stage, user-defined input, and cost estimating functions as summarized in Figure 4.6.

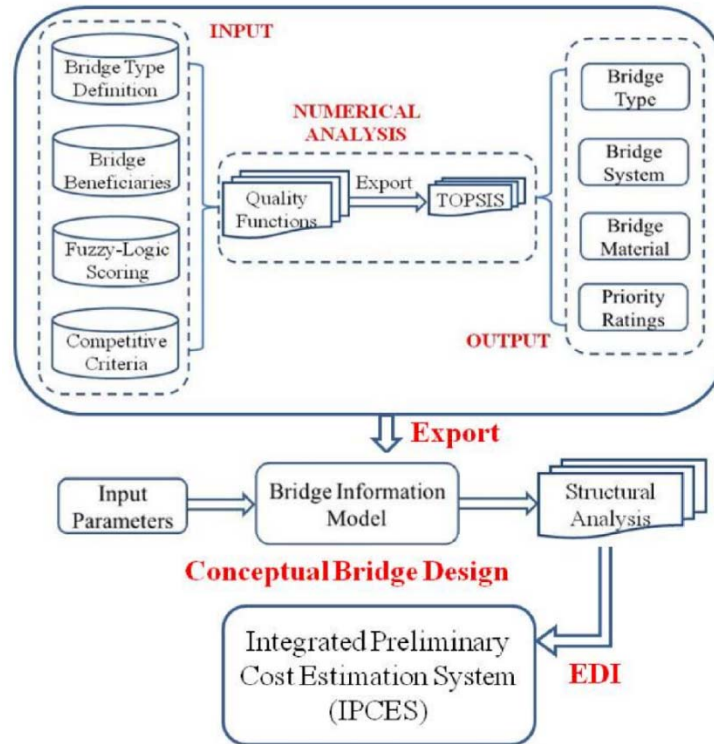


Figure 4.6 IPCES Model Development Process

At first, the user inputs bridge design survey results based on the developed fuzzy logic scoring system related to bridge type attributes for the four distinct beneficiaries defined earlier into the QFD module as shown in Figure 4.7.



Figure 4.7 IPCES Quality Function Deployment Module Interface

Afterwards, a beneficiary comparative matrix is established where parametric weights are assigned for commencement of TOPSIS analysis. Then, the following set of bridge design definitive attributes: (i) technical span; (ii) functional span; and (iii) foundation type are deployed as per Bridge Design Handbook (Chen and Duan, 2000) recommendations. At this time, the user will be provided with three curves overlaid on the same graph as a guideline 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 Figure 4.8.

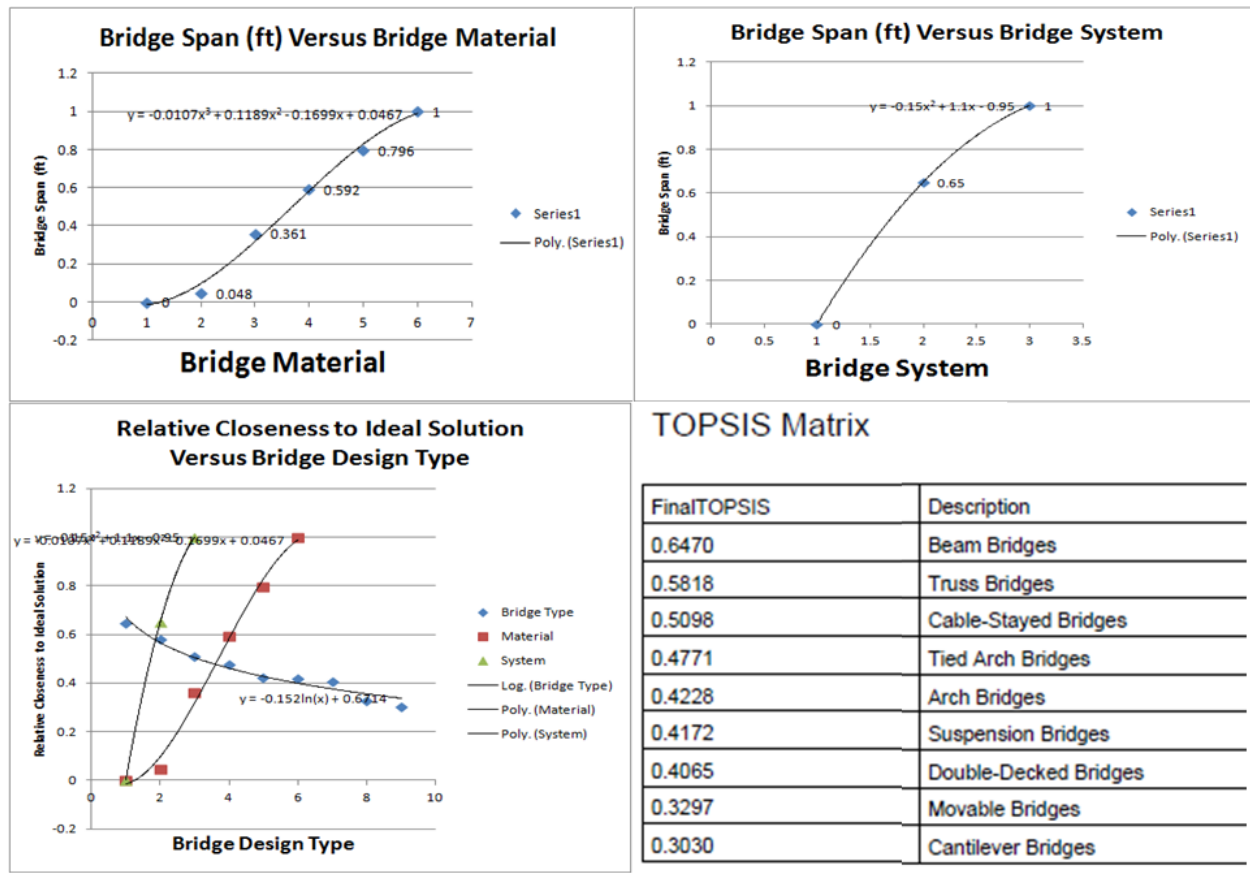


Figure 4.8 IPCES Bridge Conceptual Design Curves and Final TOPSIS Matrix

4.10 Model Validation

To validate the workability of the developed model, an actual case project located in Ottawa, Ontario and comprising a concrete box-girder bridge with a total span of 200 ft. supported with a central interior bent at 100 ft. is modeled in SAP2000. The challenge underlying the model validation is to provide a preliminary cost estimation of the bridge profile shown in Figure 4.9 necessary to execute the construction phase.

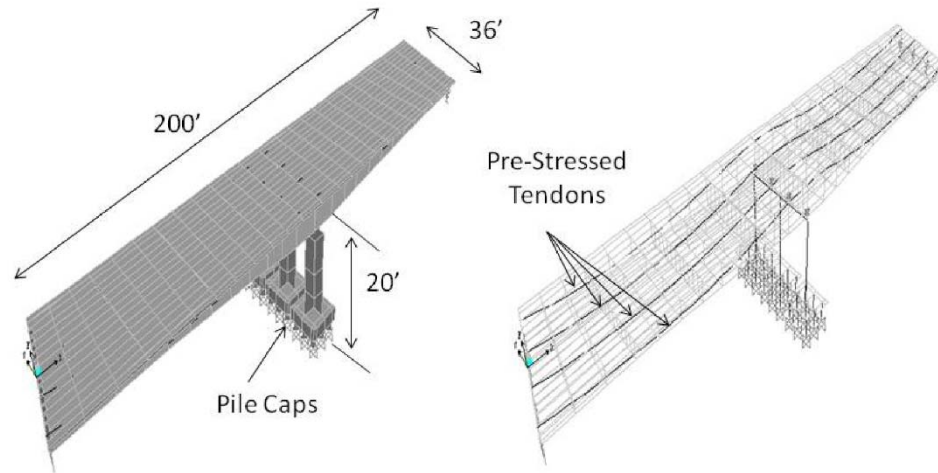


Figure 4.9 Case Project Conceptual Design Bridge Information Model Parameters

Prior to inputting project related data into BrIM tool, the following list summarizes main parametric design assumptions:

- 1) Abutment: skewed at 15 degrees and supported at bottom girder only;
- 2) Pre-stressing: 4 nos. 5 in² tendons with a 1,080 kips capacity each;
- 3) Interior bent: 3 nos. 5 ft square columns;
- 4) Deck: parabolic variation ranging from 5-10 ft in nominal depth;
- 5) Pile cap: 3 nos. 13' x 13' x 4'; and
- 6) Pile: 9 nos. 14" dia. steel pipe filled with concrete reinforced with 8 nos. #9 reinforcement bars at each pile cap.

It is important to note that the aforementioned assumptions are made based on normal job conditions. However, if geographical constraints are 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 influence overall project cost. As part of validating the proposed fuzzy logic decision support system, an interview is conducted with each of the four bridge beneficiaries. Corresponding scorings to survey questionnaires comprising the WHATs criteria and bridge competitors are recorded and transformed into a digital format for IPCES analysis in measure, crisp and fuzzy forms. Figures 4.10 through 4.12 show samples of the IPCES analysis for the Stakeholders/Government beneficiary; whereas similar analytical procedures are undertaken for the other beneficiaries.

Stakeholders/ Government										
1 Stakeholders /Government 2 Designers /Engineers 3 Contractors /Builders 4 Public /Residents 5 TOPSIS analysis										
Whats	C1	C2	C3	C4	C5	C6	C7	C8	C9	
W1. Technical	High	Very High	VeryLow	Moderate Important	High	Low	Moderate Important	VeryLow	Low	Measure
W2. Functional	High	High	Very High	Very High	Very High	Moderate Important	Very High	Very High	VeryLow	Crisp
W3. Safety	High	Moderate Important	Moderate Important	High	Moderate Important	Low	Moderate Important	Low	Low	Fuzzy
W4. Construction	High	High	Low	VeryLow	Low	VeryLow	Low	VeryLow	Low	
W5. Economics	Moderate Important	Very High	High	Moderate Important	High	Low	Moderate Important	VeryLow	VeryLow	
W6. Aesthetics	Low	Moderate Important	Moderate Important	High	Moderate Important	Very High	Very High	Moderate Important	Moderate Important	
W7. Material	Moderate Important	High	Moderate Important	Moderate Important	High	Moderate Important	High	Moderate Important	High	

Figure 4.10 Stakeholders/Government Assessment of WHATs Criteria on Bridge Competitors in Measure Form

Stakeholders/ Government									
1 Stakeholders /Government 2 Designers /Engineers 3 Contractors /Builders 4 Public /Residents 5 TOPSIS analysis									
Whats	C1	C2	C3	C4	C5	C6	C7	C8	C9
W1. Technical	7	9	1	5	7	3	5	1	3
W2. Functional	7	7	9	9	9	5	9	9	1
W3. Safety	7	5	5	7	5	3	5	3	3
W4. Construction	7	7	3	1	3	1	3	1	3
W5. Economics	5	9	7	5	7	3	5	1	1
W6. Aesthetics	3	5	5	7	5	9	9	5	5
W7. Material	5	7	5	5	7	5	7	5	7

Figure 4.11 Stakeholders/Government Assessment of WHATs Criteria on Bridge Competitors in Crisp Form

Stakeholders/ Government									
1 Stakeholders /Government 2 Designers /Engineers 3 Contractors /Builders 4 Public /Residents 5 TOPSIS analysis									
Whats	C1	C2	C3	C4	C5	C6	C7	C8	C9
W1. Technical	[6,8]	[8,10]	[0,2]	[4,6]	[6,8]	[2,4]	[4,6]	[0,2]	[2,4]
W2. Functional	[6,8]	[6,8]	[8,10]	[8,10]	[8,10]	[4,6]	[8,10]	[8,10]	[0,2]
W3. Safety	[6,8]	[4,6]	[4,6]	[6,8]	[4,6]	[2,4]	[4,6]	[2,4]	[2,4]
W4. Construction	[6,8]	[6,8]	[2,4]	[0,2]	[2,4]	[0,2]	[2,4]	[0,2]	[2,4]
W5. Economics	[4,6]	[8,10]	[6,8]	[4,6]	[6,8]	[2,4]	[4,6]	[0,2]	[0,2]
W6. Aesthetics	[2,4]	[4,6]	[4,6]	[6,8]	[4,6]	[8,10]	[8,10]	[4,6]	[4,6]
W7. Material	[4,6]	[6,8]	[4,6]	[4,6]	[6,8]	[4,6]	[6,8]	[4,6]	[6,8]

Figure 4.12 Stakeholders/Government Assessment of WHATs Criteria on Bridge Competitors in Fuzzy Form

Following bridge beneficiaries' assessment of WHATs criteria on bridge competitors, relative importance perception ratings in crisp and fuzzy forms are obtained according to equations (4.1) and (4.2). Figure 4.13 illustrates the rating for the Stakeholders/Government; whereas similar rating is conducted for the other beneficiaries.

Whats	C1.Crisp	C1.Fuzzy	C2.Crisp	C2.Fuzzy	C3.Crisp	C3.Fuzzy	C4.Crisp	C4.Fuzzy	C5.Crisp	C5.Fuzzy
W1. Technical	7	[6,8]	9	[8,10]	1	[0,2]	5	[4,6]	7	[6,8]
W2. Functional	7	[6,8]	7	[6,8]	9	[8,10]	9	[8,10]	9	[8,10]
W3. Safety	7	[6,8]	5	[4,6]	5	[4,6]	7	[6,8]	5	[4,6]
W4. Construction	7	[6,8]	7	[6,8]	3	[2,4]	1	[0,2]	3	[2,4]
W5. Economics	5	[4,6]	9	[8,10]	7	[6,8]	5	[4,6]	7	[6,8]
W6. Aesthetics	3	[2,4]	5	[4,6]	5	[4,6]	7	[6,8]	5	[4,6]
W7. Material	5	[4,6]	7	[6,8]	5	[4,6]	5	[4,6]	7	[6,8]

Whats	C6.Crisp	C6.Fuzzy	C7.Crisp	C7.Fuzzy	C8.Crisp	C8.Fuzzy	C9.Crisp	C9.Fuzzy	Relative Imp Ratings Crisp	Relative Imp Ratings Fuzzy
W1. Technical	3	[2,4]	5	[4,6]	1	[0,2]	3	[2,4]	4.56	[40.42]
W2. Functional	5	[4,6]	9	[8,10]	9	[8,10]	1	[0,2]	7.22	[64.66]
W3. Safety	3	[2,4]	5	[4,6]	3	[2,4]	3	[2,4]	4.78	[42.44]
W4. Construction	1	[0,2]	3	[2,4]	1	[0,2]	3	[2,4]	3.22	[28.30]
W5. Economics	3	[2,4]	5	[4,6]	1	[0,2]	1	[0,2]	4.78	[42.44]
W6. Aesthetics	9	[8,10]	9	[8,10]	5	[4,6]	5	[4,6]	5.89	[52.54]
W7. Material	5	[4,6]	7	[6,8]	5	[4,6]	7	[6,8]	5.89	[52.54]

Figure 4.13 Stakeholders/Government Relative Importance Perception on WHATs Criteria

Afterwards, a beneficiary comparison matrix is constructed based on equations (4.3) and (4.4) as shown in Figure 4.14.

Whats	C1	C2	C3	C4	C5	C6	C7	C8	C9	em
W1. Technical	5.5	6	4.5	6	6	5.5	5.5	3	4.5	0.14
W2. Functional	7.5	8.5	8	7.5	7	8	9	7	5	0.15
W3. Safety	6.5	5.5	6	7	6	4.5	5.5	4.5	4.5	0.15
W4. Construction	6.5	5.5	1.5	1	3	1	3	1	3	0.13
W5. Economics	4.5	6	5	4	5.5	3.5	5	2.5	3.5	0.14
W6. Aesthetics	3.5	4.5	5	7.5	7.5	8.5	7.5	5	5	0.14
W7. Material	6	6	5	5	5.5	4	6	5	6	0.15

Figure 4.14 Beneficiary Competitive Matrix Analysis

Furthermore, the probability distribution and corresponding measure of entropy of WHATs criteria determined by using equations (4.5) through (4.8) is presented in Section 4.6.2. It is clear that criterions ‘W2.Functional’; ‘W3.Safety’; and ‘W7.Material’ possess maximum weights followed by ‘W1.Technical’; ‘W5.Economics’; and ‘W6.Aesthetics’; while, ‘W7.Construction’ criterion possess the minimum weight. Generally, bridges are designed while taking into account the following main criteria: (1) technical; (2) functional; and (3) safety. However, by employing

complex quality function technique, it is determined that incorporating additional bridge beneficiaries, such as contractors/builders and public/residents, influence bridge design type criteria weights; and therefore, explicitly implying a more realistic and practical decision support system. With materials being more expensive and contribute more towards construction costs, it has been determined that its weight comes in the first place. On the other hand, it appears that construction method is of importance to some bridge beneficiaries but not to others and is determined to possess the lowest criterion weight. Usually, bridge economics criterion has always been ranked first at the bridge conceptual design stage since financial concerns and construction economics are considered the turnkey for major bridge projects. However, in this study, bridge economics is ranked second based on bridge beneficiaries' relative importance perception scorings. Following the determination of the seven WHATs criterion weights, the development of a TOPSIS matrix is automatically generated in accordance with equation (4.10). Afterwards, normalized decision and weighted matrices are constructed as per equations (4.11) and (4.12). Next, determination of positive and negative ideal solutions is undertaken as per equations (4.13) and (4.14) respectively and set as the reference datum. Towards the end, separations from positive and negative ideal solutions are obtained as per equations (4.15) and (4.16).

Finally, TOPSIS relative closeness to ideal solution decision matrix is obtained according to equation (4.17) with priority ratings. Therefore, it is indicated from the final decision matrix that a beam bridge type is the most suitable bridge design type in compliance with bridge beneficiaries' relative importance perception ratings on conceptual design criteria. Following the determination of the bridge competitors' priority ratings, technical and functional spans besides

the foundation type are incorporated into the design information model. According to bridge data, technical and functional span is 200 ft. as stated earlier in this section. Then, the developed model is capable of recommending bridge substructure and superstructure material and profile for implementation as summarized in Figure 4.15.

TOPSIS Matrix	
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

Relative closeness to Ideal Solution	
TOPSIS	Description
	Relative closeness to Ideal Solution
0.6470	Beam Bridges

Technical Span (ft) 200 RC Beam

Functional Span (ft) 200 Beam/Arch

Foundation Type Deep RC / Steel

Figure 4.15 IPCES Bridge Substructure and Superstructure Material and Profile Recommendations

In order to enhance IPCES output display, recommendations pertaining to bridge type, material, and system are extracted, normalized, and converted into a graphical format and overlaid on the same graph as the relative closeness to ideal solution priority ratings versus bridge types as illustrated in Figures 4.16 through 4.18 respectively.

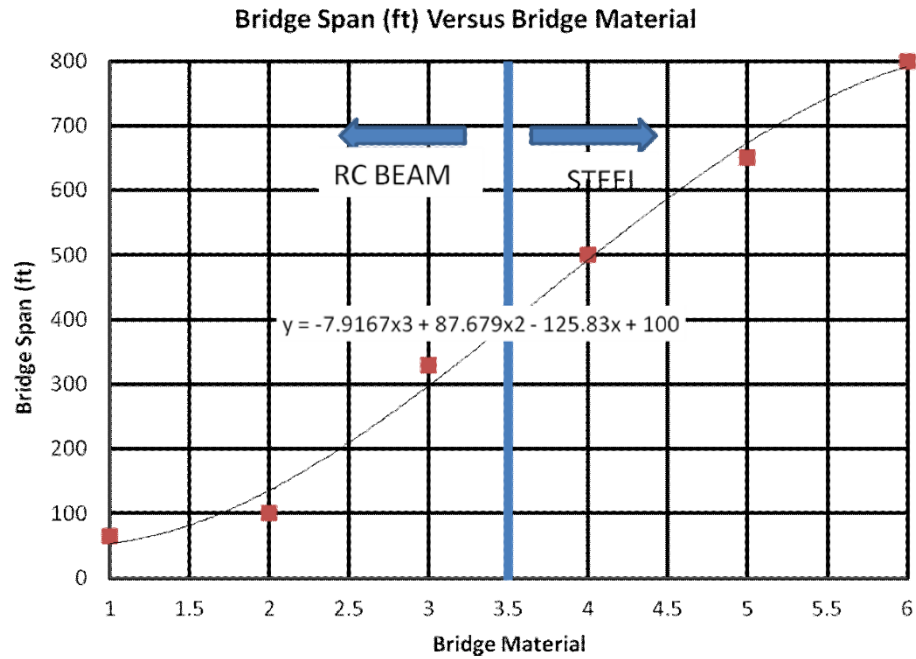


Figure 4.16 IPCES Recommendation of Bridge Material Based on Bridge Span Selection

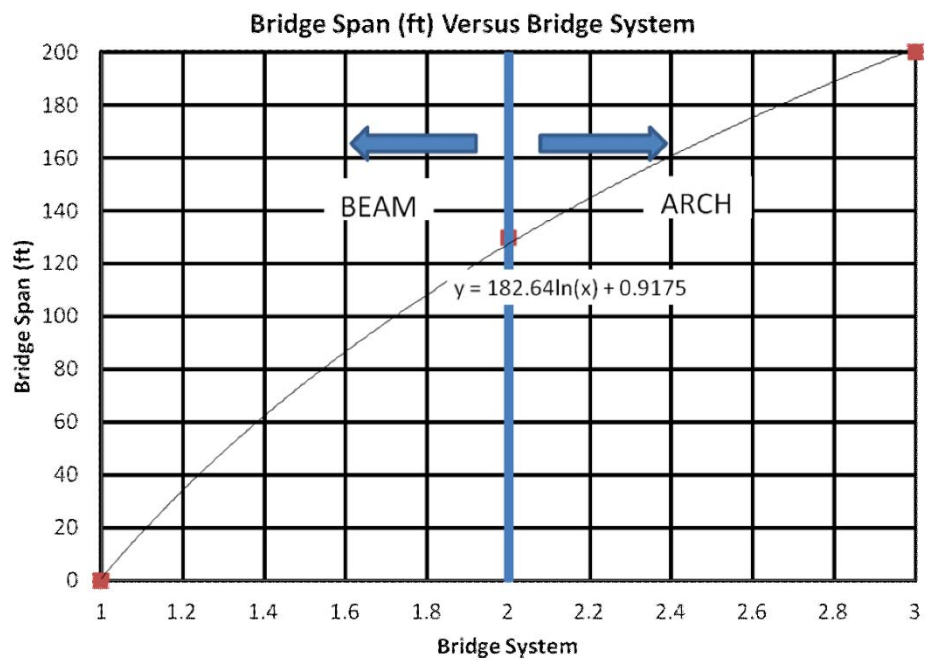


Figure 4.17 IPCES Recommendation of Bridge System Based on Bridge Span Selection

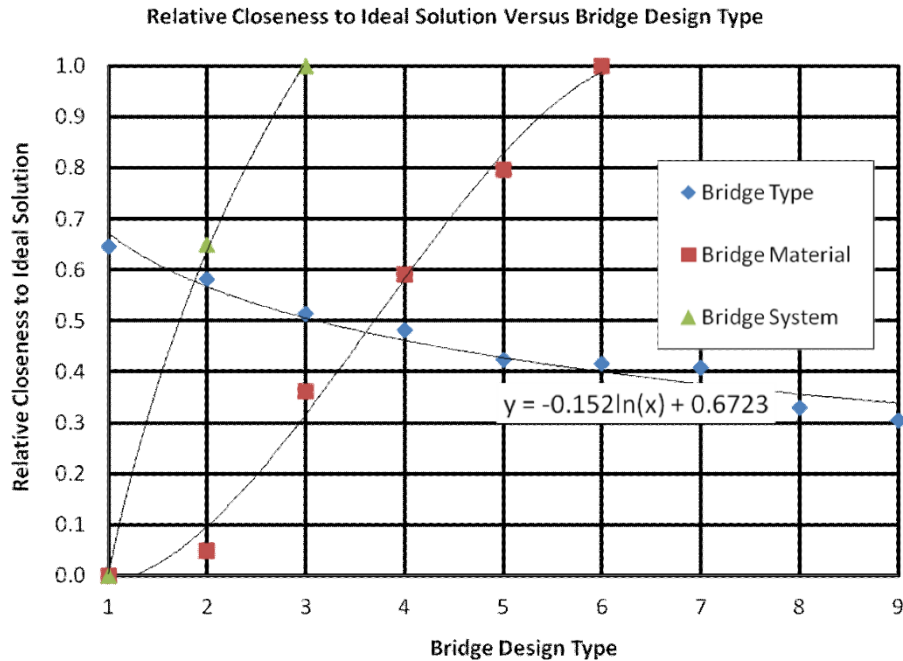


Figure 4.18 IPCES Recommendations of Bridge Design Type, Material, and System

In Figure 4.18, relative closeness to ideal solution versus bridge type curve is obtained by approximating a logarithmic trend function through error minimization technique. The bridge span versus bridge material curve is approximated similarly; however, bridge span versus bridge system curve is approximated by a third order polynomial function. By using Figure 4.18, the user is capable of having a wider perspective into bridge type, material, and system to be incorporated into the bridge information model and ‘next to kin’ alternatives accordingly. Therefore, bridge information attributes are extracted from the bridge information model and subsequently incorporated into the comprehensive cost database’ mathematical engine in order to calculate corresponding costs as illustrated in Figure 4.19.

Cost Estimation

Description	Unit	Qty	Rate	Cost
PRELIMINARIES				
Site Overheads	%	LOT	16%	\$236,990.14
Mobilization/Demobilization	%	LOT	10%	\$148,118.84
Temporary Fencing	LF	520	\$22.70	\$11,804.00
Environmental Barriers	SF	9286	\$0.12	\$1,114.32
Site Clearance	LS	LOT	\$12,000.00	\$12,000.00
Dewatering	LS	LOT	\$25,000.00	\$25,000.00
Temporary Shoring	LS	LOT	\$25,780.00	\$25,780.00
Earthmoving Operations	LS	LOT	\$78,945.00	\$78,945.00
Granular Subbase	CY	1000	\$12.00	\$12,000.00
SUBSTRUCTURE				
Steel Piling	LF	135	\$67.50	\$9,112.50
Cofferdam Footing	SF	1250	\$89.42	\$111,781.25
Concrete	CY	75	\$776.78	\$58,258.50
Shell Fill	CY	16	\$79.34	\$1,269.44
Reinforcing Steel	LB	10875	\$0.59	\$6,416.25
SUPERSTRUCTURE				
Bearing Material	EA	12	\$4,434.20	\$53,210.40
Parapet Wall	FT	68.28	\$200.00	\$13,656.00
Cast-in-Place Superstructure Concrete	CY	704	\$831.81	\$585,594.24
Concrete Waterproofing System	SY	800	\$18.00	\$14,400.00
Reinforcing Steel	LB	72750	\$0.59	\$42,922.50
Post-tensioning Steel	LB	3400	\$1.96	\$6,664.00
RAILINGS AND BARRIERS				
Traffic Barrier	LF	200	\$56.31	\$11,262.00
Pedestrian Railing	LF	200	\$72.94	\$14,588.00
Bicycle Railing	LF	200	\$88.30	\$17,660.00
MISCELLANEOUS				
Strip Seal	LF	864	\$200.00	\$172,800.00
Road Pavements	SY	800	\$32.00	\$25,600.00
Curbs, Footways, & Paved Areas	LF	200	\$31.75	\$6,350.00
Traffic Signs & Road Markings	LS	LOT	\$10,000.00	\$10,000.00
Road Lighting Columns & Brackets	LS	LOT	\$25,000.00	\$25,000.00
Electrical Work and Communications	LS	LOT	\$30,000.00	\$30,000.00
Drainage Work	LS	LOT	\$65,000.00	\$65,000.00
Landscape and Ecology	LS	LOT	\$20,000.00	\$20,000.00
Testing & Commissioning	LS	LOT	\$13,000.00	\$13,000.00
SUB TOTAL				\$1,866,297.38
Contingency (5%)				\$93,314.87
Overhead and Profit (10%)				\$186,629.74
TAXES	%			\$279,011.46
TOTAL COST				\$2,425,253.45

Figure 4.19 IPCES Preliminary Construction Costs Output Report

The cost estimation report comprises a breakdown of preliminaries, substructure, superstructure, railings and barriers, and miscellaneous elements of a concrete box-girder construction project with 5% contingency and 10% overhead and profit as shown above. It is important to note that results obtained are subject to time constraints. In other words, reasonable times are assumed for completing each estimated element based on experience from similar projects; otherwise, if the construction of the bridge is of special type, costs may vary accordingly. Prior to comparison of results, it is important to note that estimated costs are based on preliminary design of the bridge comprising moving vehicles and seismic loads. Model results are compared to the actual data and found in good agreement with a percentage difference of 13% approximately, which is an acceptable rate at the conceptual design stage of projects. Table 4.5 summarizes a comparison of elemental costs in (2012) dollar values based on model estimation and actual data.

Table 4.5 Comparison of Box-Girder Bridge Elemental Costs (2012 Values))

	Category	Element	Cost
MODEL DATA	Substructure	Steel Piling	\$ 9,113 ^a
		Cofferdam Footing	\$ 111,781 ^a
		Concrete	\$ 58,259 ^a
		Shell Fill	\$ 1,269 ^a
		Reinforcing Steel	\$ 6,416 ^a
	Superstructure	Bearing Material	\$ 53,210 ^a
		Parapet Wall	\$ 13,656 ^a
		Cast-in-Place Concrete	\$ 585,594 ^a
		Waterproofing System	\$ 14,400 ^a
		Reinforcing Steel	\$ 42,923 ^a
		Post-Tensioning Steel	\$ 6,664 ^a
ACTUAL DATA	Substructure	Steel Piling	\$ 8,036 ^b
		Cofferdam Footing	\$ 98,572 ^b
		Concrete	\$ 51,375 ^b
		Shell Fill	\$ 1,119 ^b
		Reinforcing Steel	\$ 5,658 ^b
	Superstructure	Bearing Material	\$ 46,922 ^b
		Parapet Wall	\$ 12,042 ^b
		Cast-in-Place Concrete	\$ 516,397 ^b
		Waterproofing System	\$ 12,698 ^b
		Reinforcing Steel	\$ 37,851 ^b
		Post-Tensioning Steel	\$ 5,877 ^b

^a Values were obtained by extracting total quantity from BrIM and multiplying by unit cost^b Values were obtained from actual data and adjusted to account for inflation

Discrepancy between results is due to assumptions made as well as to the availability of resources at the time of construction. For example, elemental costs are based on economical conditions at the time of the estimation. However, overall results showed that the accuracy of the model varies depending on complexity of bridge design, geographical conditions, material costs, site conditions, soil type, and project duration.

4.11 Summary, Conclusions, And Recommendations

The successful development of an integrated cost estimation model, IPCES, which assists stakeholders conceptually plan for concrete box-girder bridge construction projects by integrating BrIM with cost data resources besides user-defined input are presented. Comparative analyses of disperse bridge types is conducted utilizing complex QFD and TOPSIS systematic approaches to assist users in bridge type selection at conceptual design stages. The actual accuracy of the model is highly dependent upon the technical and functional constraints as well as user-defined input. The developed model is then validated through an actual case project, which is presently under design development, defined in one of BrIM widely-used software technology, which contains a dedicated stand-alone bridge module.

Finally, it is concluded that the model possess design and estimation limitations pursuant to complex and combined bridge sub- and super- structure designs. It is necessary to mention that the estimation model is developed as a justification tool that may be utilized to estimate preliminary costs for a concrete box-girder bridge project. The proposed model may be utilized in the design of bridge projects 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. Given the scarcity of invasive studies on integrations of bridge information modeling with fuzzy logic decision support and cost estimation systems, authors are conducting further studies in that field. Furthermore, more attention is concentrated towards the effect of incorporating complex quality functions on selection of bridge type and components. The integrated preliminary cost estimation system (IPCES) model developed has the potential to reliably model other bridge types and configurations. Authors are presently working on the expansion of the probabilistic and numerical model databases of solutions, which is an important step towards developing rational design selection rules for bridges.

4.12 References

- Chan, L. and Wu, M. (2005). "A systematic approach to quality function deployment with a full illustrative example." *Omega*, Elsevier Ltd, 33: 119-139
- Chen, W.F. and Duan, L. (2000). "Bridge engineering handbook." CRC Press LLC, Boca Raton, FL, U.S.A.
- Dabbas, A. (2002). "Lateral stability of partially restrained cantilever." University of Ottawa. MAsc dissertation, Department of Civil Engineering, ON, Canada.
- Gallaher, M., O'Conner, A., Dettbarn, J., and Gilday, L. (2004). "Cost analysis of inadequate interoperability in the U.S. capital facilities industry." NIST GCR 04-867, National Institute of Standards and Technology, Gaithersburg, MD.

Heikkilä, R., Jaakkola, M., Pulkkinen, P. (2003). "Connecting 3-D concrete bridge design to 3-D site measurements." ISARC '20th, Eindhoven, Holland, 259-264.

Hipp, D. R. (2013). "An introduction to the SQLite C/C++ interface." <<http://www.sqlite.org/cintro.html>> (Accessed on 5, May, 2013)

Hwang, C.L., Lai, Y.J., and Liu, T.Y. (1993). "A new approach for multiple objective decision making." Computers and Operational Research, 20: 889–899.

Kivimäki, T. and Heikkilä, R. (2009). "Integrating 5D product modelling to on-Site 3D surveying of bridges." ISARC '26th, Austin, Texas, U.S.A., 445-450.

Kivimäki, T. and Heikkilä, R. (2010). "Bridge information modeling (BrIM) and model utilization at worksites in Finland." ISARC '27th, Bratislava, Slovakia, 505-513.

Lee, K.M., Lee, Y.B., Shim, C.S., and Park, K.L. (2012). "Bridge information models for construction of a concrete box-girder bridge." Structure and Infrastructure Engineering, Taylor & Francis Group, 8(7): 687-703.

Malekly, H., Mousavi, S.M., Hashemi, H. (2010). "A fuzzy integrated methodology for evaluating conceptual bridge design." Expert System with Applications, Elsevier Ltd., 37(7): 4910-4920.

Markiz, N. and Jade, A., (2012). "A decision-support model utilizing a linear cost optimization approach for heavy equipment selection." Construction Research Congress, ASCE®, West Lafayette, IN, U.S.A., 100-109.

Otayek, E., Jrade, A., and Alkass, S. (2012). “Integrated decision support system for bridges at conceptual design stage.” CIB W78 ‘29th’, Beirut, Lebanon, 334-343.

Peters, D. (2009). “Bridge information modeling to cover a complete set of processes.” CE & CR, Bentley Systems, 84-86.

RSMeans[®] (2012). “RSMeans heavy construction cost data.” Reed Construction Data Construction Publishers & Consultants, Norwell, MA, U.S.A.

SAP2000[®] v14. (2009). “Introduction to SAP2000/Bridge[®] Manual.” Computers and Structures Inc., Berkeley, CA, U.S.A.

Shim, C.S., Yun, N.R., and Song, H.H. (2011). “Application of 3D Bridge Information Modeling to Design and Construction of Bridges.” Procedia Engineering, Elsevier Ltd, 14: 95-99.

Shirole, A.M., Riordan, T.J., Chen, S.S., Gao, Q., Hu, H., and Puckett, J.A. (2009). “BrIM for project delivery and the life-cycle: state of the art.” Bridge Structures, Taylor & Francis Group, 5(4): 173-187.

CHAPTER 5

TECHNICAL PAPER II

An Integrated Expert System for Linear Scheduling of Heavy Earthmoving Operations

Nizar Markiz, Ahmad Jade

(Published in Journal of Construction Engineering, Hindawi, Volume 2016, Article ID 2312057)

Abstract: Heavy earthmoving operations are repetitive in nature and vulnerable to time-related restraints and uncertainties. Therefore, at the conceptual stage, scheduling these operations can take a linear form, known as linear schedule or line of balance (LOB). In such type of work, generating a preliminary line of balance for variable sequencing of activities is crucial. In this paper, an integrated expert system for determining preliminary linear schedules for heavy earthmoving operations at the conceptual stage is presented. The proposed system incorporates numerous factors that influence the analysis of earthmoving operations, which include geological and topographical parameters used to determine productivity rates at the conceptual stage. Also, the proposed system is capable of automatically generating a line of balance based on a stochastic scheduling technique via the meta-heuristic simulated annealing intelligent approach to incorporate randomness and uncertainties in performing the associated activities. A parametric analysis is conducted in order to quantify the system's degree of accuracy. An actual case project is then utilized to illustrate its numerical capabilities. Generating accurate linear schedules for heavy earthmoving operations at the conceptual design stage is anticipated to be of major

significance to infrastructure project stakeholders, engineers, and construction managers by detecting schedule's conflicts early in order to enhance overall operational logistics.

Keywords—Expert System; Earthmoving Operations; Linear Schedule

5.1 Introduction

Heavy earthmoving operations are repetitive by nature and vulnerable to diverse restraints and uncertainties. In order to ensure proper and continuous work flow, effective scheduling of earthmoving operations based on their productivity rates is crucial. Essentially, the performance of heavy equipment and corresponding coordination of logistics via planning and scheduling contributes to the success of earthmoving projects. On another perspective, poor scheduling may result in severe losses as equipment are idle and delayed due to constraints related to the working environment. Hence, equipment resources such as earthmoving machinery as well as topographical restrictions and parameters related to the scope of work must be considered during the planning and scheduling process. Presently, the scheduling of earthmoving activities are either represented by GANTT charts or by traditional networks, such as critical path and precedence diagram methods; while, linear scheduling provides an alternative to current scheduling techniques deployed for repetitive linear projects especially at their conceptual stage. Moreover, engineers and schedulers are in dire need for a decision support system that incorporates numerical analysis of earthmoving operations so that they can use it when making important decisions related to projects in hands. Based on the afore-mentioned, the main objective of this study is geared towards the deployment of an integrated expert system with a linear scheduling method for heavy earthmoving operations based on equipment fleet

productivity rates at the conceptual design stage. Hence, an expert system comprising a knowledge base system and a hypothetical reasoning inference engine based on a forward chaining technique is presented. The expert system represents factual information pertaining to heavy earthmoving operations of infrastructure projects (i.e. static and dynamic parameters; besides working variables) where an inference engine is employed to evaluate the knowledge-base and deploy subsequent numerical models and constraints to explicitly infer new results and input into the initial knowledge base. The deployment of the proposed system is expected to assist practitioners in the field of earthmoving operations in effectively identifying the time constraint related to this type of projects besides enhancing the capability of detecting potential scheduling conflicts at the conceptual design stage. Results presented in this study are anticipated to be very helpful to stakeholders and engineers.

5.2 Literature Review

Diverse methods and models have been proposed to schedule the operations of heavy earthmoving projects based on their diverse types of activities and associated equipment. However, these models are proposed for specific types of construction work due to the many factors that contribute to the selection of equipment needed to do the work. Current models used for equipment selection utilize common methods such as; 1) genetic algorithms; 2) simulation; 3) expert systems; 4) decision support systems; and 5) analytic hierarchy process, while some of the techniques used to determine equipment productivity are: 1) bunching theory; 2) productivity curves; and 3) simulation. The majority of the studies published in the literature focus on optimizing the equipment selection needed in heavy civil work based on diverse parameters

related to the scope of work; however, none of the studies were to include or perform operation analysis. One study conducted by Agrawal et al. (2010) provided optimal algorithms to scheduling problems comprising linear workflows. Several subjective concepts such as latency and period minimization and bi-criteria problems were addressed followed by the complexity results obtained. Song et al. (2012) presented a study of a stochastic look-ahead scheduling method for linear construction projects. In their paper, traditional linear scheduling was taken one step ahead by integrating the scheduling of linear projects with performance data collected from earlier projects where a stochastic simulation model is designed and implemented by the authors. The main objective of their study was to forecast scheduling conflicts arising from uncertainties and provide corresponding productivity outputs. Moreover, König and Beißert (2009) analyzed the optimization of construction scheduling by applying simulated annealing. In their study, a prototype that integrates simulated annealing with a constraint-based simulation model by utilizing a meta-heuristic approach was presented. At the end, the authors used a case study to validate the developed prototype and to illustrate its capabilities in optimizing construction schedules. Linear scheduling has been utilized in numerous projects over the past decade; however, few studies did address the topic and did provide relative information on optimum scheduling techniques. Typically, scheduling forecasts at early planning stages are highly influenced by the subjectivity nature of the scheduler and the availability of information, which results lead to a deterministic linear schedule. The main focus of the aforementioned studies has been geared towards the utilization of linear scheduling techniques during the operational phase rather than the early design stage such that scheduling uncertainties are not well addressed, which will result in major conflicts. In a study conducted by Srisuwanrat and Ioannou (2007), an

investigation of lead-time buffer under certainty using simulation and cost optimization was presented. Fluctuations in productivity rates within repetitive activities were analyzed and their corresponding impact on scheduling was illustrated. The authors mentioned that numerous studies had proposed diverse types of buffers that focused on halt-time rather than lead-time of a particular productivity line. In their paper, two diverse approaches, Sequence Step Algorithm (SQS-AL) and the Completed Unit Algorithm (CU-AL) were comprehensively studied via an implemented Genetic Algorithm (GA). Towards the end, lead-time buffer proved to reach optimum results resulting in reaping profitable gains. Although the proposed algorithm was of contribution to scheduling optimization techniques, productivity rates were assumed to be of static nature, which was an unrealistic representation of practical situations where fluctuations and uncertainties in production rates were inevitable. Likewise, Liu et al. (2005) proposed a simulated GA system to determine linear scheduling optimum solutions. In their study, a simulated function of chaotic nature was proposed to predict uncertainties and interdependencies among temporal series of points in order to calculate corresponding productivity rates. At the end, results obtained from the GA were validated via the simulation system. Their study was of major significance and contributed towards simulated algorithms database for optimizing linear schedules; however, it is important to note that, typically, reliable data is collected from realistic cases as opposed to simulation systems to reach accurate productivity rates predictions at earlier design stages. Based on the afore-mentioned, few studies only considered numerous important factors for decision support systems; however, none of them had specifically viewed a project as a task or process that needs to be completed following definitive time constraints. Besides that, the majority of previous studies did not consider equipment operation analysis. Instead, the main

focus was geared towards developing systems, algorithms, or frameworks in an attempt to assist the user in estimating project duration. Moreover, none of the studies had investigated numerical analysis of heavy earthmoving operations based on complex equipment performance parameters, which significantly impact the productivity rates of the selected equipment fleet at the conceptual stage. Therefore, in this paper, an integrated expert system that incorporates operational analysis with a linear approach is proposed to generate a linear schedule for heavy earthmoving operations at the conceptual design stage.

5.3 Methodology and Development

Operation analysis of selected types of equipment is essential for the development of the proposed integrated expert system. Seven major activities of earthwork will be considered: 1) clearing and grubbing; 2) excavating; 3) loading; 4) hauling; 5) backfilling; 6) grading; and 7) compacting; while taking into consideration the variable factors that affect equipment productivity. The development of the system comprises the following five main steps; a) data collection; such as site topography, soil characteristics, equipment type....etc. b) numerical analysis of heavy earthmoving operations such as travel distance, rolling resistance, and cycle time, c) determining productivity rates based on the user input parameters, d) generating a linear schedule of earthmoving operations, and e) minimal reduction of activities duration by applying local and global minimization algorithms. In order to conduct the analysis of earthmoving operations, a database of equipment type, capacity, and specifications besides site topographical and material characteristics is developed. Then, equipment productivity rates are calculated based on the user input parameters; including, but not limited to, soil characteristics, site topography,

and volume of earthmoving while satisfying the following equipment constraints; rolling resistance, maximum rim pull, and horse power capacity. Following the determination of productivity rates, a linear approach to generate the schedule for heavy earthmoving operations based on a meta-heuristic simulated annealing approach that utilizes a metropolis algorithm is deployed based on the calculated productivity rates for earthmoving operations as selected by the user. Figure 5.1 illustrates the architecture of proposed integrated expert system.

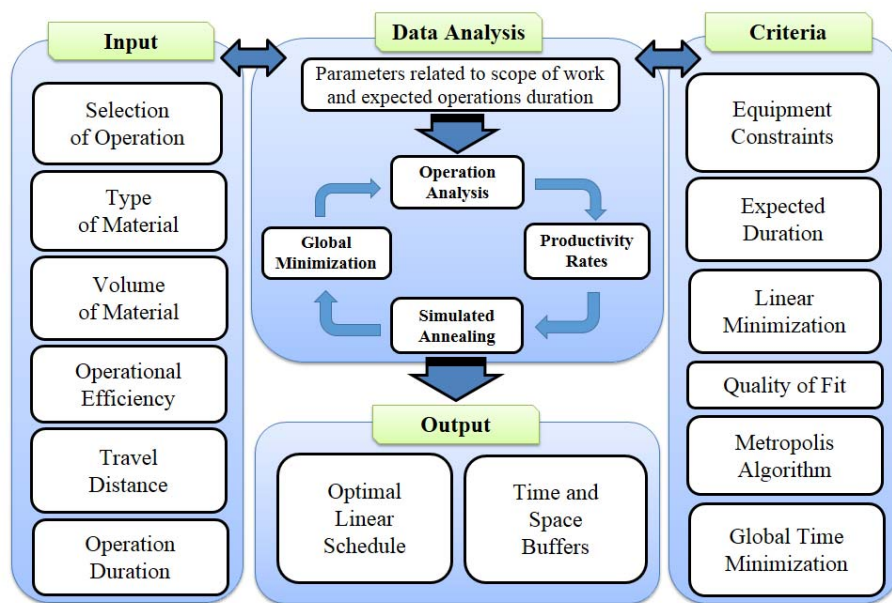


Figure 5.1 Proposed System Architecture

The proposed integrated system will be developed in an object-oriented .NET framework and undertaken by the following five main tasks: 1) Collect data related to the diverse processes of earthmoving operations and organize them into a database; 2) Conduct numerical analysis for diverse equipment used for earthmoving operations and determine corresponding productivity rates based on a set of defined user input and the aforementioned parameters related to the scope

of work; 3) Analyze productivity rates data by fitting them into a distribution fitting and measure their corresponding quality of fit; 4) Undertake the simulated annealing technique to determine the near-optimum line of balance based on numerically expected operation durations; and 5) Engage a global minimization approach to minimize operations duration. Three main processes are categorized into the integrated expert system. The processes are as follows: 1) numerical analysis, which comprises an analytical linear algorithm that utilizes user input data and equipment specific parameters to numerically determine equipment fleet productivity rates. Afterwards, an analytical strategy is utilized for productivity rates to estimate operations durations based on the program evaluation and review technique (PERT); 2) linear scheduling process, which contains a constraint-based simulated approach for scheduling heavy earthmoving activities that is automatically linked to an output report that displays an instantaneous line of balance; and 3) time minimization process; which comprises a numerical technique that minimizes operation durations by seeking the global minimum value of the operations' expected durations.

5.3.1 Earthmoving Operations Analysis Phase

Selection and management of equipment fleet is a crucial task that considerably influences the success of an infrastructure project. This is to be much more critical in heavy earthmoving operations where equipment fleet plays a vital role in performing the work. In this type of projects, the equipment fleet represent the largest portion of the bidding price (Nunnally, 1977). Consequently, practitioners in the field of infrastructure and construction industries understand the substantial impacts on their projects when equipment selection decisions are not made in a

proper and timely manner. Therefore, the selection of fleet necessitates the commencement of a thorough economical numerical analysis of earthmoving operations at the conceptual stage. Since equipment selection is highly influenced by numerous factors, most practitioners tend to rely upon their experience and historical data in similar projects to assist them in determining the optimum fleet. Other approaches such as expert systems could be useful if only integrated with a database of historical data. These approaches are helpful for those who have been in the construction industry long enough and whom are familiar with the variety and complexity of infrastructure projects. To overcome this shortcoming, the proposed system will be developed to integrate the collected data of selected equipment with an economic analysis method for diverse scopes of earthwork operations. The system will also be designed in a manner to provide users with a fleet that balances interdependent equipment such as the loading-hauling system. Although, the proposed expert system will possess few limitations pertaining to equipment suppliers, resource availability, and earth rock material; it will be capable of assisting project stakeholders and practitioners in making decisions at the conceptual project stage. The objective of any project is to get the job done according to the specified timeframe and budget limitations. In order to achieve this goal, careful calculation of productivity rates for the fleet while considering the aforementioned diverse factors related to the scope of work is required. Schaufelberger (1999) stated two general factors that must be considered in the process of selecting the equipment fleet: (a) cost effectiveness, which involves considering the equipment's size besides its proper type; and (b) versatility, which involves selecting equipment that can perform multiple tasks at the same time. In this paper, the afore-mentioned factors are incorporated into the operational analysis module. Afterwards, the operation analysis of

equipment is undertaken to determine the constraints that must be satisfied. The first constraint is defined as the loaded weight. The loaded weight must not exceed the maximum allowable weight set by the manufacture. This constraint is expressed by using equation (5.1):

$$LW \leq RW \quad (5.1)$$

Where; LW is the loaded weight and RW is the rated weight. The second constraint is defined as the total resistance. The total resistance must not exceed the allowable rim-pull or drawbar if the equipment is wheel-mounted or crawler-mounted respectively. This constraint is expressed by using either equation (5.2) or (5.3):

$$TR < RP \quad \text{if wheel-mounted} \quad (5.2)$$

$$TR < DB \quad \text{if crawler-mounted} \quad (5.3)$$

Where; TR is the total resistance, RP is the allowable rim-pull, and DB is the allowable drawbar. If any of the abovementioned constraints is not satisfied, the system will automatically eliminate the equipment from the selection process. All of the aforementioned corresponding calculations are organized in different forms based on the equipment type to ease the development of the system. Following the determination of equipment constraints, productivity rates are calculated and extracted from the numerical analysis of earthmoving operations output database. The productivity rates are determined based on operational parameters categorized into four main groups summarized as follows: 1) spatial relationships; which includes, a) topography; b) obstructions in earth excavation; c) clearance heights; d) required heights; e) required reach maneuverability; and f) location of hauling units; 2) soil characteristics; which includes, a)

rolling and grade resistances, which provide traction and soil stability; b) potential changes in characteristics during performance of work; c) required force to loosen materials; d) need for ripping and pushing attachments; and e) abrasiveness and other rough earth qualities; such as rock material that may cause problems to equipment; 3) contract provisions; which includes, a) quantity of earth involved; b) time constraints and weather conditions; c) requirements for payment and subsequent cash flow; d) legal constraints on the weight and size of equipment; and e) other restrictions; such as traffic, hours, dust, and noise; and 4) logistical considerations; which includes, a) availability of required equipment and their operators; b) mobilizing and demobilizing time and cost; c) use of equipment in preceding operations and idle time; d) economical equipment costs; and e) support facilities. In this paper, the estimation of productivity rates is performed for each type of equipment individually. Productivity rates, which are determined based on equipment specifications data and specific parameters related to the location (i.e. soil type, traveled distance, altitude, and job conditions), are calculated by using the following equation (5.4):

$$Productivity = \frac{Volume\ of\ Earth * OE}{Cycle\ Time} \quad (5.4)$$

Where; *Volume of Earth* is the required amount of earthmoving operation (bank cubic yards), *OE* is the operational efficiency (min/hr), and cycle time is the time needed to complete an earthmoving operation (minutes), which is the total of fixed and variable times and includes the time needed to complete one cycle while empty and/or loaded depending on the type of

equipment. In this study, empty and/or loaded times of an equipment are determined based on the manufacturer, Caterpillar[®], performance charts.

5.3.1.1 Estimating Activity Duration

Estimating the duration of earthmoving activity is a multifaceted task that faces engineers and schedulers as the occurrence of unforeseen events is very probable and unpredictable. In this paper, a linear scheduling technique that encompasses the capability of modeling the variability of earthmoving operations performance-related factors which significantly affect productivity data is proposed as follows: i) weather, which is taken into account within the topography, variability in soil saturation and density, and altitude parameters; ii) learning curve, which is taken into account within the equipment cycle time, tire penetration, and operational efficiency parameters; iii) overtime, which is taken into account within the rolling and grade resistances as they influence the productivity rate, and accordingly the operator wage parameters; iv) space congestion, which is taken into account within the clearance heights of adjacent structures, reach maneuverability, and obstructions in earth excavation parameters; and v) sub-/super-structure design changes, which is taken into account within the availability of equipment and operators for high risk operations, equipment capacity, and volume of earthmoving parameters. In order to provide a simulation input for a scheduler, a fleet selection system developed earlier by the authors of this study for the selection of fleet based on their productivity rates is utilized to implement into the proposed linear scheduling system (Jrade et al., 2012; Jrade and Markiz, 2012; Markiz and Jrade, 2013). Earthmoving operations and their corresponding productivity rates and most likely durations are automatically extracted from the database of the fleet

selection system in order to generate a histogram where a statistical normal distribution is utilized to quality-fit the productivity rates by utilizing the Gaussian equation (5.5):

$$f(x, \mu, \sigma) = \frac{e^{-\frac{(x-\mu)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} \quad (5.5)$$

Where; X is the random variable, μ is the mean, and σ is the standard deviation. The process begins by normalizing the normal distribution of productivity rates. Afterwards, distribution parameters are determined throughout the fitting process. Then, the expected duration of each earthmoving operations is calculated by using equation (5.6):

$$E = \frac{(O + 4M + P)}{6} \quad (5.6)$$

Where; E is the expected duration time, O is the optimistic duration time; where it is estimated to be the shortest duration, M is the most likely duration time, and P is the pessimistic duration time.

5.3.1.2 Normal Distribution Fitting

The initial step when modeling normal distribution fittings is to develop a generic histogram pertaining to earthmoving operations productivity rates. Based on the characteristic shape of the generated histogram, an indication of a standard distribution that will result in a “best-fit” fitting will be evident. Furthermore, corresponding distribution parameters, such as the mean and standard deviation may be determined from the distribution fitting. It is important to note that due to the technological advancement in normal distribution modeling software, an indefinite

number of distribution may be automatically fitted within a reasonable time frame. However, a selective number of candidate distributions are typically forwarded to quality of fit testing procedure prior to engagement in further processes.

5.3.1.3 Quality of Fitting

Although multiple standard distributions are capable of modeling a distribution fitting, significant variance may be noticed in the manner they represent the actual distribution underlying histogram data set. Testing the quality of fit for a distribution is conducted by either of the two following procedures: 1) heuristic, where manual inspection is conducted in parallel with an error minimization procedure; or 2) non-heuristic procedure, where hypothetical procedures such as the Chi-square test are deployed [3]. In order to ease the use of distribution modeling amongst owners and designers, the manual inspection of distribution fitting with an error minimization procedure is adopted since distribution fittings are automatically generated with advanced modeling software available in the market. In this study, productivity rate histograms are normalized with the suggested scaled distribution. As part of enhancing the quality of fit, an error minimization procedure is proposed for the curve-fitting of the suggested distribution to the actually obtained one. The procedure is based on applying a scaling factor to the suggested one. The sum (E) of the squares of differences between the actual and suggested fit is then minimized to obtain the magnitude of adjustment factor that results into the best fit with actual data. The error minimization procedure is identified as per equation (5.7):

$$E_{\min} = \sum_{i=1}^n \left[\frac{p_{act,i} - a(p_{sug,i})}{\bar{p}_{act,i}} \right]^2 \quad (5.7)$$

Where; $E_{\min}$ is the minimized error, $i = 1, \dots, n$ is the number of actual productivity rates, $p_{act,i}$ is the actual productivity rate at the i^{th} location, $p_{sug,i}$ is the suggested productivity rate at the i^{th} location, α is a scaling factor to be applied to the suggested productivity rate values. It is noted that the bracketed terms in equation (5.7) have been normalized with respect to the average actual productivity rate, $\bar{p}_{act,i}$ as per equation (5.8):

$$\bar{p}_{act,i} = \frac{1}{n} \sum_{i=1}^n p_{act,i} \quad (5.8)$$

Towards the end, it is important to note that the suggested productivity rates distribution fit provide a good representation of a logically sequenced line of balance where time and space buffers are respected.

5.3.2 Linear Scheduling Phase

A particular earthmoving activity is presented in linear scheduling as a linear production curve such that quantities in loose cubic yard (LCY) and duration in (days) are on the y- and x-axes respectively; and is interrelated in a 2D graphical display. Earlier studies have shown that linear scheduling method may be comprehended as a specialized construction scheduling alternative tool for phased repetitive operations that provides a visualization of scheduling information rather than the traditional scheduling methods, such as GANTT charts, in terms of relating earthmoving operations and production rates with time and space related constraints. However, it is worth noting that, typically, all operations are considered to be critical in linear scheduling and work continuity must be maintained consistently throughout the project in order to achieve

efficient heavy earthmoving operations. Authors were not able to find studies that address the major pitfall of determining effective linear scheduling solutions for heavy earthmoving operations. In this paper, efforts will be focused on designing, implementing, and enhancing earlier relative work pertaining to optimizing linear schedules in heavy earthmoving operations as follows: 1) unifying the process of maximizing fleet productivity rates while taking into account temporal variability; 2) satisfying time and space related constraints; and 3) modeling an integrated simulated approach for determining near-optimum linear schedules. In this regard, linear scheduling is deployed as a scheduling forecasting technique that permits a scheduler to balance the productivity rates and to maintain work continuity while refraining from idle production resources at the conceptual design stage of an earthmoving project life. Figure 5.2 provides an overview of the process to develop the proposed linear schedule system for earthmoving operations.

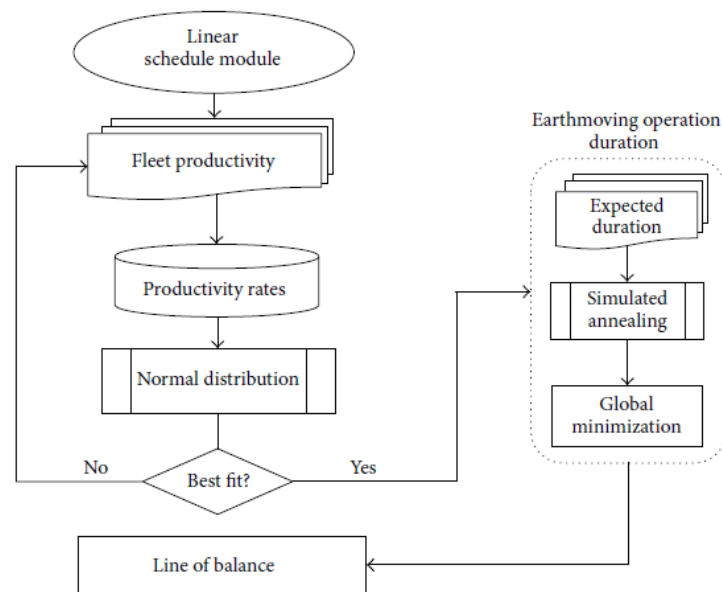


Figure 5.2 Linear Schedule System Overview

The overall process underlies the determination of equipment productivity rates by undertaking a numerical analysis of equipment operations based on a linear approach. Once determined, productivity rates are fitted into a Gaussian distribution fitting to measure its corresponding goodness of fitting. If accepted, the process automatically proceeds to the successive process to estimate operations durations by deploying equations (5.5) and (5.6) followed by the meta-heuristic simulated annealing algorithm to generate a linear schedule at the conceptual stage. At last, a global duration minimization approach is deployed to minimize the duration of the earthmoving operations.

5.4 Cost Minimization Phase

The main objective of the minimization function used in this study is to maximize productivity by minimizing equipment fleet costs, where linear programming is the methodology used for determining the equipment selection. In this study, a fleet is defined as a set of selected equipment that will yield to the least ownership and operating costs. However, since owning and operating costs are inversely proportional to equipment operation analysis, the fleet is selected based on its productivity rate and cost. For example, if a particular equipment fleet has the maximum productivity rate, it is going to yield the least owning and operating costs and vice versa. The fleet is obtained by using the cost minimization approach in a given mathematical model for a list of requirements and constraints represented as linear relationships. All constraints obtained from the operation analysis are represented in a mathematical form and incorporated into the cost minimization system. These constraints, however, limit the degree to which the objective function can be pursued. The following expression is then used to select the

equipment with the minimum unit cost; $MIN = \sum_{i=1}^n EU_i$ where; i is the number of equipment and

EU is the equipment unit cost. It is important to note that the proposed system accounts for a time-cost tradeoff that occurs during the selection process. In other words, the proposed system is designed in a manner to extract the most likely activity duration inputted by the user at the fleet selection system and compares it with the required time based on the volume of earth material involved and corresponding productivity rates. For example, if the operation duration data inputted by the user is less than the required time obtained from the proposed system calculations, the system will select a fleet with much higher costs and vice versa. Figures 5.3 and 5.4 summarize the development process of the cost minimization function and fleet selection respectively.

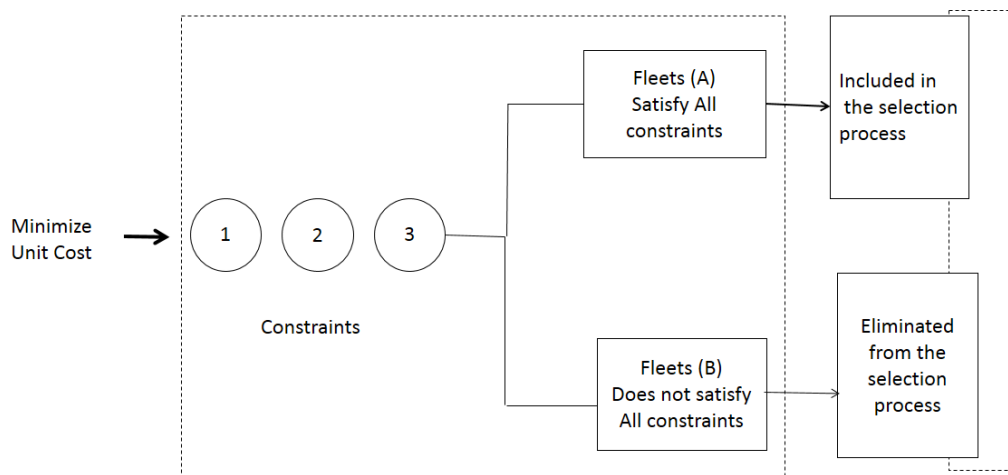


Figure 5.3 Cost Minimization Process Flow

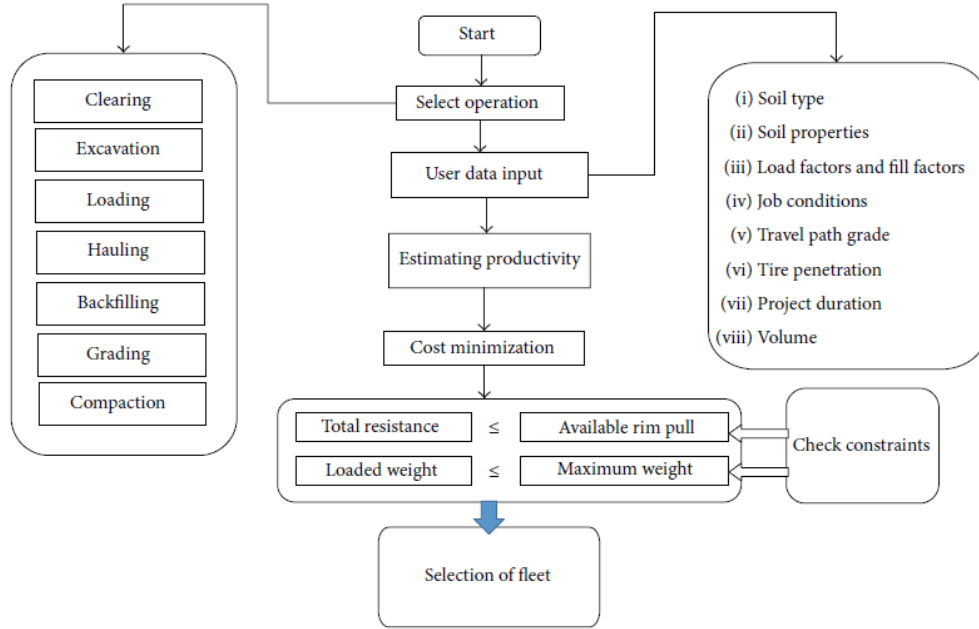


Figure 5.4 Linear Programming Process Flowchart

5.4.1 Uniform Dependence Algorithms

In order to determine a near-optimum linear schedule, a duration domain to execute a task must be defined. A unique class of algorithm termed as uniform dependence algorithm is of significance in parallel minimization problems. In this study, uniform dependence algorithms are deployed for determining a near-optimum linear schedule. A uniform dependence algorithm may be represented in accordance with Shang and Fortes (1988) expressions (5.9) and (5.10):

$$u(t) = y_t(u_t(t-d_1), \dots, u_t(t-d_i)) \quad \text{while; } t \in T; \quad T = \{x : Ax \leq b\}; \quad T \equiv (A, b) \quad (5.9)$$

$$D = (d_1, d_2, \dots, d_m) \quad \text{while; } i = 1 \dots m; \quad m \geq 0 \quad (5.10)$$

Where; i is an integer, t is an index point, T is the index set of vectors, y_t is the numerical computation at point t , u_t is the time-value function at point t , A is a matrix of dimension $(a * n)$, a is the number of constraints, n is the dimension of the domain, b is the domain constraints, D is the dependence matrix $(n * m)$, d_i is the dependence matrix vector, and m is the number of dependence vectors. In this study, a uniform dependence algorithm of $ALG = (T, D)$ is applied to determine a linear schedule such that A is a constraint matrix $(a * n)$, where a is the number of time and space buffer constraints, n is the dimension of the domain, and D is the dependence matrix $(n * m)$, where m is the number of dependence vectors. The two index points, t_1 and t_2 , are assigned to two dependent activities such that $t_1 < t_2$ and $t_2 = t_1 + d_i$ for $d_i \in D$, where d_i is the dependence matrix vector and the points t_1 and t_2 are of the index set, T such that t_2 is dependent upon t_1 . A linear schedule for the uniform dependence algorithm is then established as a mapping function, σ_Π , such that for a random index point where $\sigma_\Pi(t) = [\Pi_t + c]$ and Π is the linear schedule vector, which is subject to the constraints: $t \in T$, $\sigma_\Pi(t_1) < \sigma_\Pi(t_2)$, $\Pi D \geq 1$, and the time buffer constraint $c = -\min(\Pi t, t \in T)$, which is the offset (C) [12]. Upon satisfying the aforementioned conditions, a linear schedule is then acceptable along with its corresponding dependencies. In other words, the process of determining a linear schedule is commenced by assigning time and space buffer constraints to develop the constraint matrix $(a * n)$. Following the determination of the constraint matrix, a dependence matrix $(n * m)$ is developed to represent the number of dependent scheduling alternatives.

5.4.2 Linear Schedule Minimization Process

In order to properly minimize the durations of earthmoving activities, one must understand all related constraints; otherwise, failure to do so may lead to erroneous results. In scheduling terms, deployment of equipment resources is a multifaceted task for engineers and construction planners. In this study, an earthmoving linear scheduling system is proposed to minimize the use of available equipment by maximizing fleet productivity rates through the selection of the most suitable equipment for an earthmoving operation. The system utilizes simulated annealing as a minimization tool by utilizing expressions (5.9) and (5.10) and supported by a classical constrained-based simulated algorithm defined by the space buffer constraints $t \in T$, $\sigma_{\Pi}(t_1) < \sigma_{\Pi}(t_2)$, $\Pi D \geq 1$, and the time buffer constraint $c = -\min(\Pi t, t \in T)$.

5.4.3 Simulated Annealing

Simulated annealing is a strategic approach that may be utilized to solve scheduling conflicts. In metallurgic industries, annealing processes are the main heat treatment operations. In this study, simulated annealing is utilized in a similar manner in order to determine a linear schedule for earthmoving operations. Typically, when a metallic substance undergoes annealing, it is heated to the maximum temperature where it reaches the limit of liquefaction. Afterwards, it cools down gradually to form the desired solid shape and corresponding chemical characteristics. The final status of the substance is highly dependent upon the cooling methodology implemented. For instance, if the cooling procedure is done quickly, the substance is brittle and heterogeneous. On

the other hand, if the cooling process is controlled gradually, the substance status is ductile and homogenous. Typically, simulated annealing algorithm is undertaken in three main phases as follows: i) perturbation of solution; ii) evaluation of quality; and iii) acceptance of solution. An initially high temperature is set and utilized to plan the perturbation, evaluation, and acceptance of final solution by gradually decreasing the temperature via a defined numerical function. With simulated annealing, an enormous amount of random numbers is generated, which depend on user discretion on whether quality or speed of solution or both are desired. In this study, the quality of linear schedule is crucial and therefore the algorithm is implemented accordingly (Tobochnik, 2008).

5.4.3.1 Constraint-Based Simulation

Beißert et al. (2007) summarized few constraints for typical earthmoving projects as follows: 1) technological advancements; 2) equipment capacity; 3) availability of resources; and 4) logistical aspects. It is important to note that constraints parameters, specified among a defined set of variables, must be satisfied for one activity prior to proceeding to the next one. In addition to that, for heavy earthmoving operations, the two major constraints that must be satisfied are: 1) time- and 2) space- related constraints, which are typically referred to as time and space buffers respectively. In this study, efforts to enhance the discrete event simulation technique will be utilized such that constraint satisfaction problems are integrated with a simulated annealing approach such that interdependencies among tasks; i.e. loading-hauling are taken into consideration and results are obtained in a timely manner. In simulated annealing processes, the presumed constraint is always satisfied and controlled within the procedure itself. In other words,

no event or task can be scheduled without its time and space buffers being met, which produces a logically sequenced linear schedule where further analysis to time and space constraints may be conducted.

5.4.3.2 Metropolis Algorithm

In this context, a meta-heuristic metropolis algorithm is deployed as a local minimization approach to resolve linear scheduling combinational conflicts and reach a near-optimum solution within reasonable cycle time. The process begins when earthmoving operations unveil their original state and re-configure into a highly organized structure with lower energy than the initial state. In this study, the simulated annealing procedure may be comprehended as the methodology deployed to reach at a near-optimum solution, which represents the possibility of new configurations of the earthmoving operations. Simulated annealing is usually implemented by assuming a high initial duration and determines via a meta-heuristic approach a new solution within the neighborhood of the initial solution. It is important to note that the probability of acceptance of re-configured solutions is dependent upon the difference between immediate consecutive solutions (ϵ) and duration (α). Once accepted, the new solution is set as the starting point for the consecutive minimization cycle. Consequently, in order to implement the generic metropolis algorithm, the following criteria must be met: a) suitable neighborhood; b) proper probability of acceptance; and c) effective duration decreasing rate in order to reach a successful near-optimum linear schedule and consequently escape local minima (Dreo et al., 2006). Towards the end, simulated annealing is integrated into the constraint-based simulation in an attempt to enhance neighboring schedules by substituting operations. Once a near-optimum

linear schedule is determined, the newer solution replaces the older one and simultaneously enables formerly declined solutions to be accepted in order to escape local minima.

5.4.3.3 Neighborhood Sequencing

In simulated annealing scheduling approaches, the distinctive concept of local “neighborhooding” is crucial. Conceptually, a schedule possesses a local neighborhood only when two operations of the same ranking are substituted. Typically, tasks ranking are determined through a topological sorting technique. The concept of topological sorting is based on transforming a partial order to a total order. For instance, if $A > B$ and $B > C$, then it implies that $A > C$. Hence, the system proceeds by generating multiple solutions by substituting operations of local neighborhood with similar rankings. Once a solution is generated, neighborhood operations are assigned ranks along with a corresponding execution order for each ranked operation. For instance, operations A and B may be assigned rank one; however, operation B may precede operation A in terms of order of execution. In the next step, operations C and D of rank two may be substituted to form an alternative solution and so forth.

5.4.3.4 Rule of Acceptance

Rules of accepting a solution within a simulated annealing process is an important element of the generalized metropolis algorithm. In order to illustrate probability of acceptance process, a system in its current state described by an N-dimensional vector (x) comprising a probability function $f(t)$ is defined. Then, a set of values that control the convergence speed of an annealing algorithm must be defined and can never be predicted at the initial stage. Instead, the values

depend on the type of minimization problem and must be adjusted accordingly. Therefore, the process commences upon the selection of initial configuration, X . Then, the initial number of simulations (n_s) must be set to null. Afterwards, an initial duration (t_o) must be set to some high value. This step is considered to be one of the most significant steps as the convergence of the simulated annealing algorithm is dependent on the selection of initial duration, t_o , convergence parameter, α and decreasing rate, Δt . Within the scope of this study, the decreasing rate of the initial duration is determined as per Tobochnik and Gould (2008) equation (5.11):

$$\Delta t = t_i(1 - \alpha) \quad (5.11)$$

Where; Δt is the decreasing rate, t_i is the current duration, and α is the convergence parameter. According to Tobochnik and Gould (2008), and based on earlier studies typical values of the convergence parameter, α , vary between 0.8 and 0.999 with the latter being the closest to ideal. Prior to decreasing in duration, an initial value of the probability function must be obtained as per Tobochnik and Gould (2008) expression (5.12):

$$f_a = f(t_i) \quad (5.12)$$

Then, a second value is determined following the transition as per Tobochnik and Gould (2008) equation (5.13):

$$f_b = f(t_i - \Delta t) \quad (5.13)$$

Afterwards, the difference between the obtained values of the probability function is determined according to Tobochnik and Gould (2008) equation (5.14):

$$\Delta f = f_b - f_a \quad (5.14)$$

The following step involves an “if-then” loop console where if, $\Delta f \leq 0$, the current state is accepted; otherwise, a generic value, $\mathcal{E}$, is the value at which the algorithm is terminated. In this study, $\mathcal{E}$ is assigned a value of 0.001. The rule of accepting the state of function is then defined as per Tobochnik and Gould (2008) expression (5.15):

$$\mathcal{E} < e^{\frac{-\Delta f}{t_i}} \quad (5.15)$$

Where; $\mathcal{E}$ is the value at which the algorithm is terminated, Δf is the change in probability functions values, and t_i is the current duration. However, if the state of the function is rejected, then the process is directed to another transitional iteration, $n_s = n_s + 1$ until the initial duration reaches the value of zero. The detailed procedure for rules of accepting a function state as adopted from Tobochnik and Gould (2008) is summarized in Figure 5.5.

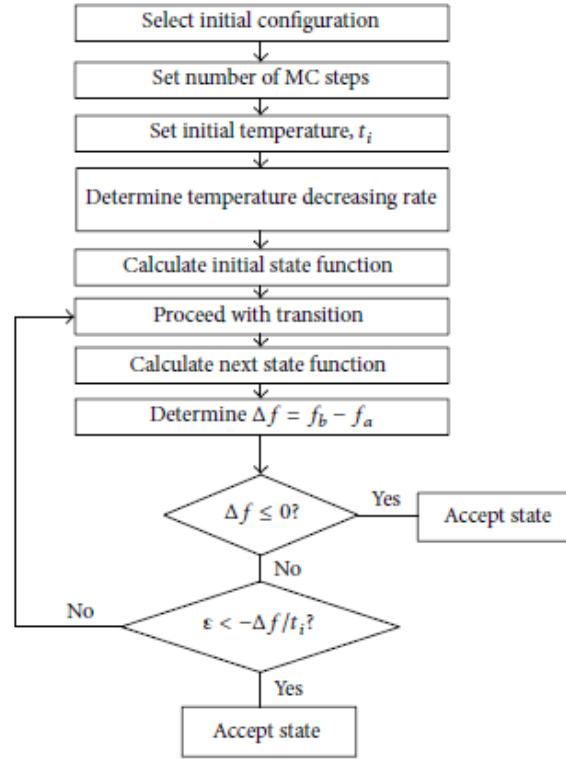


Figure 5.5 Simulated Annealing Process

5.4.4 Global Duration Minimization

Global duration minimization is an analytical procedure where the solution of an objective polynomial function is determined by obtaining the global minimum value. Global duration minimization is known for its capability in bypassing local minima and seeking a global solution of a boundary-constrained polynomial function. In this study, efforts are focused to enhance the linear scheduling technique a step further by proposing a global minimization procedure in order to minimize the duration of earthmoving activities while respecting time and space buffer constraints. Therefore, a uniform dependence algorithm of $ALG = (T, D)$ is defined such that σ_{Π}

is the linear schedule. The overall project duration is calculated as per Shang and Fortes (1988) equation (5.16):

$$\begin{aligned} T_{\Pi} &= 1 + \max(\sigma_{\Pi}(t) \mid t \in T) \\ T_{\Pi} &= 1 + \max([\Pi_{t_2}] - [\Pi_{t_1}], \text{ where } t_1, t_2 \in T) \end{aligned} \quad (5.16)$$

5.5 System Implementation

The implementation of simulated annealing algorithm is undertaken in two main steps; i) perturbation; and ii) quality evaluation. The algorithm is implemented in such a way that the error determined from the preceding solution is utilized to determine the acceptance of the new solution. At first, near-optimum problem solutions of X variables are defined as per Ledesma et al. (2008) expression (5.17):

$$X = \{x_1, x_2, x_3, \dots, x_M\} \quad (5.17)$$

Where; X is the near-optimum solution; and $x_1, x_2, x_3, \dots, x_M$ are simulated annealing solutions to a linear scheduling problem. Afterwards, the algorithm duration-gradient process is established as per Ledesma et al. (2008) expression (5.18):

$$T = T_1, T_2, T_3, \dots, T_N \quad (5.18)$$

Where; T_1 is the initial duration; and T_N is the final duration; and N is the number of durations. The selection of initial duration for the simulated annealing approach is crucial as it significantly influences the scheduling of earthmoving operations. Duration values are discrete

values selected based on a definitive convergence-gradient algorithm, which will be presented later. In order to enhance simulated annealing efficiency, a definitive number of iterative processes at each duration level are generated as per Ledesma et al. (2008) expression (5.19):

$$X_i = \{x_{1,i}, x_{2,i}, x_{3,i}, \dots, x_{M,i}\} \quad \text{where; } i=1,2,3,\dots \quad (5.19)$$

Where; i is the number of perturbations; $x_{1,i}$ is the value of x_1 following the i^{th} perturbation. Hence, the number of perturbation at the end of each duration level is of value, K ; such that X_k is the solution to the problem at the end of T_i . Generally, an error is always associated with each of the discrete solution, X_i . Therefore, E_1, E_2, E_3 are errors of the corresponding solutions X_1, X_2, X_3 respectively. Following the determination of solution errors, the evaluation of solution quality and acceptance of the perturbation process is deployed. The metropolis algorithm is then implemented in order to determine the probability of accepting a perturbed solution as per Ledesma et al. (2008) expression (5.20):

$$R_a = \begin{cases} e^{\frac{-k\Delta E}{T}} & \Delta E > 0 \\ 1 & \Delta E \leq 0 \end{cases} \quad (5.20)$$

Where; R_a is the rule of acceptance; and ΔE is the solution error obtained due to the difference in solution before and after perturbation; T is the set duration; and k is a constant determined based on initial duration and its associated error as described in the following section. It was found that at very high durations, the algorithm is susceptible to accepting any solution.

However, as the duration gradually decreases, the annealing process become more effective and adapt a selection methodology of the perturbed solution highly dependent upon the error value. Based on the aforementioned, the duration-gradient process is controlled by gradually decreasing the duration resulting in a time consuming annealing process. On the other hand, perturbed solutions along with high probability of acceptance and enhanced quality are obtained. In this study, the constant, k , is carefully chosen in an attempt to save the time consumed for the annealing process. For instance, if k equals T , then the algorithm is susceptible to accepting solutions with higher probability of acceptance along with higher corresponding errors values as well. On the other hand, as the ratio of k to T approaches unity at the initial stage, an enhanced perturbed solution with a higher probability of acceptance and lower corresponding error value is accepted.

5.5.1 Estimation of k-value

The estimation of the k -value is crucial at the initial stage of the simulated annealing process. As stated earlier, the efficiency of the simulated algorithm is highly dependent upon the set of acceptance criteria such as difference in errors and rule of acceptance. A good estimation of the k -value results in substantial minimization of computational time. Prior to commencement of the annealing process, an initial value X_0 is created based on equation (5.19) along with its corresponding error, E_0 . Afterwards, the k -value is determined by following an iterative process as per Ledesma et al. (2008) equations (5.21) and (5.22):

$$\Delta E \approx \frac{1}{Q-1} \sum_{i=1}^Q E_i - \frac{1}{Q(Q-1)} \sum_{i=1}^Q (E_i)^2 \quad (5.21)$$

$$k = \frac{T_0 \ln(0.8)}{\Delta E} \quad (5.22)$$

Where; ΔE is the difference in errors estimate; Q is the number of perturbations; and T_o is the initial duration. It is important to note that the value of ΔE is an estimate value at the initial stage as shown in equation (5.21). Upon determining the value of ΔE , the k -value is determined in accordance with equation (5.22). Once determined, the k -value is substituted into equation (5.20) to determine acceptance value in order to accept activities' durations and determine a near-optimum line of balance.

5.5.2 Fleet Selection System

In this study, the proposed fleet selection system comprises earthmoving modules with the following seven major operations; 1) clearing and grubbing; 2) excavating; 3) loading; 4) hauling; 5) backfilling; 6) grading; and 7) compacting operations. The proposed fleet selection system gateway is illustrated in Figure 5.6.



Figure 5.6 Fleet Selection System Gateway

As shown in Figure 5.6, once the user selects the desired earthmoving operation, the proposed system displays an input form where users input necessary parameters related to the scope of work. Within each operation, input forms that include common parameters to diverse equipment capable of undertaking the selected earthmoving operation are automatically extracted and imported into the database in order to proceed with the numerical analysis of the earthmoving operation as illustrated in Figure 5.7.

Figure 5.7 Clearing and Grubbing Operation Input Form I

Afterwards, the user must enter project specific data required to execute necessary calculations. It is important to note that the data required for the numerical analysis of earthmoving operations vary from one operation to the other; however, (1) material density; (2) fill factors; (3) safe factors; (4) time constraints; (5) volume; and (6) operational efficiency is a common list of parameters among the earthmoving operations. The volume of earth material to be excavated/hailed is measured in terms of bank cubic yard and is inputted by the user, which is in turn utilized for the numerical analysis of the earthmoving operation to obtain the necessary fleet and corresponding productivity rates. In case an equipment exceeds system constraints, a pop-up message notifies the user of the equipment models that will not be considered in the fleet selection process. Then, the user is directed to the operation analysis process in order to obtain fleet productivity rates. Once equipment productivity rates are determined, the user will select the equipment model desired along with its corresponding productivity rate. Also, the user may select the number of equipment required to complete the earthmoving operation.

5.5.3 Earthmoving Linear Schedule System

Once completed, the system then automatically extracts the selected productivity rates from the fleet selection system and imports them into the earthmoving linear schedule system. The productivity rates extracted from the fleet selection system are obtained in LCY/hr (loose cubic yards/hour). The daily output in LCY (loose cubic yards) is then estimated based on the assumption of eight working hours per day. Moreover, the most likely duration in days to complete an earthmoving operation are automatically extracted from the fleet selection system and imported into the earthmoving linear schedule system. The user is then invited to input

optimistic and pessimistic durations in days to complete the earthmoving operation. It is important to note that the proposed system possess one limitation pertaining to optimistic and pessimistic durations of earthmoving operations, which are mainly influenced by the scale of subjectivity involved and is highly dependent upon user experience on similar projects. In order to overcome such limitation, the proposed system incorporates the Program Evaluation and Review Technique (PERT) estimation equation (5.6), which accounts for the time variability in the duration of an earthmoving operation and determines its expected duration accordingly. On another hand, the system may be utilized as an inference engine for backward reasoning in order to determine optimistic and pessimistic durations of an earthmoving operation when the linear schedule is ‘pre-determined’ at the conceptual stage. Once expected durations are obtained, productivity rates are automatically organized into a histogram where a quality of fit is processed as presented in Section 5.3.1.3 Once completed, the user may proceed by setting an initial duration and rule of acceptance parameters as discussed in Section 5.4.3.4.

5.6 System Validation

To validate the workability of the proposed system, an actual project that comprises heavy earthmoving operations for an earth fill project along with their corresponding durations is recalled from the literature (Marzouk, 2002). The challenge underlying the system validation is to determine the near-optimum fleet necessary to execute the earthmoving operations. The project was phased into three stages, each at different elevation and spanning a complete construction season. In this study; however, the scope of earthwork at the operational stage I is

used to validate the proposed system. Table 5.1 summarizes the project fill earthmoving parameters for earthmoving operations stage I.

Table 5.1 Project Fill Parameters for Earthmoving Operations Stage I*

Soil type	Volume (BCY)	Haul distance (ft.)	Amount of equipment
Moraine	29,200	49,842	(6, 1, 1, 1)**
Granular	14,500	77,732	(6, 1, 1, 1)**
Rock	192,700	10,150	(8, 1, 1, 1)**

Source: [16].

* Clearing and grubbing, excavation, loading, hauling, backfilling, grading, and compaction.

** Hauling, loading, grading, and compaction.

Prior to inputting data, a list of assumptions is made based on normal job conditions as follows: (1) gear efficiency = 0.85; (2) operational efficiency = 50 (min/hr); (3) job conditions = average; (4) altitude = 2,500 ft.; and (5) tire penetration = 3 in. It is important to note that the assumed value of altitude reflects the stand point of the benchmark above sea level and not the corresponding elevation of the stations as listed in Table 5.1. Afterwards, the user is required to input the volume of earthwork in BCY (bank cubic yards) in order to determine the productivity rates in LCY/hr (loose cubic yards per hour) as shown in Figure 5.7. Once completed, the system displays an output report pertaining to the numerical analysis of the earthmoving operations where productivity rates of corresponding equipment for earthmoving operations are tabulated as shown in Figure 5.8.

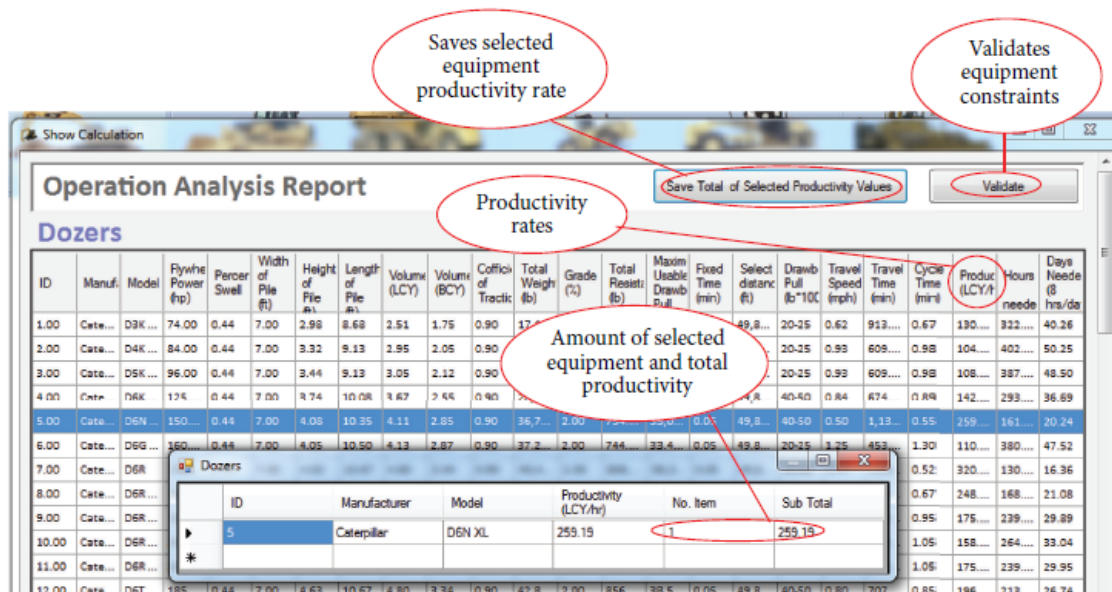


Figure 5.8 Selected Earthmoving Equipment Output Report

As shown in Figure 5.8, equipment productivity rates are tabulated in LCY/hr where the user may specify the number of equipment needed to complete the operations along with their corresponding productivity rates as shown in Figure 5.9. Once completed, the selected fleet along with corresponding productivity rate is automatically extracted and imported into the earthmoving linear scheduling system as shown in Figure 5.10.

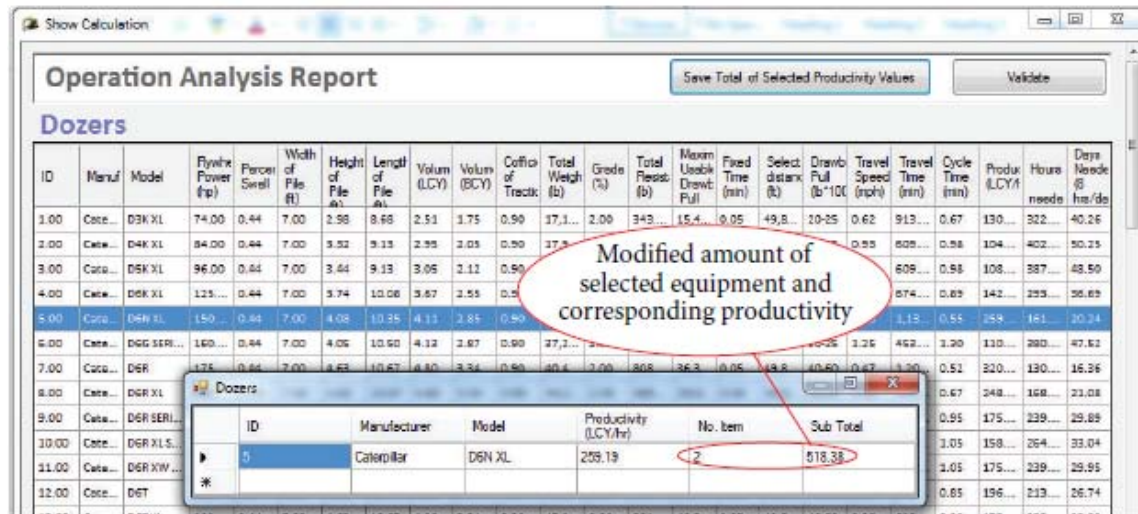


Figure 5.9 Modified Number of Selected Equipment and Corresponding Productivity

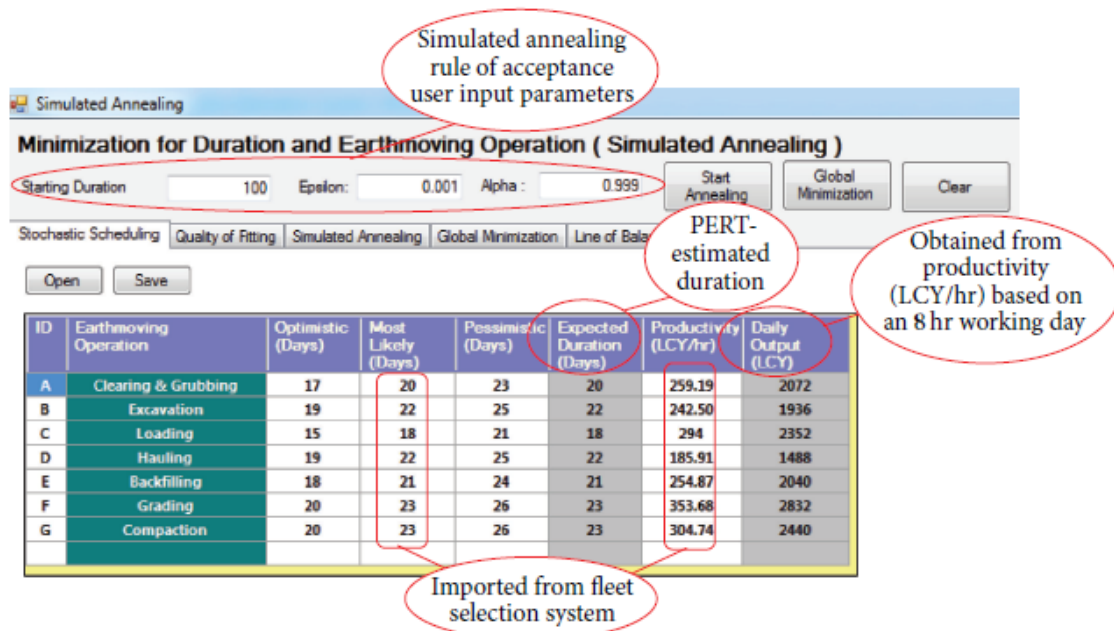


Figure 5.10 Linear Schedule Input Form I

As shown in Figure 5.10, the daily output of earthmoving operations is determined based on the volume of earthwork involved and the most likely duration required to complete the work. Once completed, the user is required to input optimistic and pessimistic operations durations in order to

calculate the corresponding expected durations. Once determined, the proposed system displays a distribution curve that presents the quality of fit of the productivity rates. In the event the distribution is satisfactory, the user may proceed with the simulated annealing process; otherwise, the user may adjust corresponding productivity rates accordingly. Then, the user is guided towards the simulated annealing process, where initial duration, error difference, and decreasing rate values are required. An initially high project duration value of '100' days is inputted in order to escape local minima and reach a near-optimum schedule duration. Furthermore, an error difference value of '0.001' is specified in order to set the rule of accepting the convergent solution. A decreasing rate of 0.999 is inputted in order to gradually decrease the initial duration and be as close to the ideal annealing process. The user then clicks on the start annealing button in order to determine the minimized earthmoving operation duration as shown in Figure 5.11. Once completed, the user will click on the global minimization button in order to minimize the total project duration by minimizing the duration of the earthmoving operation that is preceding or succeeding the operation with the global minimum duration as illustrated in Figure 5.12.

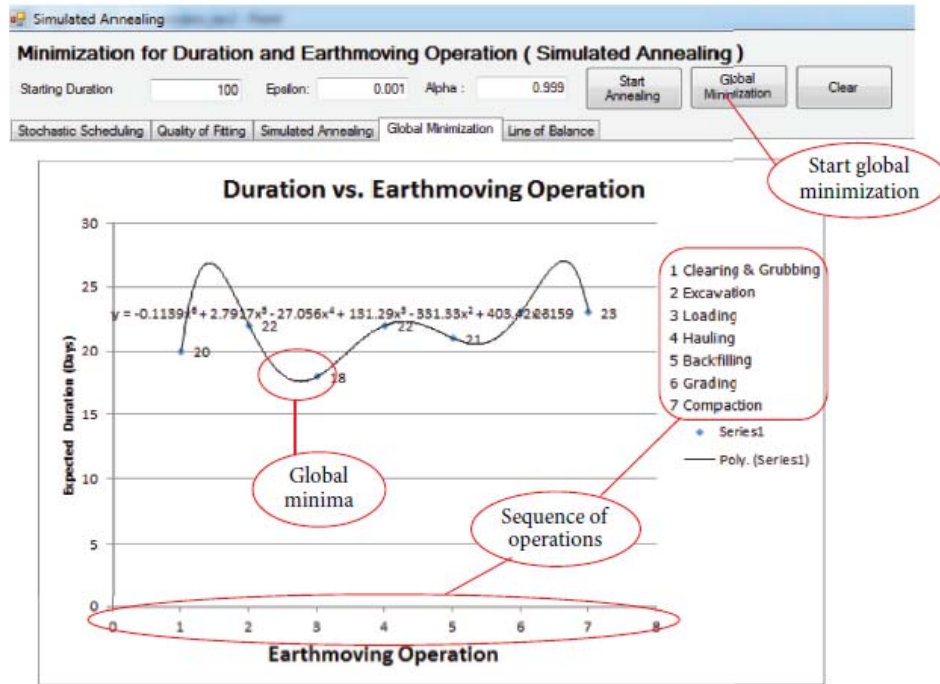


Figure 5.11 Global Time Minimization Form

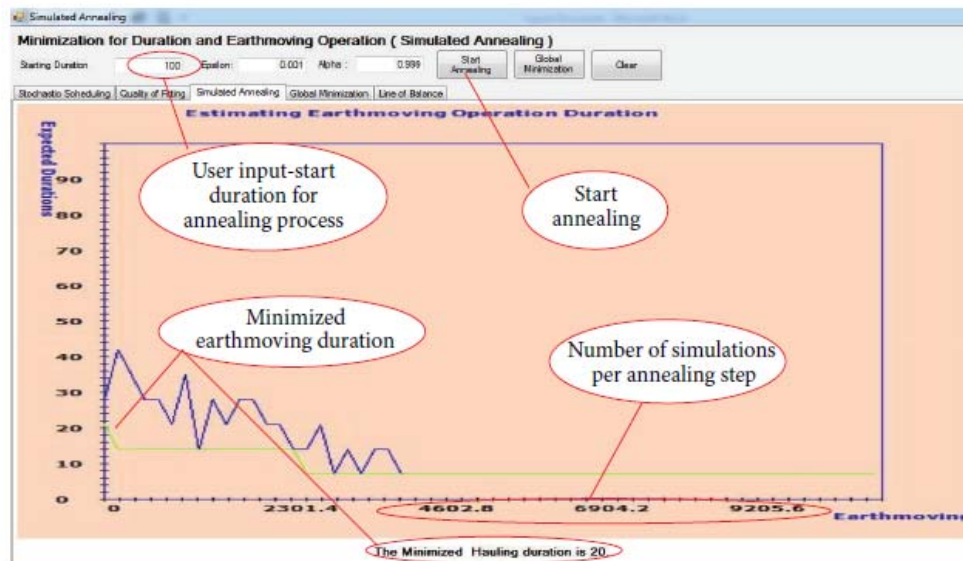


Figure 5.12 Simulated Annealing Form

As shown in Figure 5.12, the proposed system looks for a global minima among the expected duration versus earthmoving operation curve. In this study, a polynomial function of the sixth degree is found to be the best fit based on a regression analysis of earthmoving operations and corresponding expected durations. Afterwards, a near-optimum line of balance is generated along with the option to adjust earthmoving operations start duration in order to detect potential scheduling conflicts at the conceptual design stage and to modify corresponding consecutive earthmoving operations time buffers as shown in Figure 5.13.

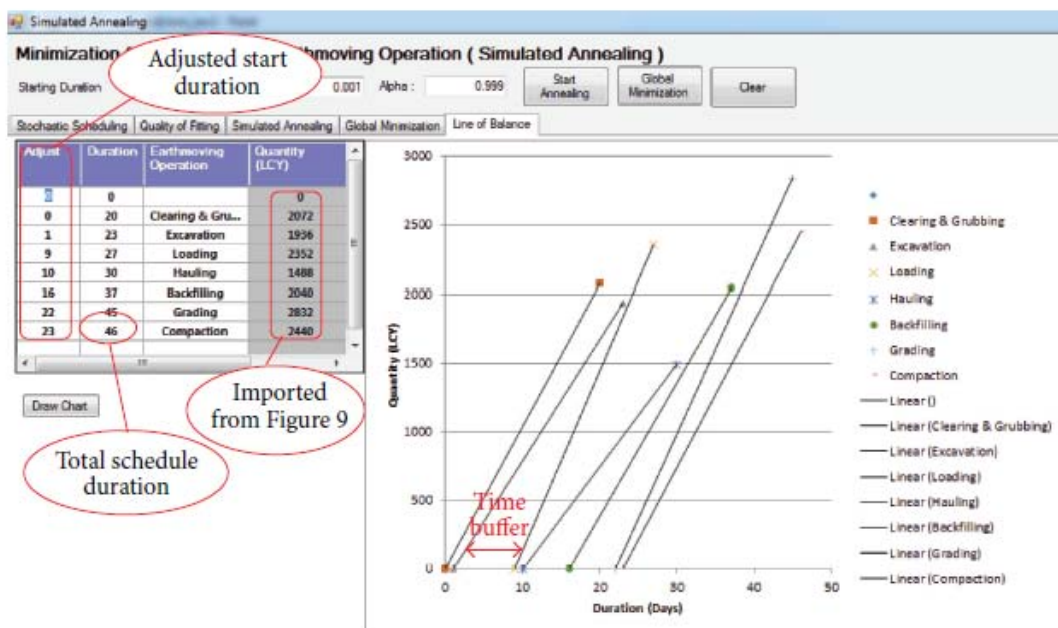


Figure 5.13 Near-Optimum Linear Schedule Form

As illustrated in Figure 5.13, the expert system presented herein is capable of detecting schedule conflicts at the conceptual design stage by deploying the meta-heuristic simulated approach in order to detect scheduling conflicts at the conceptual design stage during the reforming of earthmoving operations sequential combinations. It is important to note that the daily output

(LCY) of earthmoving equipment is obtained based on the actual volume of earthwork and the earthmoving operations durations. The user will then adjust the time buffers between earthmoving operations in an iterative process in order to determine the near-optimum linear schedule for the total project duration. Typically, fleet productivity rates are not fixed and are subject to daily and possibly hourly fluctuations due to unanticipated occurrences. Hence, it is uncommon to represent a line of balance as a straight line; however, in many cases engineers and schedulers prefer such representation for indicative purposes at the conceptual design stages. This implies that a productivity over a short duration might be considerably below that which is anticipated and at other times will far exceed the expected production rate. Table 5.2 summarizes earthmoving operations total durations as obtained from the proposed earthmoving linear schedule system.

Table 5.2 Comparison of Expected Duration (Days) Results per Earthmoving Activity

Soil type	Volume (LCY)	Actual		Proposed		Percentage difference (%)
		Total duration (days)	Amount of equipment	Total duration (days)	Amount of equipment	
Moraine	41,975	67	(6, 1, 1, 1)	46	(3, 1, 1, 1)	31
Granular	16,250	38	(6, 1, 1, 1)	32	(3, 1, 1, 1)	16
Rock	274,452	188	(8, 1, 1, 1)	137	(4, 1, 1, 1)	27

It is important to note that the size and composition of the equipment fleet recommended by the expert system differed from that utilized in the case project. The variability in size of equipment fleet is due scarcity of project site information at the conceptual design stage and availability of equipment at the operational stages. Besides that, the expert system is developed in such a way that a selected equipment fleet is not shared among the earthmoving operations where one type of

equipment is selected to perform a single earthmoving operation. Hence, the recommended equipment fleet proposed by the expert system is based on the individual evaluation of equipment productivity rates. Hence, the equipment fleet proposed by the expert system possesses enhanced productivity rates, which contributes towards the size and composition equipment fleet for a specific project duration. Furthermore, the selection of equipment fleet is directly proportional to daily productivity rates; and therefore, in order to avoid impractical size of equipment fleet, a comprehensive list of equipment types for each earthmoving operation is organized into seven major categories as discussed earlier. Towards, the end, the estimated project durations for diverse soil type and volume is compared to the actual project durations and found to be with a percentage difference ranging between 16% and 31% approximately as illustrated in Table 5.2. The variation in project duration is due to the difference in the size and composition of the equipment fleet. The range of variation in project duration is acceptable at the conceptual design stage since the overall information pertained to the project is neither fully defined nor detailed.

5.7 Summary and Conclusions

In summary, the proposed expert system is developed to assist engineers and schedulers plan for heavy earthmoving operations. The operation analysis of different types of equipment is undertaken to support equipment selection and develop linear schedules for diverse earthmoving operations. The system is then validated through a case project selected from the literature and its outputs are compared with the actual data. It is apparent that the types of soil and user entries highly influence the accuracy of the proposed system. Also, it is concluded that the system

possess some limitations with regards to rock material. That, in fact, requires much more complex studies to be conducted in order to select the required fleet for this type of work; such as earthwork involving mining construction. It is necessary to mention that the proposed integrated system is developed as an estimation tool that can be used to estimate the required time for a particular earthmoving project. Estimation results are based on user entries and are homogenous in type. The homogeneity of near-optimum results is one major limitation of the proposed system as it provides equipment productivity rates that are capable of undertaking the work for diverse soil properties except for rock material. This is an ongoing research and its authors are working on strengthening the system by enhancing the decision support tool and by incorporating additional optimization parameters and constraints to it. This will be done by considering more equipment specifications data and equipment alternatives. For instance, this system is limited to one major heavy equipment manufacturer, Caterpillar[®], where other types of equipment manufacturers may be included. Furthermore, more specific factors that can be applied for specific types of equipment (i.e. scrapers) will be considered. In general, it is not possible for the proposed system to predict fleet productivity accurately and without errors. This is simply due to the fact of the nature and characteristics of construction projects. The contribution of this study mainly resides in the development of a linear scheduling method for capturing the variability in equipment productivity rates. Furthermore, the deployment of a simulated annealing approach is a novel approach for scheduling earthmoving operations. It is also important to note that the proposed global minimization approach will significantly enhance overall project duration and result in time and cost savings in general and specifically for combinational type of earthmoving operations such as loading-hauling, compacting-grading, backfilling-compacting, etc. This paper

is the first attempt to incorporate equipment operation analysis as the framework of the linear scheduling process. The main advantage of the proposed system is the ability to automate user input data interface with equipment operation analysis. The proposed system can be utilized even in projects that involve a large volume of earthwork. This capability gives the system great advantages over other time minimization algorithms, prototypes, or models published and presented in the literature.

5.8 References

K. Agrawal, A. Benoit, L. Magnan, and Y. Robert, “Scheduling algorithms for linear workflow optimization,” in Proceedings of the 24th IEEE International Symposium on Parallel & Distributed Processing (IPDPS ’10), pp. 1–12, IEEE, Atlanta, Ga, USA, April 2010.

L. Song, S. H. Lee, and F. Rachmat, “Stochastic look-ahead scheduling method for linear construction projects,” Journal of Risk Analysis and Crisis Response, vol. 2, no. 4, pp. 252–260, 2012.

M. König. and U. Beißert, “Construction scheduling optimization by simulated annealing,” in Proceedings of the 26th International Symposium on Automation and Robotics in Construction (ISARC ’09), 2009.

C. Srisuwanrat and P. G. Ioannou, “The investigation of lead-time buffering under uncertainty using simulation and cost optimization,” in Proceedings of the 15th Annual Conference of the International Group for Lean Construction (IGLC ’15), pp. 580–589, Ann Arbor, Mich, USA, July 2007.

W. Liu, I. Flood, and R. Issa, "Simulation and optimization of linear construction projects," *Journal of Computing in Civil Engineering*, pp. 1–11, 2005.

S. Nunnally, *Managing Construction Equipment*, Prentice-Hall, Englewood Cliffs, NJ, USA, 1977.

J. Schaufelberger, *Construction Equipment Management*, Prentice-Hall, Upper Saddle River, NJ, USA, 1999.

A. Jrade, N. Markiz, and N. Albelwi, "An economical operation analysis optimization model for heavy equipment selection, *International Journal of Civil and Environmental Engineering*, vol. 6, pp. 40–45, 2012.

A. Jrade and N. Markiz, "A decision-support model utilizing a linear cost optimization approach for heavy equipment selection," in *Proceedings of the Construction Research Congress*, pp. 100–109, ASCE, West Lafayette, Ind, USA, May 2012.

N. Markiz and A. Jrade, "Integrating bridge information modeling (BrIM) with cost estimation at the conceptual design phase of bridges," in *Proceedings of the 4th Construction Specialty Conference (CSCE '13)*, pp. 1–10, Montreal, Canada, 2013.

W. Shang and J. Fortes, "Time optimal linear schedules for algorithms with uniform dependencies," in *Proceedings of the International Conference on Systolic Arrays*, pp. 393–402, IEEE, 1988.

J. Tobochnik and H. Gould, “Teaching statistical physics by thinking about models and algorithms,” *American Journal of Physics*, vol. 76, no. 4-5, pp. 353–359, 2008.

U. Beißert, M. König, and J. Bargstädt, “Constraint-based simulation of outfitting processes in building engineering,” in *Proceedings of the 24th Conseil International du Bâtiment W78 Conference*, pp. 183–190, 2007.

S. Ledesma, G. Avina, and R. Sanchez, “Practical considerations for simulated annealing implementation,” in *Simulated Annealing*, pp. 401–420, InTech, Vienna, Austria, 2008.

M. Marzouk, *Optimizing earthmoving operations using computer simulation* [Ph.D. thesis], University of Concordia, Montreal, Canada, 2002

CHAPTER 6

TECHNICAL PAPER III

Integrating Fuzzy-Logic Decision Support with a Bridge Information Management System (BrIMS) at the Conceptual Stage of Bridge Design

Nizar Markiz, Ahmad Jrade

(Addressed Comments and Resubmitted to Journal of Information Technology in Construction, ITCon)

Abstract: In recent years, infrastructure restoration has been backlogged with complex factors that have captured the attention of municipal and federal authorities in North America and Europe. The subjective nature of evaluating bridge conditions and bridge deterioration is one of the main factors that influences bridge maintenance, repair, and replacement (MR&R) decisions. This study presents a stochastic fuzzy logic decision support system integrated with a bridge information management system (BrIMS) to forecast bridge deteriorations and prioritize maintenance, repair, and replacement (MR&R) decisions at the conceptual design stage. The proposed system considers numerous factors that influence the prioritization of bridge MR&R decision making including complex time-dependent gamma shock models. A parametric analysis is conducted in order to quantify the degree of accuracy of the system. The results of this study are anticipated to be of major significance to bridge stakeholders and designers who are looking to enhance long-term bridge resistance to deterioration. The successful implementation of the integrated system signifies a technological achievement of novelty pertaining to the integration

of BrIMS solutions with fuzzy-logic deterioration forecast strategic approaches at the conceptual design stage of bridges.

KEYWORDS: Fuzzy-logic, Decision Support, Deterioration Forecast, Bridge Information Model, Bridge Information Management System

6.1 Introduction

Typically, forecasting bridge infrastructure deterioration from distinct condition assessments and statistics is a challenging task. Due to the highly complex and erratic nature of infrastructure data, deterministic bridge deterioration models are quite often not applicable. Temporal reliability analysis “hazard functions,” such as Markov chains, Bayesian networks, and gamma models, have been developed for bridge and storm sewer systems. Predicting bridge deterioration conditions is the main constituent of infrastructure asset management techniques. Furthermore, a decision support system based on fuzzy-logic theory that assists asset managers in making appropriate MR&R decisions is vital. Bridge performance indicators should be based on bridge beneficiaries’ perceptions of technical parameters. Integrating these indicators with stochastic time-dependent modeling of bridge deteriorations is important for planning and prioritizing MR&R activities. These activities may include inspection, sampling, preventative and maintenance operations. Based on the aforementioned, a time-dependent prediction of the overall bridge deteriorations necessitates the development of a thorough, reliable, and user-friendly fuzzy-logic decision support system.

6.2 Problem Definition

Nowadays, most bridge management methodologies are strictly based on life cycle analyses offset by available funds and budget constraints. Repair costs, in many situations, have proven to exceed annual or semi-annual preventive maintenance costs. Most bridge stakeholders are reluctant to pay for preventive maintenance, which appears to be of no benefit or which bridge asset managers have found from experience to be unsuccessful in preventing a bridge structure from deteriorating. In an attempt to overcome this shortcoming, this study is intended to demonstrate the viability of stretching bridge information models to capture the conceptual design of a bridge while applying sensitivity analyses to identify the most sensitive elements and subsequently to forecast bridge elemental deteriorations. Furthermore, it is understood that integrating a fuzzy logic decision support system with BrIMS and deterioration forecast for bridges is possible only if its objectives are kept simple, focused, and organized. Therefore, basic straightforward bridge information model (BrIM) processes have been researched, recalled, and analyzed. According to Bentley bridge solutions, the eight processes of BrIM are: (1) bridge type selection; (2) 3D CAD model; (3) technical analysis; (4) planning for construction; (5) production; (6) phases of construction; (7) maintenance; and (8) remediation (Peters, 2009). Extending published research that combines BrIMS with deterioration, this study introduces the idea of a fuzzy-logic decision support framework. In this study, the following processes; i) bridge type selection; ii) 3D CAD model; iii) technical analysis; and iv) maintenance and remediation are selected for the development and integration of cost estimation at the conceptual design stage. The proposed system integrates quality functions for maintenance, repair, and replacement (MR&R) alternatives with a Gaussian probabilistic matrix factorization. The resulting system

produces competitive priority ratings that eliminate ambiguities in bridge life cycle evaluation. Hence, the proposed integrated management information system becomes a new approach to informing downstream processes of bridge projects at the conceptual design stage.

6.3 Research Objectives

The integrated approach presented herein may be utilized to plan the maintenance and to monitor the deterioration of bridges and then to prioritize the maintenance, repair, and replacement alternatives; (i.e., inspection, sampling, preventative, and maintenance operations). This integration technique is a rational approach that justifies most “ineffective” spending by bridge stakeholders, since it considerably reduces subjectivity in quantifying bridge deterioration. Moreover, the integration not only contributes to the reliability of a particular bridge element but also to the reliability of the collected data and the probability of occurrence of deterioration benchmarks such as corrosion and elemental degradations. The main objective of this study, then, is to develop fuzzy logic decision support system using complex quality functions and a gamma stochastic deterioration model that is based on the integration of probabilistic models in an attempt to improve the effectiveness of bridge information management systems. Towards that goal, a wider insight into the integration of a decision support system can assist bridge asset managers in proposing a strategic solution to deteriorating bridge infrastructures. The proposed solution will be based on a standard gamma distribution, and will comprise independent non-negative increments with identical scale parameters. Hence, the main objective of this study is to propose a fuzzy-logic decision support system to predict bridge deteriorations at a given time.

This will allow bridge asset managers to prioritize subsequent MR&R decisions at the conceptual design stage.

6.4 Literature Review

Highway and transportation authorities have often relied upon deterministic deterioration curves for predicting bridge maintenance programs. In past years, bridge infrastructure management systems have been modeled using traditional Markov chain models. In the past three decades, inconsistent MR&R decisions for bridges and road infrastructures have necessitated the evolution of further investigative studies in the modeling of bridge deteriorations in parallel with developing reliable decision support solutions.

Recent bridge management systems have implemented Markov chains deterioration models which is considered a major step forward towards incorporating stochastic-natured deterioration models. Moreover, several bridge maintenance aspects and corresponding bridge asset visual inspection standards and procedures endorsed the implementation of the Markov chain model which is known to possess restrictive assumptions. Proceedings and evolutions that tailored the Markov chain approach in bridge management systems were provided in a study published by Frangopol et al. (2001). Whilst several attempts were made at modeling the deterioration of bridge infrastructures, practical developments were recorded recently, where researchers employed the gamma stochastic process effectively to temporal deteriorations and subsequently implemented into traditional MR&R decision support systems. Although advancements in bridge deterioration modeling had brought up maintenance solutions into the next level of strategic management techniques, there still exist arguments on the applicability of the gamma process

and stochastic processes to complex time-dependent bridge elements incremental degradations. Regardless, substantial efforts have been utilized for applying gamma stochastic modeling process to perseverance of bridge structures. One study conducted by Van Noortwijk et al. (2007) examined gamma processes and peaks-over-threshold distributions for time-dependent reliability. In their paper, a comprehensive discussion on the evaluation of structural reliability is presented where a methodology that integrated two stochastic processes originating from a Poisson process for obtaining the temporal reliability of a particular structural component was proposed. According to studies conducted by Golabi et al. (1993) and Hawk (1999), incremental degradation of bridge components is designed by a static Markov chain model process in which accumulating deficiencies following a stress cycle are assumed to depend on original conditions and duration of the cyclic stress loading only. However, a study conducted by Madanat et al. (1997) confirmed that most bridge deterioration models are not static and proposed descriptive variables that traditional Markov models must take into account to develop more realistic models. Furthermore, Bogdanoff (1978) and Lounis (2000) restated the capability of Markov models in predicting the remaining service life of a bridge at any time based on existing deterioration conditions. Another study conducted by Edirisinghe et al. (2013) presented the application of gamma process for stochastic deterioration prediction of building elements derived from discrete condition data obtained from the Victorian local government infrastructure asset database. The focus of their study is funneled to develop a complex and more reliable deterioration prediction system for managing their building assets. Gamma process probability and cumulative density functions were derived and plotted in addition to building elements predicted temporal deterioration. At the end, the authors concluded with the capability of the

proposed gamma process deterioration model for forecasting deterioration of building elements with time by incorporating building condition and deterioration highly scattered data. Moreover, Reddy and Ramudu (2013) analyzed a numerical arithmetic-geometric maintenance model for deteriorating system subject to a random environment. Their main goal is geared towards developing a replacement model for a particular deteriorating system in a random environment while utilizing an arithmetic-geometric approach that maximizes long-run anticipated payoff within a cycle time. System replacement average cost rate versus the replacement policy were obtained and plotted where the peak of the curves explicitly indicates an optimal replacement policy. At the end, the authors concluded that by varying the parameters of the developed model, the optimal number of failure only impacts the long-run anticipated payoff cost per cycle time. Furthermore, Pandey and Van Noortwijk (2004) investigated a gamma process model for temporal structural reliability and presented a relative assessment of random variable deterioration models based on the first order reliability methods and temporal stochastic modeling based on the gamma process. In their paper, the authors employed a stochastic model to count for both sampling and time-dependent variances allied with a structural system deterioration process. A detailed comparison of lifetime probability and cumulative density functions as well as survival curves between random variable and gamma process mechanisms were presented. It was concluded that the random variable model overestimates probability of remaining life time of a particular structure in the long-run and gamma model provides more reasonable estimates of life times which shall enhance the implementation of such stochastic deterioration models more often in structure reliability analysis. In another study, Van Noortwijk et al. (2005) examined a gamma process model for temporal structural reliability and presented a

combined computational method comprising both deterioration resistance and variable load modeled as a stochastic gamma process. It is concluded that the time at which the deteriorating resistance falls below the fluctuation load cumulative distribution function can be formulated as a functional equation which could be solved numerically by applying a series of integration and partial derivations to simulate deterioration paths of the generalized gamma process. It was also found that the proposed method contributes to the ‘well-fit’ of structural monotonic aging peaks-over-threshold distributions with extreme value figures. On the other hand, Lounis and Madanat (2002) presented a two-level decision support system that amalgamates stochastic deterioration models to enhance efficacy of bridge maintenance management systems. The first level management is based on Markov models that pin points perilously damaged structures and predicts short- and long-term deterioration and essential maintenance at a bridge-level and network- level. While the second level management is based on mechanistic models that target considerably deteriorated bridge structures classified from the first level management and assess their integrity, serviceability, and maintenance. However, although traditional Markov chain models are proven practical and relatively simple to develop, they do possess limitations especially at comprehensive project phases and are considered not sufficient for analyzing critical structures when it comes to safety matters. The most important limitation, however, is the deployment of elemental condition crisp rating systems based on vague performance indicators mainly influenced by the scale of subjectivity involved in the visual inspection and not explicitly related to qualitative and quantitative parameters such as material properties, stress-strain conditions, and structural behavior, etc. In an attempt to overcome such limitation, reliability-based deterioration models that are based on fuzzy-logic decision support system by the

deployment of complex quality functions originating from the house of quality (HOQ) model, presented latter, quantitative and qualitative fuzzy logic scorings that take into account technical, functional, and safety parameters are proposed for the bridge level and network level analysis. Moreover, such models are powerful in the manner that they are capable of analyzing single or multiple simple or complicated bridge structures of a highway bridge network that possess multiple failure modes and diverse failure consequences.

As described above, there have been substantial efforts to apply a gamma model to the perseverance of bridge structures. Although traditional Markov chain models have proven to be practical, they do possess limitations especially at the conceptual design phase. Also, they are considered insufficient for analyzing critical structures when it comes to safety matters. The most important limitation, however, is the deployment of elemental condition crisp rating systems based on vague performance indicators. These indicators are mainly influenced by the subjective nature of visual inspections and not explicitly related to qualitative and quantitative parameters such as material properties, stress-strain conditions, and structural behavior. Only recently have researchers effectively applied the gamma stochastic process to sequential deteriorations and implemented it into decision support systems.

Although advancements in deterioration modeling have influenced bridge MR&R solutions, arguments for its application to time-dependent incremental degradations of bridge elements still exist. This study presents the proposal of a reliability-based deterioration model based on the deployment of complex quality functions originating from the house of quality (HOQ) model. The proposed decision support system is based on quantitative and qualitative fuzzy logic

scorings that take into account technical, functional, and safety parameters. Moreover, such models are powerful in the manner that they are capable of analyzing single or multiple complicated bridge elements of a highway bridge that possess diverse failure modes.

In summary, the majority of the studies reviewed from the literature had not considered the integration of decision support systems with gamma models. The main advantage of such integration underlies the benefit of capturing economical maintenance routes and making strategic MR&R decisions. In contrast, most of the studies considered numerous important factors for enhancing bridge maintenance and management techniques. None of the studies; however, had specifically viewed a bridge maintenance program as a task or process that needs to be completed based on qualitative and quantitative characteristics. Hence, the bridge information management system proposed in this study incorporates a fuzzy-logic decision support system. The system includes MR&R decisions that are integrated with reliability-based gamma stochastic models for predicting time-dependent bridge deterioration at the conceptual design stage.

6.5 Methodology And Development

The proposed methodology comprises an innovative bridge information management system (BrIMS) based on a framework that is capable of integrating bridge gamma stochastic deterioration modeling with a fuzzy-logic decision support system. The framework is developed by deploying complex quality functions derived from bridge beneficiary-driven parameters and symmetrical triangular fuzzy numbers (STFN's) to capitulate bridge evaluation ambiguities. Furthermore, the proposed system possesses a unique aspect of BrIMS by incorporating diverse

bridge MR&R solutions into a multi-criteria decision making approach (MCDM) to derive competitive priority ratings. A schematic view of the interrelations among the 3D computer-aided design (CAD) solutions with the developed bridge conceptual cost estimation system is illustrated in Figure 6.1.

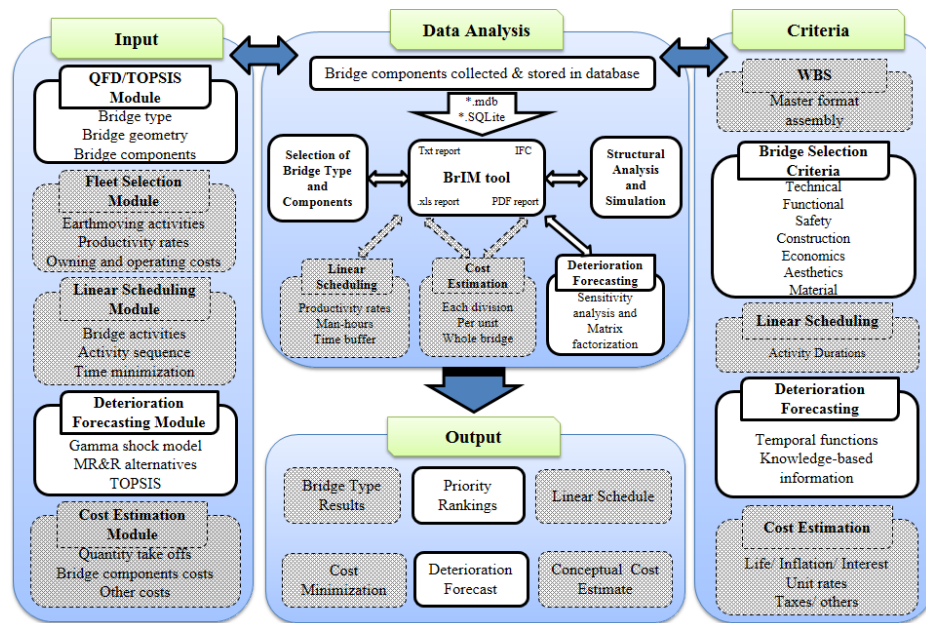


Figure 6.1 Proposed System Architecture

As illustrated in Figure 6.1, it is important to note that the proposed integrated system is part of an integrated preliminary fuzzy-logic decision support system developed earlier by the authors of this study. The following two modules: a) 'QFD/TOPSIS', and b) 'DETERIORATION FORECASTING' are an integral part of this study whereas the highlighted items that correspond to the following three modules: i) 'FLEET SELECTION', ii) 'LINEAR SCHEDULING', and iii) 'COST ESTIMATION' are not part of this study. The proposed system is developed in an object-oriented .NET framework and undertaken by completing the following six main steps: 1)

Data collection of bridge-user-driven parameters; 2) Implementation of a decision support system that assists the user in making MR&R decisions; 3) Development of complex quality functions to evaluate bridge users' relative perception of bridge components; 4) Deployment of a numerical model to evaluate bridge MR&R ratings; 5) Development of a mean deterioration resistance regression fit where MR&R rankings are determined; and 6) Optimizing and prioritizing maintenance, repair, and replacement alternatives. A proper arrangement and management of the modeling data will result in less error-prone outcomes as a result of duplication or combination of inconsistent bridge database resources. The flow of geometric and architectural information for diverse bridge types and resistance deterioration predictions begins at fuzzy logic scorings and ends at the forecasting of bridge component deterioration. Throughout the process, the deployment of the technique of preference by similarity to ideal solution (TOPSIS), a multi-criteria analytical approach utilized for the selection of the MR&R alternative based on a specified list of parameters is undertaken. It is important to note that the proposed BrIMS system presented herein is one component of a globally-integrated decision support system where deterioration forecasts of bridge components and prioritization of MR&R alternatives are achieved at the conceptual design stage.

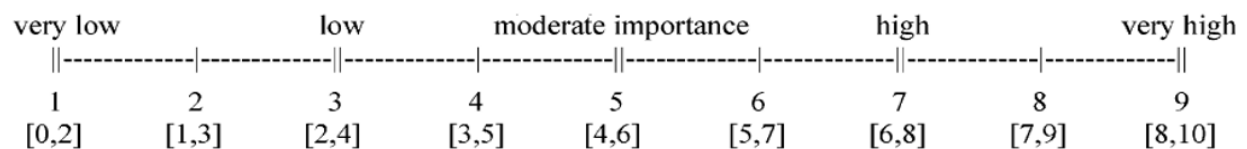
6.6 Fuzzy-Logic Decision Support System

Due to the scarcity of bridge deterioration data, it is necessary to develop a fuzzy logic scoring system in order to assist bridge stakeholders and designers in predicting bridge deterioration at conceptual design stages. Otayek et al. (2012) have 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 recommend continuous and further development in decision support systems in an attempt to assist bridge designers in predicting bridge deteriorations at conceptual phases. On the other hand, Malekly et al. (2010) have proposed a methodology of implementing a quality function deployment (QFD) technique and a technique of preference by similarity to ideal solution (TOPSIS). Their methodology is integrated in a novel oriented approach while overcoming interoperability issues among the disperse databases. Furthermore, Tee et al. (1988) studied the viability of developing a numerical approach based on fuzzy set rules such that the degree of subjectivity involved in evaluating bridge deterioration was treated systematically and was incorporated into a systematic knowledge-based system. Liang et al. (2002) proposed grey and regression models for predicting the remaining service life of existing reinforced concrete bridges. In their study, the fuzzy logic concept was introduced as a methodology for evaluating the extent of deterioration of existing bridge structures. Zhao and Chen (2002) proposed a fuzzy logic system for bridge designers to help to predict bridge deteriorations based on factors incorporated at the initial design phase. Sasmal et al. (2006) recalled earlier studies using fuzzy logic theory and stated that those methodologies were either much too simple or too complex so that key support requires considerable time. These studies, overlooked key issues pertaining to membership functions and other parameters, such as priority vectors and mappings, which are fundamental for bridge condition assessments..Therefore, authors of this study propose an integration prototype of a decision support system and a numerical methodology for forecasting deteriorations of bridge components based on fuzzy mathematics integrated with an eigen-vector technique and priority ratings at the conceptual design stage.

6.6.1 Quality Functions

Conceptual bridge design is found to be significantly influenced by each of the following nine main components: (1) approach slab ‘C₁’; (2) deck slab ‘C₂’; (3) expansion joint ‘C₃’; (4) parapet ‘C₄’; (5) girder ‘C₅’; (6) bearings ‘C₆’; (7) abutment ‘C₇’; (8) pier ‘C₈’; and (9) foundation ‘C₉’. Selection of the components is based on critical factors that bridge designers rely upon and bridge users’ perception on the importance of components. Hence, a 9-point symmetrical triangular fuzzy logic numbers (STFN) ranging from one to nine, with one being very low and nine being very high, is adopted for assisting the decision maker in predicting bridge users perception pursuant to the main nine bridge components listed above. The scoring system comprises crisp and fuzzy measures when uncertainty arises as illustrated in Figure 6.2.



*Source: Chan and Wu (2005)

Figure 6.2 Fuzzy-logic Scoring System

Where for instance, [0,2] indicates the range of fuzziness of the crisp score ‘1’. Similarly, [8,10] represents the range of fuzziness of the crisp score ‘9’. Afterwards, bridge users are identified and categorized as follows: (i) stakeholders/government; (ii) designers/engineers; (iii) contractors/builders; and (iv) public/residents. Also, the following nine common bridge types ‘alternatives’ are identified and incorporated into the database platform for QFD analyses: (1) beam bridges ‘W₁’; (2) truss bridges ‘W₂’; (3) cable-stayed bridges ‘W₃’; (4) tied-arch bridges ‘W₄’; (5) arch bridges ‘W₅’; (6) suspension bridges ‘W₆’; (7) double-decked bridges ‘W₇’; (8)

movable bridges ‘W₈’; and (9) cantilever bridges ‘W₉’. The adopted QFD analytical technology utilized for the selection of bridge type is presented in Figure 6.3.

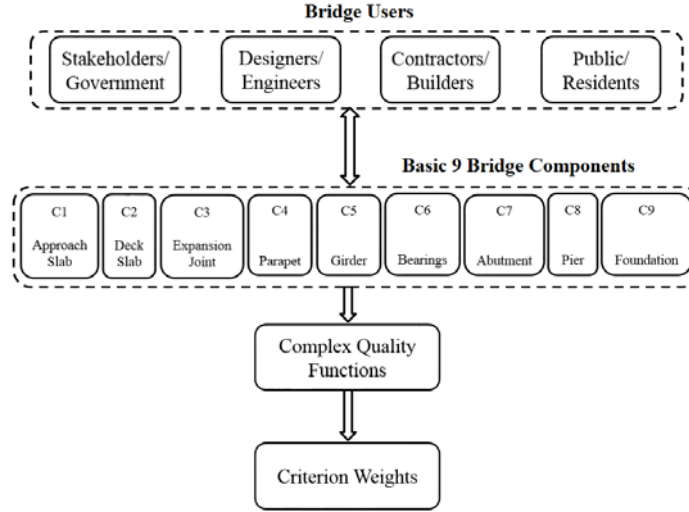


Figure 6.3 Quality Function Deployment Process Flow

Upon completion of user scorings on the nine bridge components, perception on relative importance ratings of the components is determined. In this study, Chan and Wu (2005) numerical methodology is deployed due to its efficiency, systematic characteristics, and ease of use in competitive analysis of bridge components selection. Crisp and measure forms of expected relative importance ratings are obtained in accordance with Chan and Wu (2005) equations (6.1) and (6.2):

$$g_{mk} = \frac{(g_{m1} + g_{m2} + g_{m3} + g_{m4} + g_{m5} + g_{m6} + g_{m7} + g_{m8} + g_{m9})}{9} \quad (6.1)$$

$$\tilde{g}_{mk} = \frac{(\tilde{g}_{m1} + \tilde{g}_{m2} + \tilde{g}_{m3} + \tilde{g}_{m4} + \tilde{g}_{m5} + \tilde{g}_{m6} + \tilde{g}_{m7} + \tilde{g}_{m8} + \tilde{g}_{m9})}{9} \quad (6.2)$$

Where; g_{mk} is a bridge user relative importance perception on a component in ‘crisp’ form, k is a bridge user, $\tilde{g}_{mk}$ is a bridge user relative importance perception on a component in ‘fuzzy’ form. In other words, g_{mk} is the average “integer” crisp scoring value of a bridge user on the relative importance of each of the components and $\tilde{g}_{mk}$ is the average “integer” fuzzy scoring value of a bridge user on the relative importance of each of the components. Following the determination of relative importance ratings, bridge users competitive comparison matrix analysis is developed as per Chan and Wu (2005) equations (6.3) and (6.4):

$$X = [x_{mk}]_{9 \times 9} \quad (6.3)$$

$$x_{mlk} = \frac{(x_{m11} + x_{m12} + x_{m13} + x_{m14})}{4} \quad (6.4)$$

Where; X is the bridge users’ comparison matrix, x_{mk} is a bridge user assessment on C_m , x_{mlk} is a bridge user assessment of a bridge alternative on C_m , and C_m is a bridge component. Afterwards, the probability distribution of each C_m on bridge alternatives is calculated using Chan and Wu (2005) equation (6.5):

$$p_{mk} = \frac{x_{mk}}{x_m} \quad (6.5)$$

Where; p_{mk} is the probability distribution of C_m on bridge alternatives, x_{mk} is a bridge user assessment on C_m ‘result obtained from equation (6.4)’, and x_m is the total of bridge users

assessment of all bridge alternatives on each of C_m . Following the determination of probability distribution of C_m , its measure of entropy, which is a quantification of the expected value of a system with uncertainty in random variables, may be obtained using Chan and Wu (2005) equations (6.6) and (6.7):

$$E(C_m) = -\phi_9 \sum_{l=1}^9 p_{mk} \ln(p_{mk}) \quad (6.6)$$

$$\phi_9 = \frac{1}{\ln(9)} \quad (6.7)$$

Where; $E(C_m)$ is the measure of entropy by a discrete probability distribution for C_m , ϕ_9 is the normalization factor that guarantees $0 \leq E(p_1, p_2, \dots, p_L) \leq 1$, p_{mk} is the probability distribution of C_m for the diverse bridge alternatives. Higher entropy or $(p_1, p_2, \dots, p_L)$ implies smaller variances and lesser information in a probability distribution p_L . At the end, bridge alternatives' weights on each of the nine C_m are calculated based on Chan and Wu (2005) equation (6.8):

$$e_m = \frac{E(C_m)}{\sum_{m=1}^9 E(C_m)} \quad (6.8)$$

Where; e_m is the importance weight of bridge component, C_m , and $E(C_m)$ is the measure of entropy by a discrete probability distribution for C_m . This complex quality function deployment mechanism of assigning priorities to competing alternatives is directly related to information

theory concept of entropy. Once completed, a set of improving goals strategy on each of the bridge components to enhance the bridge alternative deterioration resistance performance is defined. The performance goals on the bridge components are identified based on the 9-point STFNN scale as per Chan and Wu (2005) equation (6.9):

$$i = (i_1, i_2, i_3, i_4, i_5, i_6, i_7, i_8, i_9) \quad (6.9)$$

Where; i is the improvement goal set. It is important to note that the improvement goals must be higher than the initial performance rating of a bridge component, C_m for a bridge alternative, W_m . This implies that in case the initial rating of a component for a particular bridge alternative is high, the goal set must be higher to maintain its rating and enhance the competition amongst bridge alternatives. Otherwise, if the initial rating is lesser, then the improvement goal is set to improve the performance of the same and enhance its importance weight. Once improvement goals are set, an improvement ratio is calculated as per Chan and Wu (2005) equation (6.10):

$$r_m = \frac{i_m}{x_{mk}} \quad (6.10)$$

Where; r_m is the improvement ratio, i_m is the improvement goal set, and x_{mk} is a bridge user assessment on C_m ‘result obtained from equation (6.4)’. The competitive rating for a bridge component, C_m , in ‘crisp’ form is obtained as per Chan and Wu (2005) equation (6.11):

$$f_m = i_m * g_m * e_m \quad (6.11)$$

Where; f_m is the competitive rating, i_m is the improvement goal set, g_m is a bridge user relative importance perception on a component in ‘crisp’ form, and e_m is the importance weight. The final importance rating for a bridge component, C_m , in ‘fuzzy’ form is obtained as per Chan and Wu (2005) equation (6.12):

$$\tilde{f}_m = i_m * \tilde{g}_m * e_m \quad (6.12)$$

Where; $\tilde{f}_m$ is the competitive rating in ‘fuzzy’ form, i_m is the improvement goal set, $\tilde{g}_m$ is a bridge user relative importance perception on a component in ‘fuzzy’ form, and e_m is the importance weight. Once completed, technical measures to expected maintenance, repair, and replacement (MR&R) decisions to the deterioration of bridge components are grouped into three main categories as illustrated in Table 6.1.

Table 6.1: Maintenance, Repair, and Replacement Decisions Versus Extent of Deterioration (%)

Extent of Deterioration %	Category I	Category II	Category III
15	√	-	-
30	√	-	-
45	√	√	-
60	-	√	-
75	-	√	√
90	-	-	√
100	-	-	√

As illustrated in Table 6.1, category (I) is a ‘Maintenance’ category that comprises maintenance of bridge component for an expected extent ranging between 15% to 45% and comprising the decisions; ‘Maintenance: S₁.M15’, ‘Maintenance: S₂.M30’, and ‘Maintenance: S₃.M45’; category (II) is a ‘Repair’ category that comprises repair of bridge component for an expected extent of deterioration ranging between 45% to 75% and comprising the decision; ‘Repair: S₄.REPA45’, ‘Repair: S₅.REPA60’, and ‘Repair: S₆.REPA75’; category (III) is a ‘Replacement’ category that comprises replacement of bridge component for an expected extent of deterioration ranging between 75% to 100% and comprising the decisions; ‘Replacement: S₇.REPL75’, ‘Replacement: S₈.REPL90’, and ‘Replacement: S₉.REPL100’. It is important to note that the proposed categories and extent of deterioration is for illustrative purposes and can be customized dependent upon the bridge location and the regional weather forecast. Similar to the determination of competitive comparison matrix analysis on bridge components, user comparison matrix analysis on technical measures for expected deterioration in ‘crisp’ and ‘fuzzy’ forms respectively are determined as per Chan and Wu (2005) equations (6.13) and (6.14):

$$R = [r_{mn}]_{10 \times 9} \quad (6.13)$$

$$\tilde{R} = [\tilde{r}_{mn}]_{10 \times 9} \quad (6.14)$$

Where; R is the comparison matrix on technical measures, r_{mn} is a bridge user technical measure assessment on C_m in ‘crisp’ form, $\tilde{r}_{mn}$ is a bridge user technical measure assessment on C_m in ‘fuzzy’ form, and C_m is a bridge component. Hence, the technical rating for a measure,

t_{mn} , on a bridge component, C_m in ‘crisp’ form is obtained as per Chan and Wu (2005) equation (6.15):

$$t_{mn} = \sum_{m=1}^9 f_m * r_{mn} \quad \text{where } n=1, 2, \dots, 10 \quad (6.15)$$

Where; t_{mn} is the technical rating on a measure in ‘crisp’ form, f_m is the competitive rating ‘result obtained from equation (6.11)’ in ‘crisp’ form, and r_{mn} is a bridge user technical measure assessment on C_m in ‘crisp’ form. The technical rating for a measure, r_{mn} , on a bridge component, C_m in ‘fuzzy’ form is obtained as per Chan and Wu (2005) equation (6.16):

$$\tilde{t}_{mn} = \sum_{m=1}^9 \tilde{f}_m * \tilde{r}_{mn} \quad \text{where } n=1, 2, \dots, 10 \quad (6.16)$$

Where; $\tilde{t}_{mn}$ is the technical rating on a measure in ‘fuzzy’ form, $\tilde{f}_m$ is the competitive rating ‘result obtained from equation (6.12)’ in ‘fuzzy’ form, and $\tilde{r}_{mn}$ is a bridge user technical measure assessment on C_m in ‘fuzzy’ form. Afterwards, the probability distribution of each C_m on bridge deterioration technical measures is calculated using Chan and Wu (2005) equation (6.17):

$$p_{mn} = \frac{x_{mn}}{x_m} \quad (6.17)$$

Where; p_{mn} is the probability distribution of C_m on technical measure, x_{mn} is a bridge user assessment on C_m ‘result obtained from equation (8.4)’, and x_m is the total of bridge users

assessment of all technical measure on each of C_m . Following the determination of probability distribution of C_m , its measure of entropy, which is a quantification of the expected value of a system with uncertainty in random variables, may be obtained using Chan and Wu (2005) equations (6.18) and (6.19):

$$E(C_m) = -\phi_{10} \sum_{l=1}^{10} p_{mn} \ln(p_{mn}) \quad (6.18)$$

$$\phi_{10} = \frac{1}{\ln(10)} \quad (6.19)$$

Where; $E(C_m)$ is the measure of entropy by a discrete probability distribution for C_m , ϕ_{10} is the normalization factor that guarantees $0 \leq E(p_1, p_2, \dots, p_L) \leq 1$, p_{mn} is the probability distribution of C_m for the diverse technical measures. Higher entropy or $(p_1, p_2, \dots, p_L)$ implies smaller variances and lesser information in a probability distribution p_L . At the end, bridge technical measure weights on each of the nine C_m is calculated based on Chan and Wu (2005) equation (6.20):

$$e_t = \frac{E(C_m)}{\sum_{m=1}^9 E(C_m)} \quad (6.20)$$

Where; e_t is the importance weight of technical measure, and $E(C_m)$ is the measure of entropy by a discrete probability distribution for C_m .

6.6.2 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

Upon determination of technical measure weights, a multi-criteria decision making approach, TOPSIS, is undertaken. This approach takes into account the following criteria: (i) qualitative benefit; (ii) quantitative benefit; and (iii) cost criteria. As part of TOPSIS analysis, the following two most contradicting alternatives are surmised: (a) ideal alternative in which the maximum gain from each of the criteria values is taken; and (b) negative ideal alternative in which the maximum loss from each of the criteria values is taken. Towards the end, TOPSIS opts in for the alternative that converges to the ideal solution and opts out from the negative ideal alternative. Prior to undertaking the multi-criteria decision making approach, a TOPSIS matrix is created based on equation (6.21):

$$X = (x_{ij}) \quad (6.21)$$

Where; X is the bridge users comparison matrix; and x_{ij} is an “m x n” matrix; where, ‘m’ represents the technical measures and ‘n’ represents the bridge components that display the score of bridge user ‘i’ on bridge component ‘j’. TOPSIS analysis comprises the following consecutive five steps: (i) normalized decision matrix; (ii) weighted normalized decision matrix; (iii) ideal and negative ideal solutions; (iv) bridge components separation measures; and (v) relative closeness to ideal solution as shown in Figure 6.4.

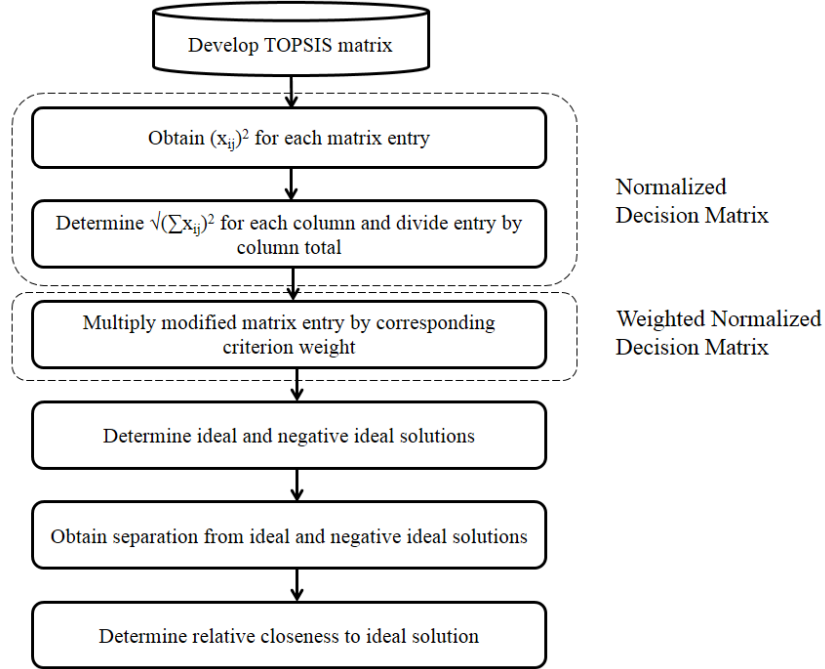


Figure 6.4 TOPSIS Process Flow

In this study, Hwang et al. (1993) numerical methodology is deployed based on its direct applicability to ranking bridge MR&R priorities and proven reliability. Generating the normalized decision matrix is intended to convert various parametric dimensions into non-dimensional parameters to allow for contrasting among criteria using Hwang et al. (1993) equation (6.22):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum x_{ij}^2}} \quad (6.22)$$

Where; r_{ij} is the normalized scoring value of bridge users on bridge components. Afterwards, the development of a weighted decision matrix is obtained by multiplying the importance weights

determined from equations (6.8) and (6.20) by its corresponding column of the normalized decision matrix obtained from equation (6.22) through the deployment of Hwang et al. (1993) equation (6.23):

$$v_{ij} = w_i \times r_{ij} \quad \text{where } w_i = e_m^* e_t \quad (6.23)$$

Where; v_{ij} is the weighted normalized element of the TOPSIS matrix, and w_i is the final importance weight, e_t is the importance weight of technical measure, and e_m is the importance weight of bridge component. Afterwards, the ideal and negative ideal solutions are determined using Hwang et al. (1993) equations (6.24) and (6.25):

$$A^* = \{v_1^*, \dots, v_j^*\} \quad (6.24)$$

$$A' = \{v_1', \dots, v_j'\} \quad (6.25)$$

Where; A^* is the positive ideal solution; where $v_j^* = \{\max v_{ij}\}$ if $j \in J$; minimum v_{ij} if $j \in J'$; A' is the negative ideal solution where $v_j' = \{\min v_{ij}\}$ if $j \in J$; maximum v_{ij} if $j \in J'$; where J is the set of positive attributes or criteria; and J' is the set of negative attributes or criteria. Afterwards, bridge competitors' separation measures from ideal and negative ideal solutions are calculated by using Hwang et al. (1993) equations (6.26) and (6.27):

$$S_i^* = \left[\sum (v_j^* - v_{ij})^2 \right]^{1/2} \quad (6.26)$$

$$S_i' = \left[\sum (v_j' - v_{ij})^2 \right]^{1/2} \quad (6.27)$$

Where; S_i^* is the separation from the positive ideal solution; S_i' is the separation from the negative ideal solution; and i is the number of bridge competitors. Finally, relative closeness to ideal solution is calculated by using Hwang et al. (1993) equation (6.28):

$$C_i^* = \frac{S_i'}{(S_i^* + S_i')} \quad ; \quad 0 < C_i^* < 1 \quad (6.28)$$

Where; C_i^* is the relative closeness to positive ideal solution. The highest-ranked bridge component for MR&R priorities is the one with a corresponding C_i^* closest to the value of unity '1'.

6.6.3 Gamma Deterioration Model

Typically, bridge deteriorations are mainly caused by chemical and/or physical mechanisms that significantly affect infrastructure material characteristics and subsequent components. In this study, the deterioration of an aging bridge infrastructure is typically modelled as a function of its resistance capacity. The deterioration function is defined as per Noortwijk et al. (2007) in equation (6.29):

$$D(t) = R_o - R(t_k) \quad (6.29)$$

Where $D(t)$ is the deterioration function, R_o is the initial resistance, and $R(t_k)$ is the resistance at time t_k . The deterioration function is assumed to be an ascending-order process with independent deterioration time intervals. For instance, suppose a sequence of shock load effects occur at discrete times such that the overall bridge service period is divided into independent time intervals. Hence, the resistance deterioration function, $R(t_k)$, at time t_k , is represented as equations (6.30) and (6.31) from Wang et al. (2015):

$$R(t_k) = R_o \times D(t_k) \quad (6.30)$$

$$D(t_k) = 1 - \sum_{i=1}^k G_i \quad \text{where, } k = 1, 2, \dots, n \quad (6.31)$$

Where $R(t_k)$ is the resistance deterioration function, R_o is the initial resistance; $D(t_k)$ is the deterioration at time t_k ; and $G_i \sim Ga(\gamma, \beta)$ denotes a gamma function with the shape parameter, γ , and the scale parameter, β . It is important to note that equation (6.30) is a descending-order process with a corresponding mean and variance calculated as per Wang et al. (2015) in equations (6.32-a), (6.32-b), and (6.32-c):

$$\mu[D(t_k)] = 1 - \beta \times \sum_{i=1}^k \gamma_i \quad (6.32-a)$$

$$\sigma^2[D(t_k)] = \beta^2 \times \sum_{i=1}^k \gamma_i \quad \text{where; } k = 1, 2, \dots, n \quad (6.32-b)$$

$$\gamma_i^* = \kappa \times (t_i^\gamma - t_{i-1}^\gamma) \quad (6.32-$$

c)

Where μ is the mean; $D(t_k)$ is the deterioration at time t_k ; σ^2 is the variance, γ_i^* is the deterioration parameter; β is the scale parameter; and κ is the rate of deterioration. It is important to note that the scale and shape parameters presented herein are assigned as deterioration parameters of random variables and are determined independently.

6.6.4 Determination of Deterioration Function

Typically, bridge element conditions are evaluated by conducting site inspections based on municipal and/or national standards. These inspections contribute significantly towards the resistance deterioration condition of bridge elements and reflect their existing state which may be predicted as a ratio of the existing deterioration resistance to its initial resistance as per Wang et al. (2015), in equation (6.33):

$$D(t_k) = \frac{R_k}{R_o} \quad (6.33)$$

Where $D(t_k)$ is the deterioration function at time t_k ; R_k is the current resistance deterioration function at time t_k ; and R_o is the initial resistance. The existing resistance deterioration function R_k , and the initial resistance R_o , are typically estimated according to bridge design manuals and national code standards. Bridge deterioration resistance is rarely assessed due to the high costs incurred, which implies that very little or no information on existing bridge resistance is

available. Hence, this study proposes a numerical method to estimate deterioration parameters based on previous data of similar bridges.

6.6.4.1 Estimation of Deterioration Parameters

In order to estimate the deterioration parameters (γ) and (β), the shape and scale deterioration function $D(t_k)$ presented in equation (6.33) will be utilized to determine the deterioration of similar existing bridges k , with a corresponding service life of $t_1, t_2, \dots, t_k$. By substitution, the deterioration function is presented as per Wang et al. (2015) in equation (6.34):

$$1 - D(t)_i = \beta \times \kappa \times (t_i)^\gamma \quad \text{where; } i = 1, 2, \dots, k \quad (6.34)$$

Where $D(t_i)$ is the deterioration at time t_i ; γ and β are the random shape and scale and deterioration parameters, and κ is the rate of deterioration. By taking the logarithmic for both sides of equation (6.34), the deterioration function is expressed as per Wang et al. (2015) in equation (6.35):

$$\ln(1 - D(t)_i) = \ln(\beta \times \kappa) + \gamma \ln(t_i) \quad (6.35)$$

Now, the deterioration parameters γ and β can be estimated graphically by utilizing a regression analysis of previous similar bridges' deterioration data; where the slope γ is the ratio of $\ln(1 - D(t)_i)$ to $\ln(t_i)$ and the y-intercept is $\beta \times \kappa$. In equation (6.32-b), the variance does not

account for the dynamic nature of the temporal deterioration function. Hence, an average variance formulation is presented as per Wang et al. (2015) in equation (6.36):

$$\hat{\beta}^2 \times \hat{\kappa} \times \sum_{i=1}^k t_i^{\hat{\gamma}} = \sum_{i=1}^k (D(t)_i - \hat{D}(t_i))^2 \quad \text{where ;} \quad (6.36)$$

$$\hat{\beta} = \frac{\sum_{i=1}^k (D(t)_i - \hat{D}(t_i))^2}{\hat{\beta} \times \hat{\kappa} \times \sum_{i=1}^k t_k^{\hat{\gamma}}} \quad \text{and} \quad \hat{\kappa} = \frac{\hat{\beta} \times \hat{\kappa}}{\hat{\beta}}$$

Where $\hat{\gamma}$ and $\hat{\beta}$ are the estimated shape and scale deterioration parameters respectively; $\hat{\kappa}$ is the estimated rate of deterioration; $D(t_i)$ is the deterioration at time t_i ; and $\hat{D}(t_i)$ is the estimated deterioration at time t_i .

6.7 System Implementation

The implementation of the decision support system is undertaken in two main steps; i) perturbation; and ii) quality evaluation. The algorithm is implemented as a probabilistic distribution function such that a random deterioration variable, D , possesses a standard Gamma distribution of a distinguished shape parameter, γ , and scale parameter, β , defined as per Johnson et al. (1995) in equation (6.37):

$$f_D(x) = \frac{\left(\frac{x}{\beta}\right)^{\gamma-1}}{\beta \Gamma(\gamma)} e^{\left(\frac{-x}{\beta}\right)} \quad \text{where; } x, \gamma, \text{ and } \beta \geq 0 \quad (6.37)$$

Where x is the deterioration parameter, γ is the shape parameter, β is the scale parameter, and Γ is the gamma function defined as per Johnson et al. (1995) in equation (8.38):

$$\Gamma(\gamma) = \int_0^{\infty} x^{\gamma-1} e^{-x} dt \quad (6.38)$$

In this study, a gamma model with shape and scale parameters greater than zero is assumed to be a continuous stochastic model if the following conditions are satisfied: i) probability of $D(0) = 0$ is unity; ii) $D(t)$ comprises independent deterioration increments; and iii) increments follow a gamma function such that the mean and variance are determined as per Johnson et al. (1995) in equation (6.39):

$$\mu[D(t)] = \gamma \times \beta \quad \text{and} \quad \sigma^2[D(t)] = \gamma \times \beta^2 \quad (6.39)$$

Where μ is the mean, σ^2 is the variance, γ is the shape parameter, and β is the scale parameter.

6.7.1 Quality of Fitting

Although regression analysis is capable of modeling a data scatter, significant variance may be noticed in the manner it represents the actual data value. Testing the quality of fit of a regression analysis trend line is typically conducted by either of the two following procedures: 1) heuristic,

where manual inspection is conducted in parallel with an error minimization procedure; or 2) non-heuristic procedure, where hypothetical procedures such as the Chi-square test are deployed. In order to ease the use of regression analysis, the manual inspection of trend line fitting with an error minimization procedure is adopted since such fittings are automatically generated with advanced modeling software available in the market. The procedure is based on adjusting the fitted trend line to minimize the error. The sum (E) of the squares of differences between the actual and proposed trend line fit is then minimized to obtain the magnitude of adjustment factor that results in the best fit with the actual data scatter. The error minimization procedure is identified as per equation (6.40):

$$E_{\min} = \sum_{i=1}^n \left[\frac{d_{act,i} - a(d_{pro,i})}{\bar{d}_{act,i}} \right]^2 \quad (6.40)$$

Where $E_{\min}$ is the minimized error, $i = 1 \dots n$ is the number of actual data scatters, $d_{act,i}$ is the actual data value at the i^{th} location, $d_{pro,i}$ is the proposed data value at the i^{th} location, and a is a scaling factor to be applied to the proposed trend line. It is noted that the bracketed terms in equation (6.20) have been normalized with respect to the average of actual data, $\bar{d}_{act,i}$ as per equation (6.41):

$$\bar{d}_{act,i} = \frac{1}{n} \sum_{i=1}^n d_{act,i} \quad (6.41)$$

Towards the end, it is important to note that the proposed trend line fit contributes towards an accurate estimation of the shape and scale deterioration parameters such that error tolerances are respected.

6.7.1.1 Probabilistic Matrix Factorization

As part of enhancing dataset quality, filtering algorithms to determine interrelationships among deterioration parameters are investigated. The matrix factorization approach is found to be the most effective amongst the examined techniques due to its latent feature in determining the underlying correlations amongst independent variables. In this study, a probabilistic matrix factorization technique is deployed to predict deterioration datasets of existing bridges while overcoming biased and over-fitted values. The model-based approach is undertaken by the following four main processes: (1) singular value matrix decomposition (SVMD); (2) data normalization; (3) factorization; and (4) regularization. Firstly, the matrix decomposition process is deployed to predict resistance deterioration values, $\mu[g(t)]$, of a bridge component as per Takács et al. (2008), in equation (6.42):

$$\hat{r}_{ij} = p_i^T q_j = \sum_1^k p_{ik} q_{kj} \quad (6.42)$$

Where $\hat{r}_{ij}$ is the predicted resistance deterioration; p_i^T is the bridge preference factor vector; q_j is the resistance deterioration factor vector; p_{ik} is the bridge preference factor matrix; and q_{kj} is the resistance deterioration factor matrix such that the dot product of p_{ik} and q_{kj} approximates the $\hat{r}_{ij}$. Afterwards, a gradient descent technique is deployed in order to determine the bridge

preference and resistance deterioration factor vectors p_i^T and q_j respectively. The error between the predicted and actual resistance deterioration value to obtain a local minima of each ‘bridge-resistance deterioration’ pair is determined as per Takács et al. (2008) as in equation (6.43):

$$e^2_{ij} = (r_{ij} - \hat{r}_{ij})^2 = (r_{ij} - \sum_1^k p_{ik} q_{kj})^2 \quad (6.43)$$

Where; e^2_{ij} is the squared error difference; r_{ij} is the actual resistance deterioration; $\hat{r}_{ij}$ is the predicted resistance deterioration; p_{ik} is the bridge preference factor matrix; and q_{kj} is the resistance deterioration factor matrix. It is important to note that the squared error of the predicted and actual resistance deterioration data is implemented in order to account for over- or under-estimated values.

6.7.1.2 Error Minimization

In order to minimize the error value, a modification to p_{ik} and q_{kj} matrices is required to determine the value of the gradient at its present state. Hence, a differentiation of equation (6.43) with respect to p_{ik} is deployed as per Takács et al. (2008) in equation (6.44):

$$\begin{aligned} \frac{\partial}{\partial p_{ik}} e^2_{ij} &= -2(r_{ij} - \hat{r}_{ij})(q_{kj}) = -2e_{ij} q_{kj} \\ \frac{\partial}{\partial q_{kj}} e^2_{ij} &= -2(r_{ij} - \hat{r}_{ij})(p_{ik}) = -2e_{ij} p_{ik} \end{aligned} \quad (6.44)$$

Where e_{ij}^2 is the squared error difference; e_{ij} is the error difference; r_{ij} is the actual resistance deterioration; $\hat{r}_{ij}$ is the predicted resistance deterioration; p_{ik} is the bridge preference factor matrix; and q_{kj} is the resistance deterioration factor matrix. Upon determination of the gradient descent value, the differentiation of equation (6.23) is rearranged as per Takács et al. (2008) in equation (6.45):

$$\begin{aligned} p'_{ik} &= p_{ik} + \alpha \frac{\partial}{\partial p_{ik}} e_{ij}^2 = p_{ik} + 2\alpha e_{ij} q_{kj} \\ q'_{kj} &= q_{kj} + \alpha \frac{\partial}{\partial q_{kj}} e_{ij}^2 = q_{kj} + 2\alpha e_{ij} p_{ik} \end{aligned} \quad (6.45)$$

Where p'_{ik} is the differentiated bridge preference factor matrix; q'_{kj} is the differentiated resistance deterioration factor matrix; e_{ij}^2 is the squared error difference; α is the gradient descent rate factor; e_{ij} is the error difference; p_{ik} is the bridge preference factor matrix; and q_{kj} is the resistance deterioration factor matrix. It is important to note that the α factor in equation (6.45) is the tolerance value that defines the rate of gradient descent approaching the minimum. In order to avoid excessive oscillations and bypassing the local minima, a modification factor α , with a value of 0.0002 is assumed. In this study, the error minimization procedure is proposed for the bridge-resistance deterioration pairs. For instance, let N be a finite ordered set of training data in the form of $(q_{kj}, p_{ik}, \hat{r}_{ij})$, the error, e_{ij} , for each iterative dataset will be minimized when the connotations amongst the attributes is learnt. Afterwards, the error

minimization process is concluded when the iteratively determined error converges to its minimum as per Takács et al. (2008) in equation (6.46):

$$E = \sum_{(q_{kj}, p_{ik}, \hat{r}_{ij}) \in N} (r_{ij} - \sum_1^k p_{ik} q_{kj})^2 \quad (6.46)$$

Where E is the minimized error value; q_{kj} is the resistance deterioration factor; p_{ik} is the bridge preference factor matrix; $\hat{r}_{ij}$ is the predicted resistance deterioration; and r_{ij} is the actual resistance deterioration.

6.7.1.3 Regularization

In order to avoid dataset over-fitting, a regularization process is implemented by incorporating a parameter factor γ , to regularize the magnitudes of the bridge-deterioration resistance factor vectors. Also, a regularization parameter γ with a value of 0.02 is assumed in order to avoid large number approximations and achieve a better approximation of the bridge deterioration resistance capacity. The squared-error difference between the predicted and actual resistance deterioration value to obtain a local minima of each ‘bridge-resistance deterioration’ pair is rearranged as per Takács et al. (2008) in equation (6.47):

$$e^2_{ij} = (r_{ij} - \hat{r}_{ij})^2 = (r_{ij} - \sum_1^k p_{ik} q_{kj})^2 + \frac{\gamma}{2} \sum_1^k (\|p_{ik}\|^2 + \|q_{kj}\|^2) \quad (6.47)$$

Where e^2_{ij} is the squared error difference; r_{ij} is the actual resistance deterioration; and $\hat{r}_{ij}$ is the predicted resistance deterioration; p_{ik} is the bridge preference factor matrix; and q_{kj} is the

resistance deterioration factor matrix. Upon determination of the squared error difference, the differentiation of the equation (6.43) is rearranged as per Takács et al. (2008) in equation (6.48):

$$\begin{aligned} p'_{ik} &= p_{ik} + \alpha \frac{\partial}{\partial p_{ik}} e^2_{ij} = p_{ik} + \alpha(2e_{ij}q_{kj} - \gamma p_{ik}) \\ q'_{kj} &= q_{kj} + \alpha \frac{\partial}{\partial q_{kj}} e^2_{ij} = q_{kj} + \alpha(2e_{ij}p_{ik} - \gamma q_{kj}) \end{aligned} \quad (6.48)$$

Where p'_{ik} is the differentiated bridge preference factor matrix; q'_{kj} is the differentiated resistance deterioration factor matrix; e^2_{ij} is the squared error difference; α is the gradient descent rate factor; γ is the regularization parameter; e_{ij} is the error difference; p_{ik} is the bridge preference factor matrix; and q_{kj} is the resistance deterioration factor matrix.

6.8 System Validation

To validate the workability of the proposed system, a case study of a bridge in Ottawa, Canada composed of a concrete box-girder with a total span of 200 ft. supported with a central interior bent at 100 ft. is developed in CSiBridge as illustrated in Figure 6.5. The challenge underlying the system validation is to provide priority ranking to MR&R decisions for the diverse bridge components.

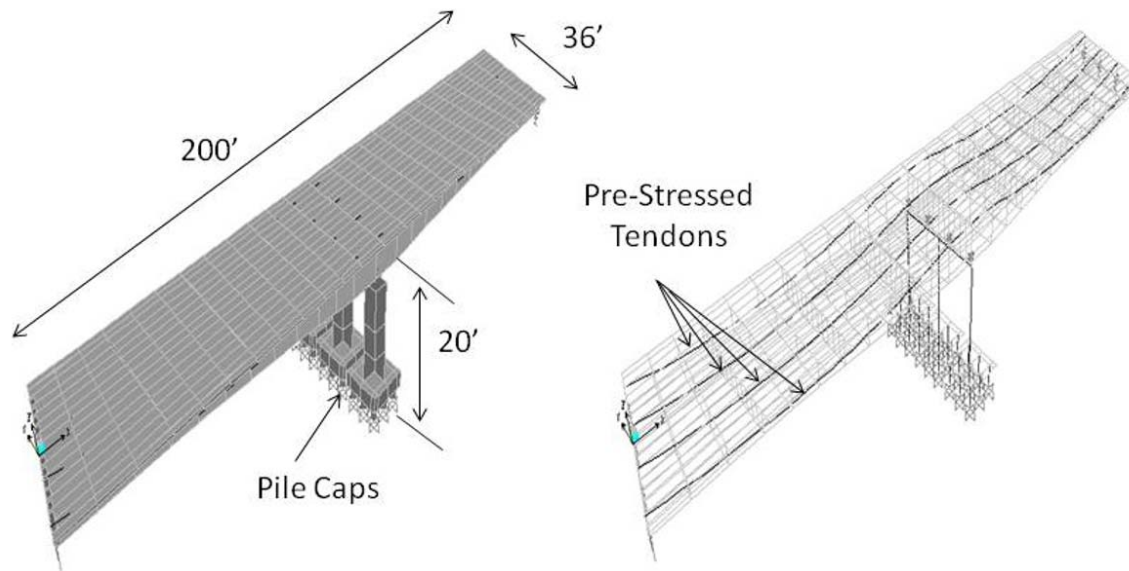


Figure 6.5 Conceptual Bridge Design Information Model

Prior to inputting project related data into BrIM tool, the following list summarizes main parametric design assumptions: 1) Abutment: skewed at 15 degrees and supported at bottom girder only; 2) Pre-stressing: 4 nos. 5 in² tendons with a 1,080 kips capacity each; 3) Interior bent: 3 nos. 5 ft square columns; 4) Deck: parabolic variation ranging from 5-10 ft in nominal depth; 5) Pile cap: 3 nos. 13' x 13' x 4'; and 6) Pile: 9 nos. 14" dia. steel pipe filled with concrete reinforced with 8 nos. of #9 reinforcement bars at each pile cap. It is important to note that the aforementioned assumptions are made based on normal job conditions. However, if geographical constraints are 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 influence overall project cost. The systematic procedure of the integrated system is demonstrated in a step-by-step process in Figures 6.6 through 6.12 which

present snapshots of the proposed system modules. Figure 6.6 presents the integrated deterioration gateway module.

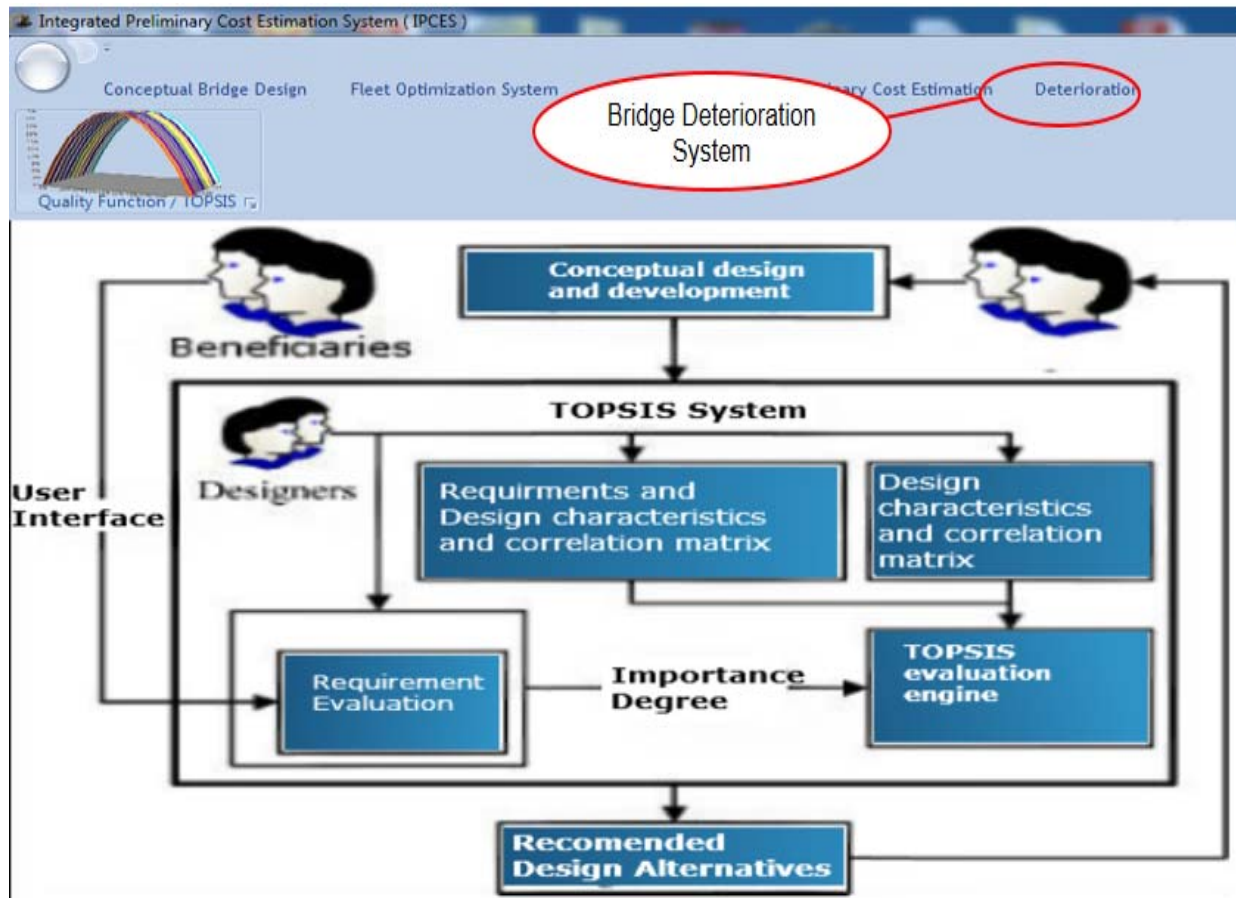


Figure 6.6 Deterioration System Gateway Module

Once the user selects the desired deterioration module, the system displays a module within the activity main module where the user inputs importance rating on bridge components as shown in Figure 6.7.

Whats	C1	C2	C3	C4	C5	C6	C7	C8	C9
W1. Beam	High	High Important	High	Moderate Important	Moderate High	High	High Important	High	Moderate High
W2. Truss	Moderate High	High	Moderate High	High Important	Important	Moderate High	High	High Important	Low
W3. Cable-Stayed	Very High	High Important	High	Moderate High	Moderate High	Very High	High Important	Moderate Important	
W4. Tied Arch	Moderate Important	High	Moderate High	Moderate Important	High Important	Important	High Important	Moderate Important	Moderate Important
W5. Arch	Very High	High	High Important	Important	Moderate Important	High Important	Moderate High	High Important	High
W6. Suspension	Moderate High	Moderate Important	Moderate Low	Low	Important	Moderate High	High	High Important	Important
W7. Double-Decker	High	Moderate High	Moderate Important	Very High	High	Moderate Important	Important	Moderate High	Important
W8.	Moderate	Important	High	Moderate	High	High	High	Moderate	Moderate

Figure 6.7 Bridge User Importance Rating on Bridge Components

Following bridge user's assessment on the importance of relative bridge components on bridge alternatives, relative importance perception ratings in crisp and fuzzy forms are obtained according to equations (6.1) and (6.2). Figure 6.8 illustrates the rating for the Stakeholders/Government; whereas similar rating is conducted for the other users.

Whats	C1.Crisp	C1.Fuzzy	C2.Crisp	C2.Fuzzy	C3.Crisp	C3.Fuzzy	C4.Crisp	C4.Fuzzy	C5.Crisp	C5.Fuzzy
W1. Beam	7	[6.8]	6	[5.7]	7	[6.8]	5	[4.6]	8	[7.9]
W2. Truss	8	[7.9]	7	[6.8]	8	[7.9]	6	[5.7]	4	[3.5]
W3. Cable-Stayed	9	[8.10]	6	[5.7]	7	[6.8]	8	[7.9]	8	[7.9]
W4. Tied Arch	5	[4.6]	7	[6.8]	8	[7.9]	5	[4.6]	6	[5.7]
W5. Arch	9	[8.10]	7	[6.8]	6	[5.7]	4	[3.5]	5	[4.6]
W6. Suspension	8	[7.9]	5	[4.6]	2	[1.3]	3	[2.4]	4	[3.5]
W7. Double-Decked	7	[6.8]	8	[7.9]	5	[4.6]	9	[8.10]	7	[6.8]
W8. Movable	8	[7.9]	4	[3.5]	6	[5.7]	4	[3.5]	7	[6.8]
W9. Cantilever	9	[8.10]	7	[6.8]	8	[7.9]	5	[4.6]	6	[5.7]

Whats	C6.Crisp	C6.Fuzzy	C7.Crisp	C7.Fuzzy	C8.Crisp	C8.Fuzzy	C9.Crisp	C9.Fuzzy	Relative Imp Ratings Crisp	Relative Imp Ratings Fuzzy
W1. Beam	7	[6.8]	6	[5.7]	7	[6.8]	8	[7.9]	6.78	[60.62]
W2. Truss	8	[7.9]	7	[6.8]	6	[5.7]	3	[2.4]	6.33	[56.58]
W3. Cable-Stayed	9	[8.10]	6	[5.7]	5	[4.6]	7	[6.8]	7.22	[64.66]
W4. Tied Arch	4	[3.5]	6	[5.7]	5	[4.6]	5	[4.6]	5.67	[50.52]
W5. Arch	6	[5.7]	8	[7.9]	6	[5.7]	7	[6.8]	6.44	[57.59]
W6. Suspension	8	[7.9]	7	[6.8]	6	[5.7]	4	[3.5]	5.22	[46.48]
W7. Double-Decked	5	[4.6]	4	[3.5]	8	[7.9]	4	[3.5]	6.33	[56.58]
W8. Movable	6	[5.7]	7	[6.8]	8	[7.9]	5	[4.6]	6.22	[55.57]
W9. Cantilever	6	[5.7]	5	[4.6]	6	[5.7]	7	[6.8]	6.56	[58.60]

Figure 6.8 Relative Importance Rating on Bridge Components

Afterwards, a bridge users' competitive matrix is developed based on equations (6.3) and (6.4). Then, the probability distribution and corresponding measure of entropy of bridge components is determined by using equations (6.5) through (6.8) as shown in Figure 6.9.

Whats	C1	C2	C3	C4	C5	C6	C7	C8	C9	em
W1. Beam	7	6.25	6.75	5.75	7.5	6	6.75	6.25	6.5	0.11
W2. Truss	6.5	6	5.5	5	7	5.75	6.25	6.25	6.5	0.11
W3. Cable-Stayed	7.5	5.75	5.25	8.25	7	6	3.25	7.5	6	0.11
W4. Tied Arch	4.75	6.5	5.75	5.75	4.75	3.75	5.75	5.25	6.25	0.11
W5. Arch	5.5	5.75	5.5	3.75	5.5	7	6.5	6.25	5.25	0.11
W6. Suspension	6.25	5	4.75	4.75	5.25	7	6.75	5.25	6.75	0.11
W7. Double-Decked	6.75	5.5	6	6.25	7.5	5	6	7.25	5.75	0.11
W8. Movable	8	5.5	6.75	5.75	4.75	5.5	4	5.25	4	0.11
W9. Cantilever	7.75	6	6.25	4.25	7	6.5	5	5.5	6.5	0.11

Figure 6.9 Bridge Users Competitive Matrix on Bridge Components

Once completed, the user can proceed with inputting a set of improvement goals for bridge components as illustrated in Figure 6.10.

Whats	Goals
Abutment	9
Approach Slab	8
Bearings	9
Deck Slab	7
Expansion Joint	8
Foundation	8
Girder	9
Parapet	9

Figure 6.10: Improvement Goals for Bridge Components

Following the input of goals, the user can proceed with TOPSIS operations by clicking on TOPSIS matrix to develop priority rankings of bridge components as shown in Figures 6.11 and 6.12.

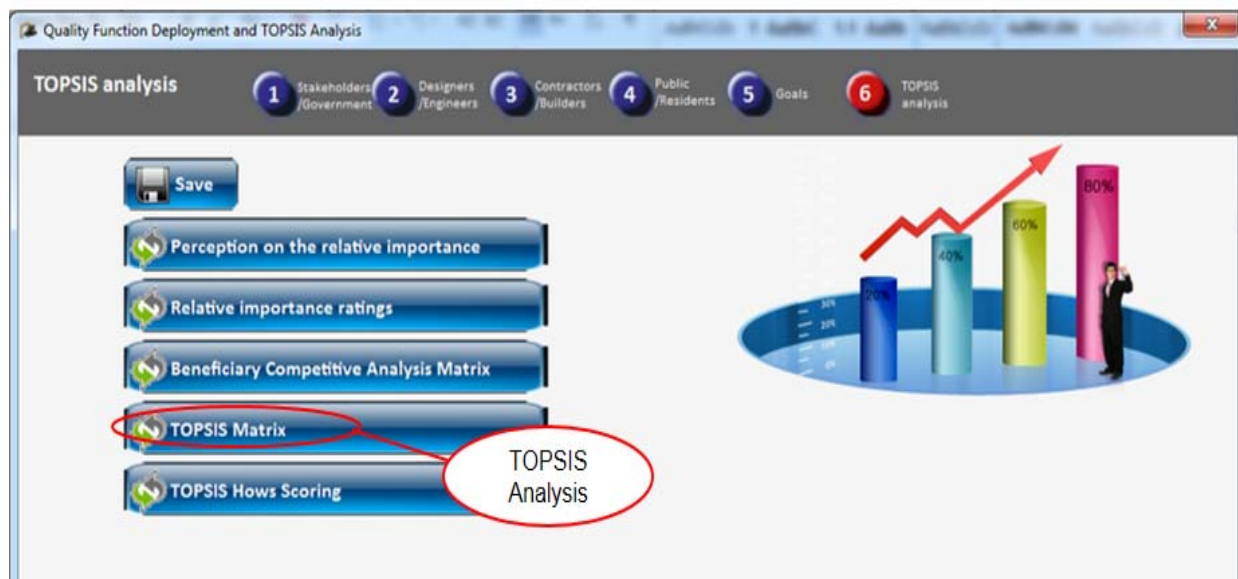


Figure 6.11 TOPSIS Analysis Module

FinalTOPSIS	Description
0.7153	Approach Slab
0.5583	Girder
0.5428	Parapet
0.5076	Pier
0.5045	Expansion Joint
0.4853	Foundation
0.4798	Deck Slab
0.4054	Bearings
0.3249	Abutment

Bridge Components Ranking

Relative closeness to Ideal Solution

TOPSIS	Description
0.7153	Approach Slab

First-Rank Component

Figure 6.12 Final Ranking of Bridge Components

As shown in Figure 6.12, bridge components ‘C₁.Approach Slab; ‘C₅.Girder’; and ‘C₄.Parapet’ possess maximum weights followed by ‘C₈.Pier; ‘C₃.Expansion Joint; ‘C₉.Foundation; and ‘C₂.Deck Slab; while, ‘C₆.Bearings and ‘C₇.Abutment’ components possess the minimum weights. Typically, bridges are designed while taking into account the following main criteria: (1) Girder; (2) Pier; and (3) Foundation. However, by deploying the complex quality function technique, it is determined that incorporating additional bridge users, such as contractors/builders and public/residents, influence bridge components importance weights; and hence, explicitly implying a more realistic and practical decision support system. With approach slab and girder components being the most expensive and contribute significantly towards construction costs, it has been determined that its importance weight is at the highest rank. On the other hand, the bearings and abutment components are determined to possess the least importance weight. Typically, bridge piers and foundation have been ranked first at the bridge conceptual design stage since they are the major components for bridge projects. However, in this study, bridge pier and foundation are ranked second based on bridge users’ relative importance perception scorings.

This implies that bridge users did not anticipate deterioration on piers to affect bridge performance as opposed to the approach slab, girder, and parapet components. Following the determination of components rankings, the user is guided to the HOWs scoring input form where the user inputs importance rating on bridge maintenance, repair, and replacement alternatives as shown in Figure 6.13.

The screenshot shows a software window titled "Quality Function Deployment and TOPSIS Analysis". At the top, there are five tabs: "Stakeholders/Government" (selected), "Designers/Engineers", "Contractors/Builders", "Public/Residents", and "TOPSIS analysis". Below the tabs is a grid for rating bridge components (Whats) against alternatives (Hows). The grid has 9 columns (S1-S9) and 8 rows (Abutment, Approach Slab, Bearings, Deck Slab, Expansion Joint, Foundation, Girder, Parapet). A red circle highlights the "Bridge MR&R Alternatives" section, which includes buttons for "Measure", "Crisp", and "Fuzzy".

Whats	S1	S2	S3	S4	S5	S6	S7	S8	S9
Abutment	High Important	Moderate Important	High	Important	High	High Important	Moderate Important	High Important	High
Approach Slab	High	High Important	Moderate High	Moderate Important	Low	High	High Important	Moderate Important	Moderate Low
Bearings	Moderate High	Moderate Important	High	High				Important	High Important
Deck Slab	Important	High Important	Moderate High	Important	Moderate Important	Low	Moderate Important	Important	Important
Expansion Joint	Moderate High	High Important	High Important	Low	Important	Moderate Important	High	Moderate Important	High Important
Foundation	High	Important	Moderate Low	Moderate Low	Low	High	High Important	Moderate Important	Low
Girder	High Important	High	Moderate Important	Moderate High	High Important	Important	Low	High	Low
Parapet	High	Low	High	Important	High	Moderate	High	High	Important

Figure 6.13 Bridge User Importance Rating on MR&R Alternatives

Following bridge user's assessment on the importance of relative bridge components on bridge MR&R alternatives, relative importance perception ratings in crisp and fuzzy forms are obtained according to equations (6.1) and (6.2). Afterwards, a bridge users' competitive matrix is developed based on equations (6.3) and (6.4). Then, the probability distribution and corresponding measure of entropy along with competitive ranking of bridge components is determined by using equations (6.5) through (6.8) and (6.11) respectively as shown in Figure 6.14.

Whats	S1	S2	S3	S4	S5	S6	S7	S8	S9	em	
Abutment	4.5	Competitive Ranking of Bridge Components	3.75	4.75	3.5	4.5	4	3.75	0.11		
Approach Slab	3		2.75	5.25	3	3.75	3.75	4	0.11		
Bearings	4.5		3.5	2.75	5.5	4.25	3	1.25	5.5	3.5	0.11
Deck Slab	2.75		4	3.25	3.75	2.75	2.5	3.75	3.25	4.25	0.11
Expansion Joint	2.5		3.25	3.25	2	3.5	4.75	3.75	4	2.75	0.11
Foundation	3.5		3	3.5	3.25	3.5	4.25	4.25	3	5	0.11
Girder	4.25		2.75	4	3.25	5	3	4.25	4.5	4	0.11
Parapet	5.25		2.5	4.5	3.75	2.5	3.25	1.5	2.75	2	0.11
Pier	4.75		4.25	3.5	2.25	4.75	4.25	3.25	3.25	4	0.11

Figure 6.14 Bridge Components Competitive Matrix on MR&R Alternatives

It is important to note that improvement goals to evaluate the competitiveness rating amongst bridge components for diverse bridge type alternatives are set for each component. Accordingly, corresponding improvement ratios and competitive ratings are determined. In comparison with Figure 6.9, bridge component ‘C₁’ possesses the second highest importance weight and competitive rating as opposed to ‘C₇’ which possess the first ranking from an importance standpoint; however, ‘C₅’ had dropped to the seventh ranking in terms of competitiveness. A similar analogy is observed for the other bridge components; such as ‘C₃’ and ‘C₄’. Once completed, a TOPSIS matrix is developed based on equation (6.21). Afterwards, normalized decision and weighted matrices are constructed as per equations (6.22) and (6.23) respectively. Next, the determination of positive and negative ideal solutions is undertaken as per equations (6.24) and (6.25) respectively and set as the reference datum. Towards the end, separations from positive and negative ideal solutions are obtained as per equations (6.26) and (6.27) respectively. Finally, TOPSIS relative closeness to ideal solution decision matrix is obtained according to equation (6.28) with priority ratings as illustrated in Figure 6.15.

FinalTOPSIS	Bridge MR&R Alternative Ranking	Description
0.7014		M15
0.5815		REPA60
0.5138		REPA45
0.5039		REPL90
0.5024		M45
0.4661		REPL100
0.4215		M30
0.3933		REPA75
0.3025		REPL75

Relative closeness to Ideal Solution		First-Rank MR&R Alternative
TOPSIS	Description	
	Relative closeness to Ideal Solution	
0.7014	M15	

Figure 6.15 Final Ranking of Bridge MR&R Alternatives

As illustrated in Figure 6.15, ‘C₁.Approach Slab’ is the bridge component that requires further consideration at the conceptual design stage. Besides that, the MR&R solution ‘S₁.M15’, which implies the maintenance solution when the approach slab component extent of deterioration is at 15%, is the most favorable. On the other hand, ‘REPA60’; which implies the repair solution when approach slab component extent of deterioration is at 60%, is the MR&R solution with the second rank. Based on the afore-mentioned, it is shown that bridge users have no preference to maintenance works when the approach slab extent of deterioration exceeds 15%. Furthermore, the deterioration resistance capacity of the approach slab must be reconsidered at the conceptual design stage in order to withstand a 60% extent of deterioration. Once completed, a deterioration model for each of the bridge components is necessary to predict their time-dependent deterioration behavior. Hence, mean values of the resistance function for the bridge ‘approach slab’ is obtained from previous similar bridges at diverse years throughout their service life. Table 6.2 summarizes approach slab mean deterioration resistance data at diverse years.

Table 6.2 Approach Slab Mean Deterioration Resistance Data at Diverse Years

Time, t (years)	Bridge 1 $\mu[g(t)]$ (%)	Bridge 2 $\mu[g(t)]$ (%)	Bridge 3 $\mu[g(t)]$ (%)
11	-	20.3	11.0
12	26.2	41.2	12.8
13	21.4	-	10.3
14	24.3	24.4	-
15	-	38.3	22.4
16	25.7	23.8	13.4
17	-	26.8	16.4
18	10.4	27.6	15.8
19	26.2	-	15.5
20	-	33.8	-
21	-	34.4	19.1
22	17.4	48.3	-
23	-	34.5	19.8
24	-	39.2	22.3
25	44.1	50.3	29.4

Upon obtaining mean resistance data, the user can then proceed with mean resistance deterioration module as shown in Figure 6.16.

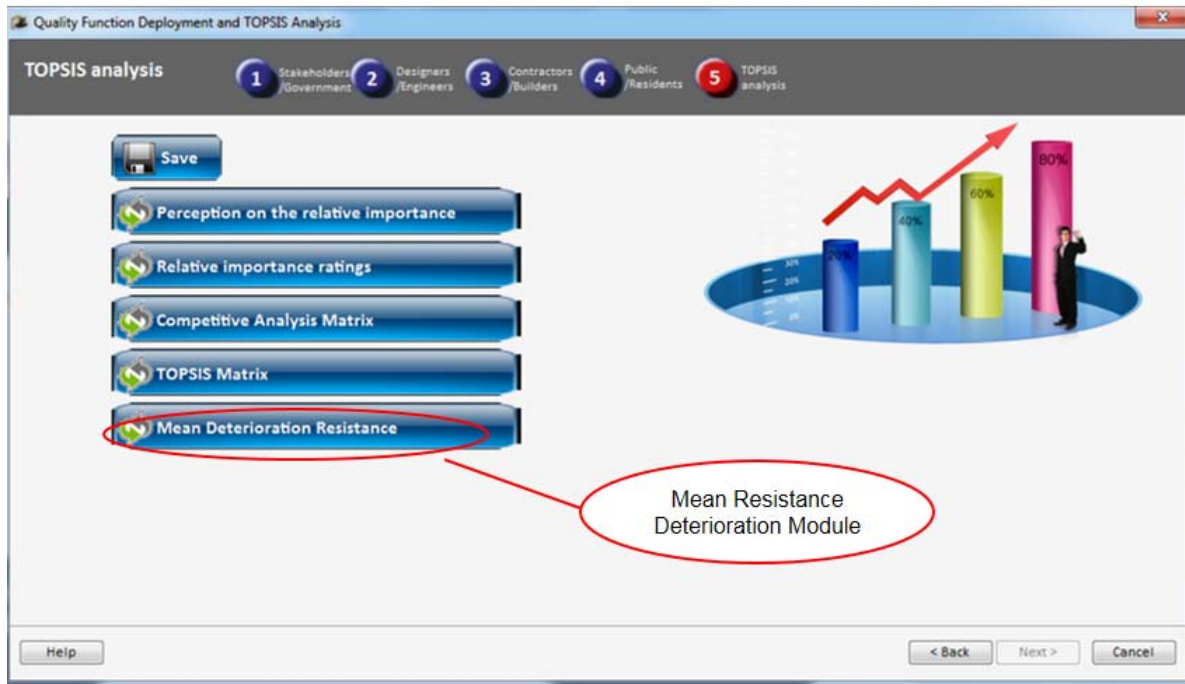


Figure 6.16 Mean Resistance Deterioration Module

Afterwards, the user inputs the year and corresponding mean deterioration percentages such that a regression analysis along with the quality of fit methodology is deployed as illustrated in Figure 6.17.

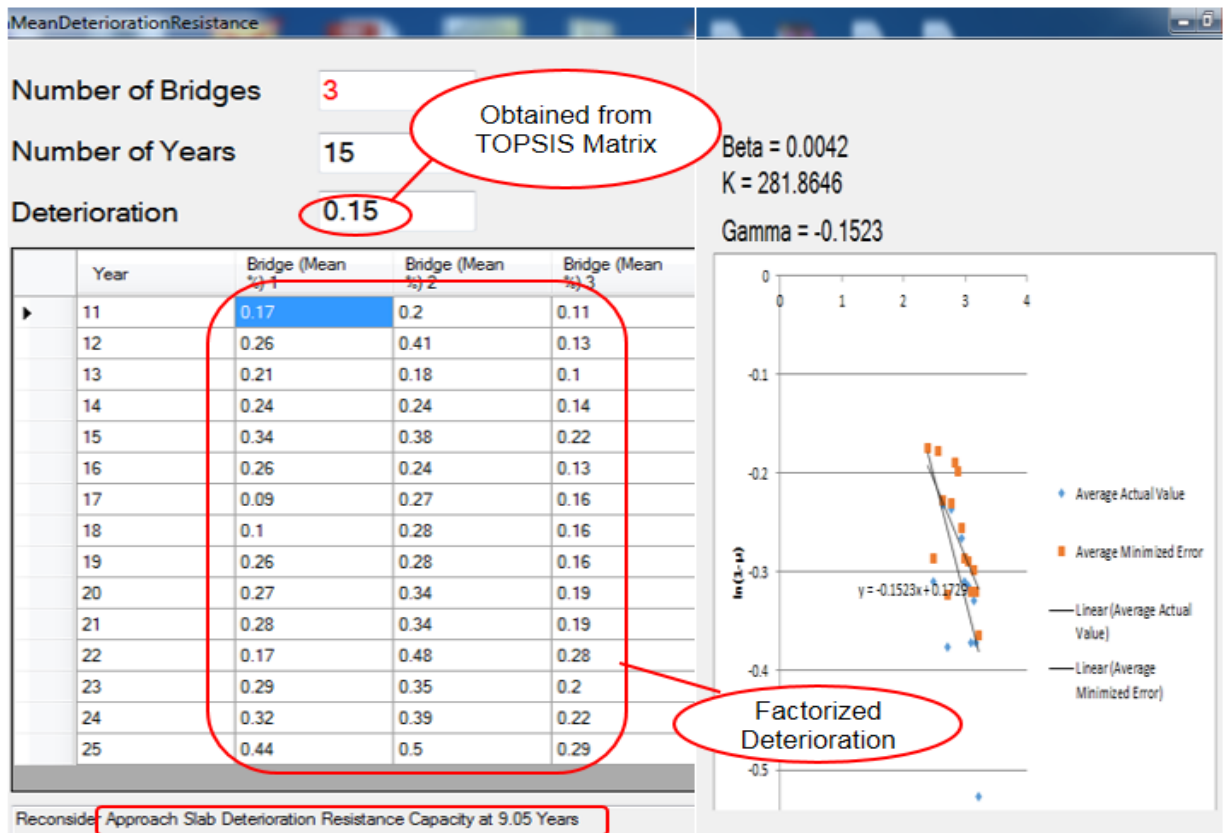


Figure 6.17 'Approach Slab' Regression Analysis at 15% Deterioration

As shown in Figure 6.17, a probabilistic matrix factorization process is deployed to avoid biased and over-fitted values. The proposed technique predicts missing data from Table 6.2. The predicted data is plotted in a scatter fit where a regression analysis is conducted in order to determine the best of fit. Based on equations (6.38) and (6.39), the deterioration parameters, $\hat{\gamma}$ and $\hat{\beta}$, are estimated to be 1.1944 and $\hat{\beta} \times \hat{\kappa} = e^{-4.7878} = 0.00833$ respectively; where $\hat{\beta}$ and $\hat{\kappa}$ are determined as per equation (6.40) and equal to 0.0085 and 0.978 respectively as per the minimized error-fitted trend line. Once completed, the proposed system presents a recommendation statement to reconsider the performance of the approach slab at the conceptual

design stage in order to enhance its corresponding deterioration resistance capacity at the age of 9 years as shown in Figure 6.17.

6.9 Discussion of Results

The proposed system presented herein is capable of forecasting bridge components elemental degradation at the conceptual design stage. It is important to note that the results presented herein are intended for life cycle cost analysis and may be incorporated for allocating preventative maintenance budget at the conceptual design stage of a bridge project. Furthermore, future studies may utilize the findings of this study to enhance the performance of bridge components. In this study, the case study presented herein is used to validate the accuracy of the proposed system; where the results obtained are verified with findings of similar bridges and shared with experienced qualified asset managers and found to be of acceptable form. One limitation of the proposed system; however, underlies the shortage of similar bridges deterioration resistance data which could significantly affect the predicted regression fit and corresponding life cycle cost analysis. Towards the end, the forecasted bridge deteriorations are compared to the actual bridge deteriorations and found to be within a percentage difference ranging from approximately 10 to 15%, as illustrated in Table 6.3.

Table 6.3 Comparison of Forecasted Bridge Maintenance Deterioration Results

Year	System Data (%)	Actual Data (%)	Percentage Difference (%)
5	4.5	5.2	13.5
6	9.4	10.7	12.1
7	12.6	14.7	14.3
8	13.7	16.2	15.4
9	15.3	17.1	10.5

Source: Ministry of Transportation, Highway and Bridges, Ontario

Prior to comparison of results, it is important to note that the discrepancy between the results is due to the multiple assumptions made as well as to the availability of deterioration data for similar bridge projects. For instance, deterioration forecast is based on moderate weather conditions. If severe conditions occur, the forecasting result would be instantly affected. Also, the deterioration forecast is estimated based on a probabilistic matrix factorization approach. The range of variation in maintenance deterioration results is somehow acceptable at the conceptual design stage since the overall information pertaining to the project is neither fully defined nor detailed. Overall results show that the accuracy of the system varies depending on the weather conditions and availability of historical data for similar bridges.

6.10 Summary And Conclusions

In this study, an integrated fuzzy logic decision support system with bridge information management system (BrIMS) in order to assist bridge stakeholders and engineers/designers predict bridge MR&R decisions is proposed. Comparative analyses of diverse bridge components are conducted utilizing complex QFD and TOPSIS systematic approaches to assist users in predicting MR&R decisions at the conceptual design stage. The proposed system is then

validated through a case study and is presently under further development in a .NET framework. The proposed system is found to possess an advantage over existing decision support algorithms and deterioration forecast applications known to the industry by including the following distinguishing features:

- Developing an integrated stand-alone all-in-one system capable of providing the user with recommendations for bridge components MR&R alternatives based on a combination of decision support, probabilistic matrix factorization, and deterioration forecast at the conceptual design stage.
- Facilitating the interoperability and compatibility among the diverse modules, sub-modules and database resources.
- Applicability of the proposed system for the following list of bridge categories anywhere around the globe: (1) beam bridges; (2) truss bridges; (3) cantilever bridges; (4) arch bridges; (5) tied-arch bridges; (6) suspension bridges; (7) cable-stayed bridges; (8) movable bridges; and (9) double-decked bridges regardless of the differences noted in design codes among bridge asset management authorities as system databases presented in this study are designed in such a way that they may be customized to suit accordingly.
- Implementing the TOPSIS technique for BrIM model to assist in prioritizing preventative maintenance, repair, and replacement decisions along with the deployment of complex cyclic gamma shock models for prediction of bridge temporal deteriorations at the conceptual design stage.

Given the scarcity of studies on integrations of fuzzy logic decision support systems with bridge information management systems, the authors are conducting further studies in that field to include life-cycle cost analysis of bridge components. Furthermore, more attention is focused towards the effect of incorporating complex quality functions on prioritizing MR&R decisions for bridge components. The authors are presently working on the expansion of the probabilistic and numerical model databases of solutions, which is an important step towards developing rational design rules for bridge components.

Finally, it is concluded that the proposed system possesses design and prediction limitations pertaining to complex and combined bridge sub- and super-structure designs. It is necessary to mention that the proposed system is developed as a validation tool that may be utilized to predict and prioritize MR&R decisions to components for diverse bridge alternatives. The proposed system may be utilized in the design of bridge projects compiled with BrIMS integration. This capability provides the system a great advantage over other management information algorithms, prototypes, or models published in the literature. Also, the results presented in this study are anticipated to be of major significance to the bridge construction industry and would be a novel contribution to advancements in BrIMS integrations with deterioration forecast at the conceptual design stage of bridge projects.

6.11 References

Bogdanoff J. (1978). A new cumulative damage model-part 1. *Journal of Applied Mechanics*, 45(2), 246-250.

Chan L. and Wu M. (2005). A systematic approach to quality function deployment with a full illustrative example. *Omega*, Elsevier Ltd, 33, 119-139.

Edirisinghe R., Setunge S., Zhang G. (2013). Application of gamma process for deterioration prediction of buildings from discrete condition data. *Sri Lankan Journal of Applied Statistics*, Institute of Applied Statistics, 12, 13-26.

Frangopol D., Kong J., and Gharaibeh E. (2001). Reliability-based life-cycle management of highway bridges. *Journal of Computing in Civil Engineering*, ASCE, 15(1), 27-34.

Golabi K., Thompson P., and Hyman W. (1993). PONTIS Version 2.0 Technical Manual: A network optimization system for bridge improvements and maintenance. Report FHWA-SA-94-031, Office of Technology Applications, Washington, DC.

Hawk H. (1999). Bridgit: User-friendly approach to bridge management. 8th International Conference on Bridge Management, Denver, CO, Paper E7.

Hwang C., Lai Y., and Liu T. (1993). A new approach for multiple objective decision making. *Computers and Operational Research*, 20, 889–899.

Johnson N., Kotz S., and Balakrishnan N. (1995). Continuous univariate distributions. 2nd Edition, Volume 2, Wiley, New York.

Liang M., Chang J., and Li Q., (2002). Grey and regression models predicting the remaining service life of existing reinforced concrete bridges. *Journal of Grey System*, 14(4), 291-310.

Lounis Z, and Madanat S. (2002). Integrating mechanistic and statistical deterioration models for effective bridge managements. 7th International Conference on Applications of Advanced Technology in Transportation, ASCE, Boston, MA, 513-520.

Lounis Z. (2000). Reliability-based life prediction of aging concrete bridge decks. In Life Prediction and Aging Management of Concrete Structures, RILEM, France, 229-238

Madanat S., Karlaftis M., and McCarthy P. (1997). Probabilistic infrastructure deterioration models with panel data. Journal of Infrastructure Systems, ASCE, 3(1), 4-9.

Malekly H., Mousavi S., Hashemi H. (2010). A fuzzy integrated methodology for evaluating conceptual bridge design. Expert System with Applications, Elsevier Ltd., 37(7), 4910-4920.

Otayek E., Jrade A., and Alkass S. (2012). Integrated decision support system for bridges at conceptual design stage. CIB W78 '29th', Beirut, Lebanon, 334-343.

Pandey M., and Van Noortwijk J. (2004). Gamma process model for time-dependent structural reliability analysis, Proceedings of the 2nd International Conference on Bridge Maintenance, Taylor and Francis, London, UK, 18-22.

Peters D. (2009). Bridge information modeling to cover a complete set of processes. CE & CR, Bentley Systems, 84-86.

Reddy C., Ramudu B. (2013). Arithmetico geometric process maintenance model for deteriorating system under random environment. International Journal of Engineering Science and Technology, 5(3), 460-467.

Sasmal S., Ramanjaneyulu K., Gopalakrishnan S., and Lakshmanan N. (2006). Fuzzy logic based condition rating of existing reinforced concrete bridges. *Journal of Performance of Constructed Facilities*, 20(3), 261-273.

Takács et al. (2008). Matrix factorization and neighbor based algorithms for the Netflix prize problem. *Proceedings of the 2008 ACM Conference on Recommender Systems*, Lausanne, Switzerland, 267-274.

Tee A., Bowman M., and Sinha K. (1988). A fuzzy mathematical approach for bridge condition evaluation. *Civil Engineering Systems*, 5(1), 17-24.

Van Noortwijk J., Van Der Weide J., Kallen M., and Pandey M. (2007). Gamma processes and peaks-over-threshold distributions for time-dependent reliability. *Reliability Engineering & System Safety*, Elsevier, 92(12), 1651-1658.

Van Noortwijk J., Kallen M., and Pandey M. (2005). Gamma processes for time-dependent reliability of structures. *Advances in Safety and Reliability*, PERGAMON, Canada, 1, 1457-1464.

Wang C., Li Q., Zou A., and Zhang L. (2015). A realistic resistance deterioration model for time-dependent reliability analysis of aging bridges. *Journal of Zhejiang University Science A*, 16(7), 513-524.

Zhao Z., and Chen C. (2002). A fuzzy system for concrete bridge damage diagnosis. *Computers and Structures*, 80(7-8), 629-641.

CHAPTER 7

TECHNICAL PAPER IV

Integrating an Expert System with BrIMS, Cost Estimation, and Linear Scheduling at the Conceptual Design Stage of Bridge Projects

Nizar Markiz, Ahmad Jrade

(Submitted to Journal of Construction Engineering, HINDAWI)

Abstract: Capital investment in North America's bridge asset management has been enormous and has contributed towards the success of the economy. In addition, estimating bridge construction costs is an increasing necessity for accurate budgeting and effective allocation of funding. In this study, the main objective is to develop a systematic multi-objective knowledge-based approach for estimating bridge construction costs and linear scheduling at the conceptual design stage. System development methodology comprises a framework to deploy a system that automatically generates conceptual cost estimates by integrating qualitative objective functions with a bridge information management system (BrIMS) through an external data interchange protocol in synchrony with interoperability standards. Deployment of the proposed system will minimize the subjectivity while making investment decisions related to bridge projects and assisting bridge designers and cost engineers to obtain results in an integrated quantitative, qualitative, and systematic manner. The proposed system is engineered to enhance existing stand-alone estimating techniques implemented by bridge stakeholders and designers to determine cost estimates. An actual case project is then used to validate the proposed system and

to illustrate its numerical capabilities. Results presented in this study are anticipated to be of major significance to owners, designers, and construction managers specializing in bridge asset management and would contribute to the database of integrated platforms by incorporating a system that integrates an expert system with BrIMS, cost estimation, and linear scheduling at the conceptual design stage of bridge projects. The successful implementation of the expert system is a technological achievement of novelty pertaining to the integration of BrIMS solutions with probabilistic fuzzy logic strategic approaches at the conceptual design stage of bridges.

KEYWORDS: Expert System, Bridge Information Management System, Cost Estimation, Linear Schedule

7.1 Brief Background

Bridge asset management has become the main focus of transportation authorities, enforcing a systematic approach that emphasizes downstream operations of an infrastructure facility. The success of any infrastructure project is evaluated according to the level of closeness between the actual and estimated costs. In practice, cost estimation at the conceptual design stage of a bridge project is known to be highly influenced by the adopted method of estimation as well as previous experience and availability of cost data. Over time, technological advancements have paved the way for “time-enhanced” cost estimation techniques and have resulted in less error-prone outcomes. Nowadays, interoperability among diverse information databases of the construction of a bridge project has proven to be ineffective due to the dynamic nature of shared information technologies. Only recently, federal and municipal transportation authorities have recognized the necessity for an integrated platform of expert systems combined with bridge information

management system solutions at the conceptual design stage of bridge projects. Hence, technological advancements in interoperability and compatibility are crucial for more productive transfer of information among diverse database applications.

7.2 Problem Definition

Major federal and provincial transportation agencies are in need of objective-oriented knowledge-based systems that assist decision makers to develop cost estimates and linear schedules of bridge projects at the conceptual design stage. Presently, bridge stakeholders forecast the feasibility of a bridge based on its conceptual cost estimate to determine whether construction funds are available strictly based on life cycle analyses offset by available funds and budget constraints. Whilst multiple bridge management systems have already been developed; they still possess major drawbacks pertaining to interoperability and integration with time and cost functions. Only a few industries have incorporated integrated expert systems with bridge processes along with introducing “broadly-accepted” interoperability standards. Although the deployment of a powerful object-oriented programming (OOP) approach in the bridge construction industry has reduced error-prone data duplication, many engineers and researchers are still unaware of the benefits of using such technology to estimate the cost of bridge projects at the conceptual design stage..

7.3 Research Objectives

The main objective of this study is to develop a fuzzy logic decision support system using quality functions and a multi-criteria decision making approach to assist bridge stakeholders to

determine bridge construction cost estimates and linear schedules at the conceptual design stage. In this study, cost estimates are considered to fall within conceptual and budgetary estimate categories where such estimates are strictly and solely dependent upon the available project data at the conceptual design stage. This study focuses on the methodology to be incorporated while considering interoperability standards. The deployment of the proposed system shall minimize the degree of subjectivity involved in decision making and shall assist bridge designers and estimators to obtain results in an integrated quantitative, qualitative, and systematic manner. Extending published research that combines bridge information management systems (BrIMS) with cost estimation at the conceptual design stage, this study introduces a framework of an integration platform.

In this study, one of the objectives is to design, implement, and enhance earlier relative work on optimizing linear schedules as follows: 1) unifying the process of optimizing equipment productivity rates while taking into account temporal variability; 2) satisfying time- and space-related constraints; and 3) modeling an integrated stochastic simulated approach for optimizing linear schedules. Another goal of the present study is to develop a near-optimum linear schedule for bridge construction operations at the conceptual design stage. Although traditional selection models have proven to be practical, they do possess limitations especially at the conceptual design phase. In an attempt to overcome such limitations, an integrated expert system based on fuzzy-logic theory is proposed. This study presents the deployment of complex quality functions based on quantitative and qualitative scorings that take into account technical, functional, and safety parameters.

7.4 Literature Review

Recent bridge management system have implemented computational tools to assist bridge stakeholders in decision makings. However, aspects of bridge design were tackled independently due to variability of unsynchronized data resources. In a study conducted by Brown et al. (1996), computer-integrated construction (CIC) is promoted through the deployment of a supporting system using distributed object technology to standardize and effectively link information among different objects in a computer integrated construction (CIC) system. In another study, Jung and Gibson (1999) proposed a methodology to deploy computer-integrated construction (CIC) techniques in real world applications where crucial automated integration aspects of CIC pertaining to 3D CAD modeling, engineering design, and management information applications are illustrated. In contrast, Gallaher et al. (2004)restated that the lack of effective interoperability among modelling solutions could substantially refrain users from reaping remarkable benefits. On the other hand, Arayici and Aouad (2005) concluded that computer-integrated construction (CIC) is a promising technique with a potential of determining technical requirements of the developed integrated systems and capable of enhancing the productivity and efficiency of the bridge construction industry. Furthermore, Boddy et al. (2007) stated that advancements in CIC studies related to virtual modeling are needed to be applied to the construction industry where a model, along with a proposed system architecture, is illustrated. According to Shim et al. (2011),existing simulation tools are not sufficient for bridge information models since technical improvements on interoperable aspects for the effective exchange of information amongst compatible software are required.

On another perspective, decision makings pertaining to the selection of bridge design alternative along with associated costs is a major undertaking for bridge stakeholders. Presently, bridge design involves a large amount of subjectivity in the selection of bridge design alternative at the conceptual design stage. Bridge stakeholders are directly influenced solely by subjective opinions of designers, engineers, and asset managers. In order to overcome the shortcomings of the subjective nature of decisions involved in the construction of bridge projects, the proposed system includes a unique aspect of BrIMS by incorporating intelligent agent tools (i.e. neural networks) that include optimization techniques based on numerical approximations. Tremendous research efforts have been expended to overcome the complications of neural networks. In a study conducted by Otayek et al. (2012), the integration of an intelligent decision support system is studied using Artificial Intelligence (AI) and Neural Networks (NN). The authors recommended further and continuous development in decision support systems to try to assist bridge designers in selecting bridge design alternatives at the conceptual design stages. In another study, Malekly et al. (2010) proposed a methodology of implementing quality functions, a client-based quality management system based on bridge users' relative importance perception on a set of defined competitors and the technique of preference by similarity to ideal solution (TOPSIS), a multi-criteria analytical approach used for the selection of the best bridge design alternative based on a specified list of parameters. In this study, the proposed expert system includes an intelligent system along with design-related attributes for bridge components integrated with elemental cost estimation at the conceptual design stage.

More importantly, the availability of project information database is of major significance to project stakeholders in particular when it comes to funding decision making. Furthermore, the

success of a bridge project is evaluated based on the level of closeness between the actual and estimated costs. In a study conducted by Forrest and Lorenzoni (1997), a cost estimate is considered a strategic technique to forecast the execution mode of a construction project. In other words, their study presents a cost estimate as a break-down for completion of project milestones. In another study conducted by Uppal (1999), a cost estimation process is defined as the anticipation of costs for a definite scope of works necessary to successfully complete a project. In a later study, Peurifoy and Oberlender (2002) conclude that since cost estimation is not a precise discipline, the construction industry is in dire need of knowledge experts, logic, and experienced personal judgment to achieve less error-prone decision making. In practice, cost estimation at the conceptual design stage of a bridge project is known to be highly influenced by the adopted method of estimation as well as previous experience and availability of relative cost data. Over time, technological advancements have paved the way for ‘time-enhanced’ cost estimation techniques and have resulted in less error-prone outcomes. Furthermore, maintaining a strict and definitive project budget at the early stage of a project assists owners and stakeholders in cost-controlling the subsequent phases including the construction phase (Westney, 1997). In estimation standards, effective cost estimates pave the way towards the success of a project management strategy and subsequent control of budget, cost, and corresponding schedule.

Furthermore, linear scheduling is deployed as a strategic scheduling forecasting technique at the conceptual design stage that permits a scheduler plan to balance the productivity rates. Typically, scheduling forecasts at early planning stages are highly influenced by the availability of data resulting in deterministic linear schedules. The focus of earlier studies was to utilize linear scheduling techniques during bridge operational phases rather than at an early design stage.

Earlier studies have focused on linear scheduling during operational phases rather than during early design stages. Since scheduling uncertainty is not addressed, this causes major conflicts. El Sayegh (1998) developed generic deterministic and stochastic systems for obtaining linear schedules. The first system is a resource-based technique and the latter is based on a Monte Carlo simulation that accounts for fluctuation and corresponding uncertainties. One study conducted by Liu et al. (2005) proposed a simulated genetic algorithm system to determine linear scheduling optimum solutions. Furthermore, Srisuwanrat and Ioannou (2007) studied lead-time buffer under certainty using simulation and cost optimization. According to Hinze (2008), few resources in the literature have focused on the linear scheduling method and few have reflected information on current trends in scheduling, such as short-interval scheduling, computer scheduling, and linear scheduling. In another study, Agrawal et al. (2010) provided optimal algorithms to scheduling problems comprising linear workflows. Afterwards, Song et al. (2012) presented a study of a stochastic look-ahead scheduling method for linear construction projects. As stated earlier, related research work has shown that the linear scheduling method may be used as an alternative tool for scheduling phased repetitive construction operations, providing a visualization of scheduling information not available with traditional scheduling methods, such as GANTT charts, in terms of relating operations and production rates with time- and space-related constraints.

In summary, the majority of the studies did not consider cost estimation applications for bridge projects. In contrast, most of the studies considered numerous factors for improving bridge information management systems; however, none of them has specifically viewed a bridge project as a task or process that needs to be accomplished within time and cost constraints and

based on qualitative and quantitative parameters. Hence, the authors of this study propose an integrated expert system that assists bridge stakeholders, designers, and estimators to generate preliminary estimates of construction costs, and derive linear schedules for bridge sequential operations at the conceptual design stage. The proposed integration is designed as a platform that unifies diverse applications and enhances interdisciplinary sharing of project information among its participants. Besides that, the integration platform is capable of facilitating interoperability, compatibility, and subsequent productivity of information systems, and enhancing time and cost effectiveness in bridge projects at the conceptual design stage.

7.5 Methodology and Development

The proposed methodology comprises the development of a bridge information management system (BrIMS) based on a strategic framework that is capable of integrating a fuzzy logic decision support system with construction cost estimation at the conceptual design stage. System development methodology is divided into the following four main phases: (1) categorization of system components; (2) definition of system architecture; (3) development of sub-modules; and (4) deployment of the global integration platform. The first phase is the development of relevant databases of heavy equipment and their associated costs. These will be necessary for preliminary cost estimates at the conceptual design stage. The second phase includes defining the correlated sub-modules that fit into the fuzzy logic decision support system architecture. The third phase is the physical deployment of the sub-modules that will be integrated into the global module. Finally, the last phase is the development of the overall integrated platform.

7.5.1 System Architecture

The proposed integrated system is part of an integrated preliminary fuzzy-logic decision support system developed earlier by the authors comprising the following five modules: i) 'Conceptual Bridge Design', ii) 'Fleet Selection', iii) 'Preliminary Cost Estimation', iv) 'Deterioration Forecast' and v) 'Bridge Line of Balance'. The proposed system is developed in an object-oriented .NET framework and undertaken using the following six main steps: 1) Data collection of bridge-user-driven parameters; 2) Implementation of a decision support system that assists the user in making decisions about bridge design alternatives; 3) Development of complex quality functions to evaluate bridge users relative perception of bridge components; 4) Deployment of a numerical model to evaluate bridge component ratings; 5) Development of a mean deterioration resistance regression fit where component rankings are determined; and 6) Optimize and prioritize maintenance, repair and replacement (MR&R) alternatives. A proper arrangement and management of the modeling data will result in outcomes less prone to error as a result of duplication or combination of inconsistent bridge database resources. A schematic view of the interrelations among the 3D computer-aided design (CAD) solutions with the proposed bridge conceptual cost estimation system is shown in Figure 7.1.

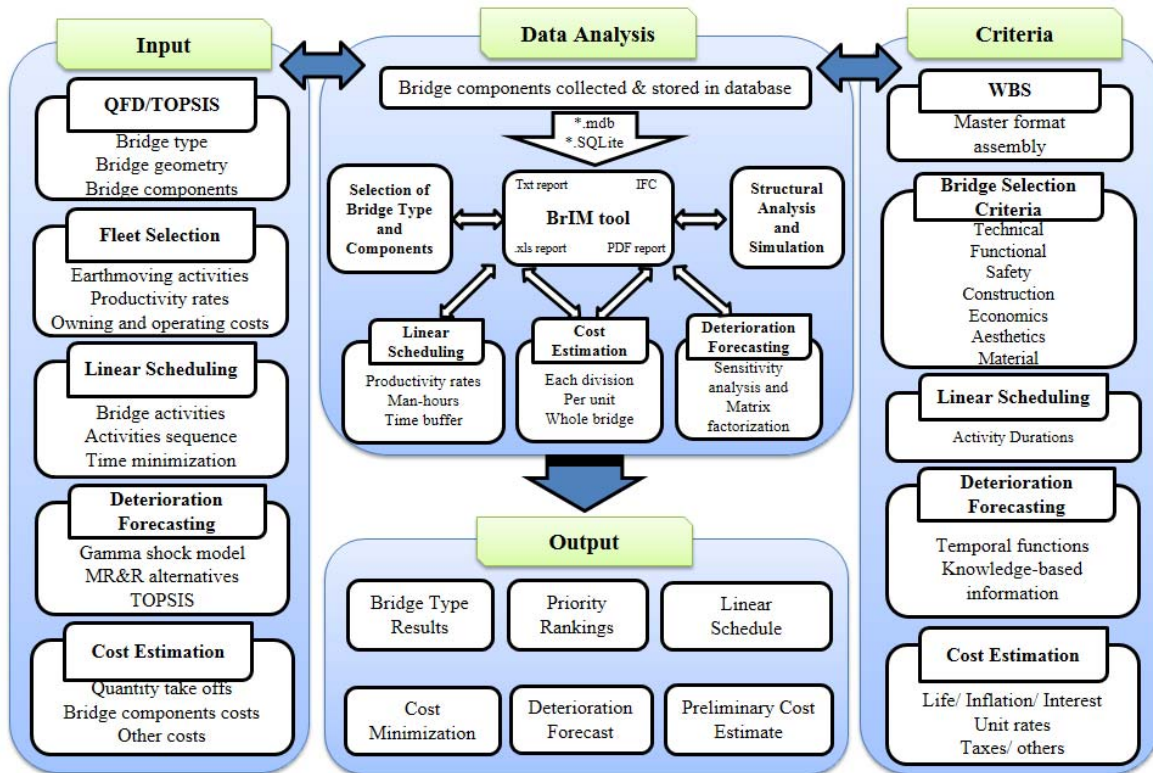


Figure 7.1 Proposed System Architecture

7.5.2 System Integration

Integration of the decision support system includes the implementation of a bridge information management process based on a strategic framework that is capable of integrating a fuzzy logic decision support system with linear scheduling and cost estimation through the deployment of complex quality functions derived from bridge-user-driven parameters and symmetrical triangular fuzzy numbers (STFN's). Based on that, the proposed system requirements and components are defined and categorized accordingly. It is important to note that the development of the integrated methodology is for a system that facilitates the effective integration of information and contributes towards less error prone outcomes as well as fostering proper sharing

of project information among participants via a user-friendly linking tool that is available upon request. The implementation of the proposed integrated system is undertaken by following the five main phases illustrated in Figure 7.2.

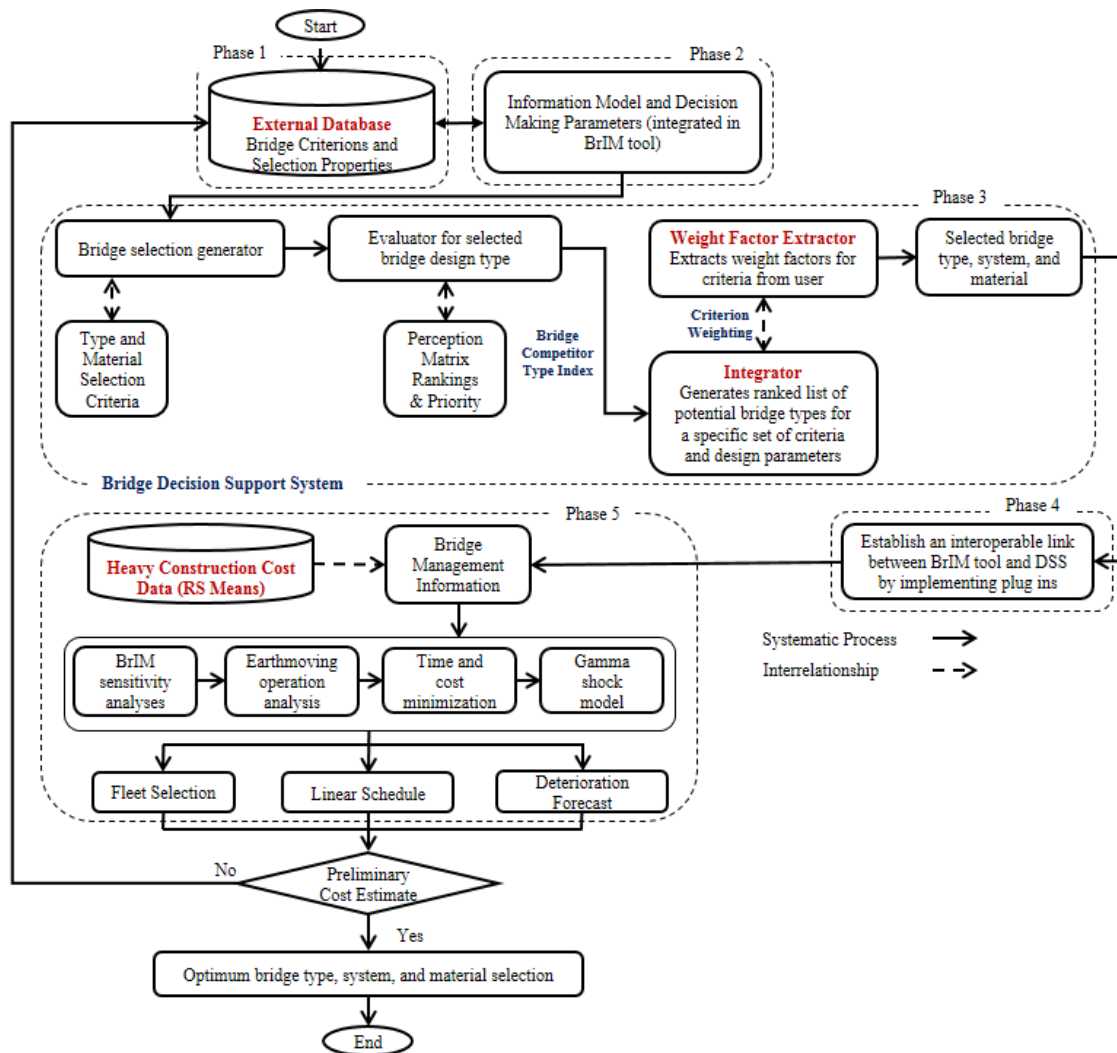


Figure 7.2 Flowchart of the Integrated Process

Phase I - Collect data pertaining to the bridge user-driven parameters and BrIM components and implement into a database server. The development of the database server starts by completing

the conceptual design where problems are identified from earlier studies. Next, the conceptual database design is transformed into a physical implementation. The external database is developed as a stand-alone server, where its path is defined and directly linked to the pre-defined library of the 3D CAD tool. Data pertaining to diverse bridge design alternatives, elemental costs, selection criteria, etc., are arranged into tables based on a Work Breakdown Structure (WBS) elemental classification.

Phase II - Create an integrated 3D bridge information model that is customized based on decision making parameters. At first, a 3D CAD bridge information model is designed to geometrically define elemental bridge components, which are stored in a pre-defined library that is linked to an external database server of Phase I via interoperable extension files (XML). Afterwards, bridge elements' material properties are assigned in order to assist the user with fitting the customized BrIM into design requirements. Once completed, bridge elements are assigned annotations in text format in order to assist the weight factor extractor and system integrator in query indexing and element selection processes.

Phase III - Implement a decision support system (DSS) that assists designers in the selection of bridge type and elements through the development of complex quality functions that analyze bridge designers' relative perception on the multiple evaluation criteria. Due to the scarcity of bridge deterioration data, it is necessary to develop a fuzzy logic scoring system to assist the bridge stakeholders and designers in predicting bridge deterioration at conceptual design stages. Hence, a 9-point symmetrical triangular fuzzy logic numbers (STFN) ranging from one to nine, with one being very low importance and nine being very important, is adopted for assisting the

decision maker in predicting bridge users' perceptions. Afterwards, the user scoring on selection criteria is weighted and integrated with attributes for bridge design alternatives to reach at a final ranking.

Phase IV - Establish an interoperable link amongst phases of the BrIM and DSS through the deployment of plug-ins using an application programming interface (API). First, a knowledge-based support system that extracts information from the 3D CAD tool via a Dynamic Link Library (DLL) - invoked Application Programming Interface (API) method that automatically recalls the parametric enriched object-oriented model is deployed. The plug-in is designed to extract all necessary information from the assigned model by exporting the BrIM input databases via Industry Foundation Classes (IFC) file formats which reduce loss of information during file transmission. After that, the plug-ins are objectively developed for bridges such that capturing of the data displayed in the calling software is conducted by utilizing the 3D CAD library objects. Finally, bridge element attributes are recalled and organized via the plug-in application and incorporated into the database server.

Phase V - Deploy a mathematical model to manage complex bridge information related to information model parametric analysis, heavy earthmoving operations, time and cost minimization approaches, and bridge deteriorations. The cost estimation system uses information extracted from the 3D model objects that is stored in the database server for obtaining elemental costs. For instance, a bridge cross-sectional area is extracted via IFC file formats by implementing a DLL-invoked call function and incorporated into the database server subsequently for numerical multiplication by its corresponding parametric unit cost obtained

from the R.S. Means heavy construction cost data catalogue for the year 2012 in order to determine bridge construction costs at the conceptual design stage.

In summary, the proposed integration platform may be used by bridge stakeholders, asset managers, designers, and estimators to evaluate the feasibility of a bridge project. The decision support system is capable of providing the user with recommendations of bridge design alternatives based on heavy earthmoving equipment and deterioration forecast at the conceptual design stage and an all-in-one cost estimation tool that is capable of automating the required cost and time normalization and optimization techniques.

7.5.3 System Modules

A proper handling of the modeling data will result in less error-prone outcomes that tend to be caused by duplication or amalgamation of inconsistent bridge database resources. To overcome such limitations, the proposed system includes a unique aspect of BrIMS by incorporating bridge design alternatives and components into a multi-criteria decision making (MCDM) approach to derive priority ratings among competitive alternatives. The proposed integrated system consists of the following five main modules:

7.5.3.1 Module 1: Conceptual Bridge Design

In this study, the methodology of Malekly et al. (2010) is adopted and integrated into a novel approach, while overcoming interoperability issues among the diverse databases. First, bridge users are identified and corresponding needs (WHATs) will be obtained. There are generally four main bridge users, i) shareholders; b) designers c) contractors; and d) public. Generally, the main

focus is on the ultimate user who could be identified through public feedback and research. The best approach for obtaining users' perceptions on the seven WHATs is either by interviews or public feedback. For instance, an interview component for the "technical" WHAT will be: "What is (user) score from 1 to 10 on the fuzzy-logic scoring system for a bridge (Technical) criterion?" Secondly, relative importance ratings of user needs are determined. Typically, user needs (WHATs) are of variable degrees of importance. Following bridge users' assessments of WHATs criteria on bridge competitors, relative importance perception ratings in crisp and fuzzy forms are obtained. Furthermore, the probability distribution and corresponding measure of entropy of WHATs criteria are determined. Afterwards, a user competitive matrix is established where parametric weights are assigned for TOPSIS analysis.

7.5.3.2 Module 2: Fleet Selection

Heavy equipment selection for civil earthmoving operations is an essential component; therefore, operation analysis for selected equipment based on comprehensive owning and operating costs is performed for major operations of earthwork. Following the user's input of all necessary scope-of-work-related parameters, the proposed fleet selection system is designed to efficiently undertake operational analysis mathematical formulations. After that, output data is stored and recalled for owning and operating cost computations, which would be further analyzed for optimization. The proposed system is designed to automatically extract information entered by the user (i.e., volume of earthmoving, piling, backfilling, and subsequent grading and compaction). Then, the user selects the required module that corresponds to the earthwork operation (i.e., clearing and grubbing, excavation, loading, hauling, backfilling, grading, or

compacting) from a user-friendly gateway. After inputting all necessary information, the proposed system is capable of determining the near-optimum fleet system. The results include the number of pieces of equipment needed, combined fleet productivity (loose yd³/hr), unit cost (\$/loose yd³), and the total cost (\$) of the project based on ownership and operational costs.

7.5.3.3 Module 3: Preliminary Cost Estimation

Cost data pertaining to fleet selection comprehensive owning and operating costs is 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 proposed system includes 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) tire replacement; (d) emergency reserves; (e) wages; and (f) wear items.

7.5.3.4 Module 4: Deterioration Forecast

The proposed methodology comprises an innovative bridge information management system (BrIMS) based on a framework that is capable of integrating bridge gamma stochastic deterioration modeling with a fuzzy-logic decision support system. The framework is developed by deploying complex quality functions derived from bridge user-driven parameters and symmetrical triangular fuzzy numbers (STFNs) to minimize uncertainties in importance ratings. Furthermore, the proposed system possesses a unique aspect of BrIMS by incorporating diverse

bridge MR&R solutions into a multi-criteria decision making approach (MCDM) to derive competitive priority ratings.

7.5.3.5 Module 5: Bridge Line of Balance

The proposed methodology includes the development of a linear scheduling optimization system based on a strategic framework that is capable of integrating a simulated annealing approach with global duration minimization. First, productivity rates determined from the fleet selection system are automatically imported and plotted into a histogram. The rates are then organized so that a statistical normal distribution can be fitted accordingly followed by the stochastic linear scheduling process. Afterwards, a near-optimum line of balance is established throughout a simulated annealing approach accompanied by a global optimization objective function where time and space buffer conflicts are automatically detected. Next, the proposed system enables the user to modify operation durations to resolve conflicts and reach a near-optimum linear schedule.

7.6 Normalization of Multi-Attribute Decision Making Approach (TOPSIS)

Due to the scarcity of bridge component deterioration data, it is necessary to develop a fuzzy logic scoring system in order to assist bridge stakeholders and designers in predicting bridge component deterioration at conceptual design stages. Conceptual bridge design is found to be subjectively influenced by each the following nine bridge components; (1) approach slab ‘C₁’, (2) deck slab ‘C₂’, (3) expansion joint ‘C₃’, (4) parapet ‘C₄’, (5) girder ‘C₅’, (6) bearings ‘C₆’, (7) abutment ‘C₇’, (8) pier ‘C₈’, and (9) foundation ‘C₉’. Selection of the components is based on critical factors that bridge designers rely upon and bridge users’ perception of corresponding

impact factors while taking into account the following equally important criteria: (i) qualitative benefit; (ii) quantitative benefit; and (iii) cost criteria, as shown in Figure 7.3.

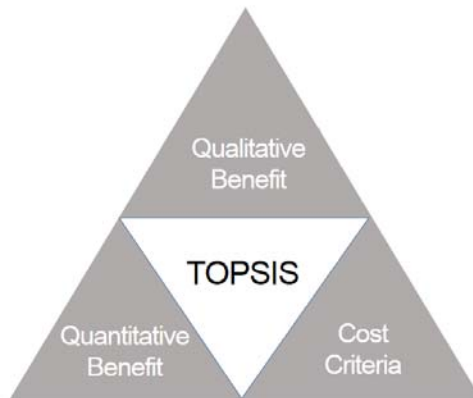


Figure 7.3 TOPSIS Main Criteria

As shown in Figure 7.3, TOPSIS opts in for the alternative that converges to the solution that offers a balance between the desired quality, quantity, and the cost effective solution. In order to include the preferences of multiple decision makers, maximum positive and negative ideal solution separation measures are taken into account where normalization techniques and separation measures are considered simultaneously. In comparison to the conventional TOPSIS approach, the normalized model enhances the TOPSIS approach with multi-group preference amalgamations illustrated in the step-by-step procedure summarized below:

Step 1. Develop a decision matrix P^k , $k = 1, \dots, K$, where k is the bridge stakeholder decision on competitive bridge maintenance, repair and replacement alternatives. Prior to undertaking the

multi-attribute decision making approach (TOPSIS), a decision matrix, P^k is then developed as per equation (7.1):

$$\begin{array}{cccccc}
 & x_1 & x_2 & \dots & x_j & \dots & x_n & \text{Criterion (n)} \\
 \\
 \begin{array}{c} C_1 \\ C_2 \\ \vdots \\ C_i \\ \vdots \\ C_m \end{array} & P^k = & \begin{bmatrix} x_{11}^k & x_{12}^k & \dots & x_{1j}^k & \dots & x_{1n}^k \\ x_{21}^k & x_{22}^k & \dots & x_{2j}^k & \dots & x_{2n}^k \\ \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ x_{i1}^k & x_{i2}^k & \dots & x_{ij}^k & \dots & x_{in}^k \\ \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ x_{m1}^k & x_{m2}^k & \dots & x_{mj}^k & \dots & x_{mn}^k \end{bmatrix} & (7.1)
 \end{array}$$

Bridge Types (m)

Where C_i is the competitive alternative $i, i = 1, \dots, m$, x_j is the entry value of attribute j , $j = 1, \dots, n$, x_{ij}^k is the performance assessment rating on alternative C_i based on x_j by stakeholder k , $k = 1, \dots, K$.

Step 2. Develop a normalized decision matrix N^k , $k = 1, \dots, K$, where k is the bridge stakeholder decision on competitive alternatives. In a normalized decision matrix, entry value n_{ij}^k is the vector normalization of entry value x_{ij}^k such that; $0 \leq n_{ij}^k \leq 1$. The normalization process is undertaken as per equation (7.2):

$$n_{ij}^k = \frac{x_{ij}^k}{\sqrt{\sum_{j=1}^n (x_{ij}^k)^2}} \quad (7.2)$$

Where n_{ij}^k is the normalized performance assessment rating on alternative C_i , and x_{ij}^k is the performance assessment rating on alternative C_i based on X_j by stakeholder k , $k = 1, \dots, K$.

Step 3. Determine positive and negative ideal solutions prior to proceeding to the conventional weighted TOPSIS matrix process. This step is considered to be the overturn stake of the normalization technique presented herein. Afterwards, positive and negative ideal solutions for individual stakeholders, k is determined as per equation (7.3):

$$POS^k = \{ \max n_1^k, \dots, \max n_n^k \} = \left\{ \left(\max_i n_{ij}^k \mid j \in J \right), \left(\min_i n_{ij}^k \mid j \in J' \right) \right\} \quad (7.3)$$

$$NEG^k = \{ \min n_1^k, \dots, \min n_n^k \} = \left\{ \left(\min_i n_{ij}^k \mid j \in J \right), \left(\max_i n_{ij}^k \mid j \in J' \right) \right\}$$

Where POS^k is the positive ideal solution, NEG^k is the negative ideal solution, $\max_i n_{ij}^k$ is the normalized decision matrix entry with highest ranking for alternative i , $\min_i n_{ij}^k$ is the normalized decision matrix entry with lowest ranking for alternative i , J and J' are the maximum positive and negative solutions for $i = 1, \dots, m$, $j = 1, \dots, n$, $k = 1, \dots, K$.

Step 4. Introduce an improvement goal value, G , to the set of attributes. The improved normalized competitive rating, n_{ij}^k , for alternative i and attribute j is then obtained as per Chan and Wu (2005) equation (7.4):

$$IGn_{ij}^k = G_{ij}^k * n_{ij}^k * e_m \quad (7.4)$$

Where IGn_{ij}^k is the improved normalized competitive rating, G_{ij}^k is the improvement goal set, n_{ij}^k is the normalized performance assessment rating on alternative i and attribute j based on stakeholder k , and e_m is the alternative i importance weight.

Step 5. Calculate relative separation from positive and negative ideal solutions for the attribute group as per equation (7.5):

$$PSEP^k = \sum_{j=1}^n (IGn_{ij}^k - \max_i n_{ij}^k) \quad \text{for alternative } i, i = 1, \dots, m \quad (7.5)$$

$$NSEP^k = \sum_{j=1}^n (IGn_{ij}^k - \min_i n_{ij}^k) \quad \text{for alternative } i, i = 1, \dots, m$$

Where $PSEP^k$ is the separation from positive ideal solution, $NSEP^k$ is the separation from negative ideal solution, IGn_{ij}^k is the improved normalized competitive rating, $\max_i n_{ij}^k$ is the normalized decision matrix entry with highest ranking for alternative i , and $\min_i n_{ij}^k$ is the

normalized decision matrix entry with lowest ranking for alternative i . Afterwards, the relative separation of positive and negative ideal solutions for the stakeholders group, K is calculated as per equation (7.6):

$$GPSEP = \left(\prod_{k=1}^K PSEP^k \right)^{1/K} ; \quad \text{for alternative } i, i = 1, \dots, m \quad (7.6)$$

$$GNSEP = \left(\prod_{k=1}^K NSEP^k \right)^{1/K} ; \quad \text{for alternative } i, i = 1, \dots, m$$

Where $GPSEP$ is the group separation from positive ideal solution, $GNSEP$ is the group separation from negative ideal solution, $PSEP^k$ and $NSEP^k$ are the separations from positive and negative ideal solutions respectively for the alternative i based on stakeholder k .

Step 6. Calculate relative closeness to ideal solution and rank alternatives in descending order based on their relative closeness to positive ideal solution as per equation (7.7):

$$C_i^* = \frac{GNSEP}{(GPSEP + GNSEP)} ; \quad 0 < C_i^* < 1 \quad (7.7)$$

Where C_i^* is the relative closeness to positive ideal solution? The recommended selection of alternative i is the one with a corresponding C_i^* closest to the value of unity '1'.

7.7 Decision-Support System Integrated Platform

Decision making pertaining to the selection of bridge type necessitates the deployment of an integrated platform comprising: 1) decision-support system; 2) BrIMS; 3) cost estimation; and 4) linear scheduling. The proposed integration includes a knowledge-based support system that extracts information from the BrIM tool, CSiBridge, via a Dynamic Link Library (DLL) - invoked Application Programming Interface (API) method that automatically recalls the parametric enriched object-oriented model. For instance, the proposed system provides the user with an option to develop an information module by utilizing the fuzzy logic scoring system in order to determine the bridge type based on the deployment of the aforementioned processes (i.e. QFD and TOPSIS) and automatically extracts relative data from the developed BrIM model and presents results pertaining to recommendations of selected bridge type based on technical and functional spans as well as geotechnical attributes. Figure 7.4 presents the data flow diagram of QFD/TOPSIS.

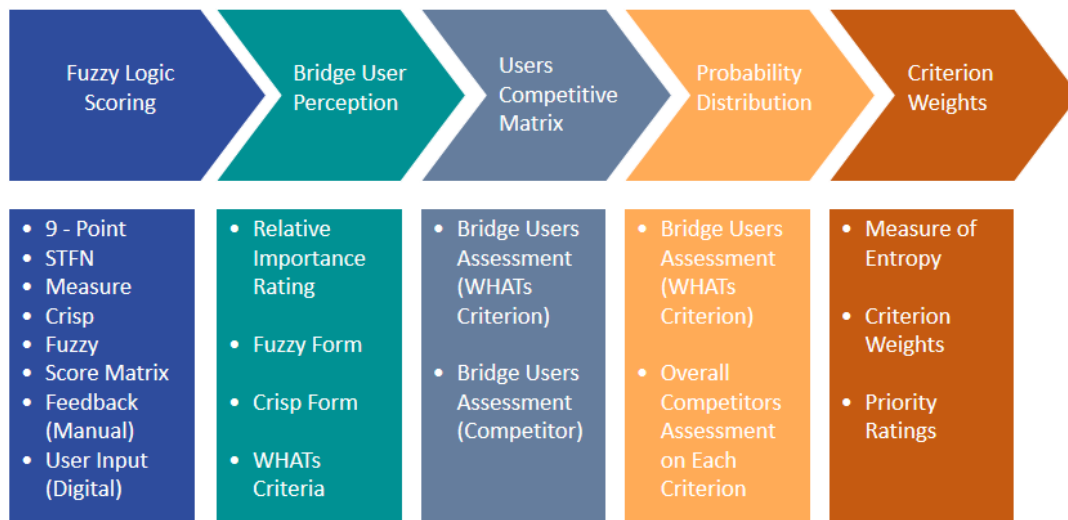


Figure 7.4 QFD/TOPSIS Data Process flow Diagram

As shown in Figure 7.4, the QFD/TOPSIS approach comprises the following five main processes: a) fuzzy logic scoring system; b) bridge user perception; c) users competitive matrix; d) probability distribution; and d) criterion weights. Conceptual bridge design is found to be significantly influenced by each the following seven main (WHATs) criterion: (1) technical ‘W₁’; (2) functional ‘W₂’; (3) safety ‘W₃’; (4) construction ‘W₄’; (5) economics ‘W₅’; (6) aesthetics ‘W₆’; and (7) material ‘W₇’. Selection of the WHATs criteria is based on earlier studies on critical factors that bridge designers rely upon and authors’ perception on bridge criterion importance and evaluation in selection of bridge type. A 9-point symmetrical triangular fuzzy logic numbers (STFN) ranging from one to nine, with one being very low and nine being very important, is adopted for assisting the user in predicting bridge users perception pursuant to the seven main criteria listed above. The scoring system comprises crisp and fuzzy measures when uncertainty arises as shown in Figure 7.5.

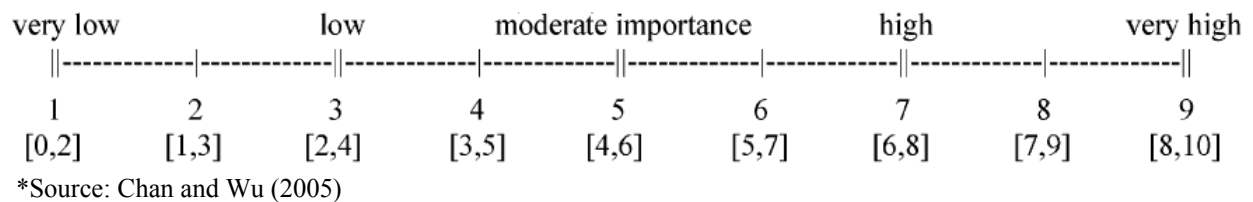


Figure 7.5 Fuzzy-logic Scoring System

On the other hand, bridge users are identified in this study and classified as follows: (i) stakeholders/government; (ii) designers/engineers; (iii) contractors/builders; and (iv) public/residents. Also, the following nine common bridge design alternative “competitors” are identified and incorporated into the database platform for QFD analyses: (1) beam bridges ‘C₁’;

(2) truss bridges ‘C₂’; (3) cantilever bridges ‘C₃’; (4) arch bridges ‘C₄’; (5) tied-arch bridges ‘C₅’; (6) suspension bridges ‘C₆’; (7) cable-stayed bridges ‘C₇’; (8) movable bridges ‘C₈’; and (9) double-decked bridges ‘C₉’. The adopted QFD analytical technology utilized for selection of bridge design alternative as shown in Figure 7.6.

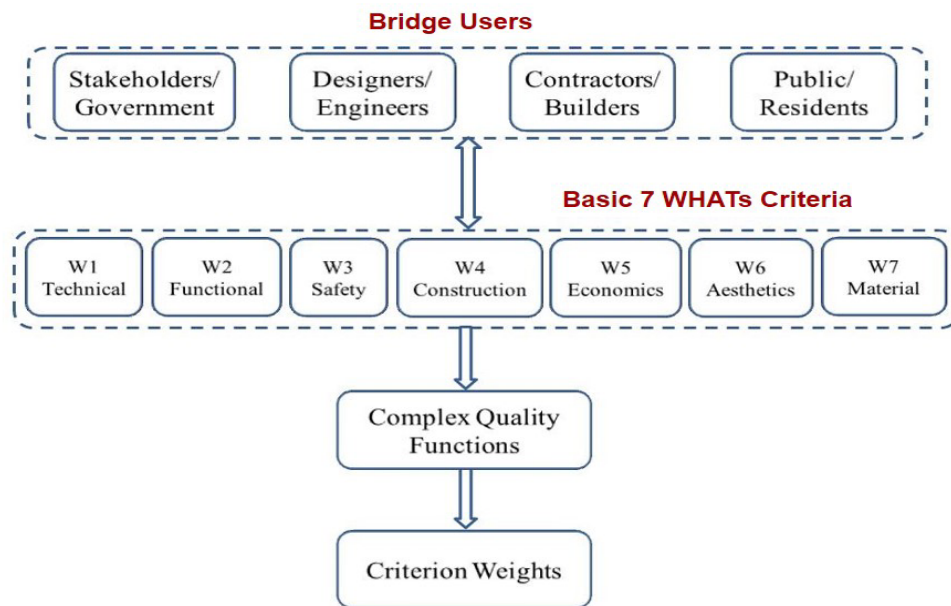


Figure 7.6 Quality Function Deployment Flowchart

Upon completion of bridge users’ scorings on the seven WHATs, perception on relative importance ratings of the seven WHATs is determined. Upon determination of the seven WHATs, a multi-criteria decision making approach, TOPSIS, is undertaken while considering the following criteria: (i) qualitative benefit; (ii) quantitative benefit; and (iii) cost criteria. TOPSIS opts in for the alternative that converges to the ideal solution and opts out from the negative ideal alternative. Prior to undertaking the multi-criteria decision making approach, a

TOPSIS matrix is developed where attributes' measure of entropy, criterion weights, and priority rankings are used to assist in the selection of bridge type and system alternative with the highest rank provided the scorings to the diverse attributes given. Table 7.1 summarizes the main WHATs criteria including sub-criteria as part of the fuzzy logic scoring system where bridge users input relative perception scorings.

Table 7.1 Fuzzy Logic Scoring System WHATs Criteria and Sub-Criteria

Criteria	Sub-Criteria
Technical	Design Requirements
	Code Compliance
	Load-Bearing Capacity
Functional	Traffic Capacity
	Freight Efficiency
	Sustainability
Safety	Parapet Wall
	Protective Shields
	Traffic Barriers
Construction	Methodology
	Inspection Accessibility
	Traffic Diversification
Economics	Direct/Indirect Costs
	Fund Allocation
	Benefit/Cost Ratio
Aesthetics	Architectural Design
	Urban/Sub-Urban Perspective
	Touristic Attraction
Material	Aggressive Environment Durability
	Environmental Impact
	Maintainability

7.8 System Implementation

The proposed system is implemented in an object-oriented .NET framework “C#” using SQLite, which was found to resolve interoperability issues among the “sub-database” applications within

the developed framework. The main purpose of the integrated system is to facilitate the interface between conceptual bridge design, fleet selection, and optimization functions. The fleet selection modules are organized by operation types where every module has four sub-modules. The sub-modules are as follows: (1) an operation analysis module that contains equipment operation calculations; (2) an economic analysis module that includes all owning and operating cost-related parameters and calculations; (3) an optimization module that displays near optimum results; and (4) a report module which contains professional output reports that summarize results extracted from the optimization module.

Firstly, the expert system is designed to automatically extract information entered by the user (i.e. volume of earthmovings, piling, backfilling, and subsequent grading and compaction). Then, the user would select the required module that corresponds to the earthwork operation (i.e., clearing and grubbing, excavation, loading, hauling, backfilling, grading, compacting) from a user-friendly gateway. It is important to note that the data required for the economic operation analysis vary from one earthwork operation module to the other; however, (1) material density; (2) fill factors; (3) safe factors; (4) time constraints; (5) volume of work; and (6) operational efficiency is a common list of data variables among all seven operation modules. The work to be undertaken is measured in terms of volume of earth material in loose cubic yards and is a user-input parameter which is in turn used by the economic operation analysis module to obtain fleet productivity rates. If any of the constraints set by the system are not satisfied, an error message pops up to inform the user that some equipment will not be considered in the optimization process.

Towards the end, the proposed system recalls the obtained productivity rates from the fleet selection module for diverse operation types. Once completed, a near-optimum line-of-balance is established throughout a simulated annealing approach accompanied by a global optimization objective function where time and space buffer conflicts are automatically flagged. The line of balance is obtained by automatically extracting corresponding productivity rates of ranked operations and plotting them against the calculated expected. Afterwards, the operation rankings are represented graphically with duration being on the y-axis and operation being on the x-axis. The user can then modify operation durations to resolve conflicts and reach at a near-optimum linear schedule.

7.8.1 Linear Scheduling Optimization

In order to properly optimize logistics linear scheduling, one must understand all related constraints; otherwise, failure to do so may lead to erroneous results. In scheduling terms, deployment of near optimum resources is a multifaceted task for construction managers. In this study, a linear scheduling optimization module is proposed to optimize the use of available resources by optimizing heavy fleet productivity and selecting most suitable equipment for an earthmoving operation. The expert system utilizes simulated annealing as an optimization tool supported by a classical constraint-based simulated algorithm, which indicates that linear scheduling constraints must be satisfied prior to the commencement of the associated task.

7.8.2 Simulated Annealing System Process

In this context, a meta-heuristic metropolis algorithm is deployed as a local optimization approach to resolve linear scheduling combinational conflicts and reach a near-optimum solution within reasonable cycle time. According to Dreio et al. (2006), the annealing process begins when metal particles unveil their original state and re-configure into a highly organized structure with lower energy than the initial state. In this study, the simulated annealing procedure is used to determine a near-optimum linear schedule. Simulated annealing is typically implemented by assuming an initial duration and meta-heuristically determines a new solution within the neighborhood of the initial solution. Once accepted, the new solution is set as the starting point for the consecutive optimization cycle. Consequently, in order to implement the generic metropolis algorithm, the following criteria must be met: (1) suitable neighborhood; (2) proper probability of acceptance; and (3) effective temperature decreasing rate in order to reach a successful near-optimum linear schedule and consequently escape local minima. Toward the end, simulated annealing is integrated in order to enhance neighboring schedules by substituting tasks. Once a near-optimum schedule is determined, the newer solution replaces the older one and simultaneously enables formerly declined solutions to be accepted in order to escape local minima.

7.8.3 Global Optimization

Global optimization is a numerical analysis procedure that optimizes an objective nonlinear function by determining the near-optimum solution globally. Global optimization is known for its capability in bypassing local optima and seeking a global solution of a boundary-constrained

objective function. In this study, research efforts are focused on enhancing linear scheduling optimization a step further by enhancing an optimized linear schedule by proposing a global optimization procedure in order to combine the expected durations of neighborhood operations of similar productivity rates while respecting time and space buffer constraints.

7.9 System Validation

To validate the workability of the proposed system, an actual project that consists of a bridge located in the City of Ottawa, Ontario, composed of a beam girder spanning 200 ft., supported by a central interior bent 40 ft. wide was developed in CSiBridge. The challenge underlying the system validation is to provide priority rankings for bridge design alternatives and conceptual cost estimates for diverse bridge components. The systematic procedure of the integrated system is demonstrated in a step-by-step process. Once the user selects ‘Module 1: Conceptual bridge design’, the system displays a module within the operation main module where the user inputs interview results of bridge users assessment on WHATs criteria as shown in Figure 7.7. Then, bridge users importance perception ratings on the WHATs criteria are evaluated and organized into a bridge competitive matrix. Afterwards, the probability distribution and criterion weights are determined as shown in Figure 7.8.

Stakeholders/
Government

1 Stakeholders /Government 2 Designers /Engineers 3 Contractors /Builders 4 Public /Residents 5 TOPSIS analysis

Whats	C1	C2	C3	C4	C5	C6	C7	C8	C9
W1. Technical	High	Very High	VeryLow	Moderate Important	High	Low	Moderate Important	VeryLow	Low
W6. Aesthetics	Low	Moderate Important	Moderate Important	High	Moderate Important	Very High	Very High	Moderate Important	Moderate Important
W7. Material	Moderate Important	High	Moderate Important	Moderate Important	High	Moderate Important	High	Moderate Important	High

[Competitive . WHATs of Conceptual] = 7 [6.8] W1. Technical Beam Bridges

Very Low Low Moderate Importance High Very High

1 2 3 4 5 6 7 8 9

10.21 11.31 12.41 13.51 14.61 15.71 16.81 17.91 18.10

Economics Important Very High High Important High Low Important VeryLow VeryLow

Help < Back Next > Cancel

Figure 7.7 Bridge User Assessment on WHATs Criteria

Quality Function Development and TOPSIS Analysis

Stakeholders/
Government

1 Stakeholders /Government 2 Designers /Engineers 3 Contractors /Builders 4 Public /Residents 5 TOPSIS analysis

Quality Function Development and TOPSIS Analysis

Designers /
Engineers

1 Stakeholders /Government 2 Designers /Engineers 3 Contractors /Builders 4 Public /Residents 5 TOPSIS analysis

Quality Function Development and TOPSIS Analysis

Contractors /
Builders

1 Stakeholders /Government 2 Designers /Engineers 3 Contractors /Builders 4 Public /Residents 5 TOPSIS analysis

Quality Function Development and TOPSIS Analysis

Public /Residents

1 Stakeholders /Government 2 Designers /Engineers 3 Contractors /Builders 4 Public /Residents 5 TOPSIS analysis

Quality Function Development and TOPSIS Analysis

TOPSIS analysis

Save

Perception on the relative importance

Relative importance ratings

Beneficiary Competitive Analysis Matrix

Conceptual Bridge Design Parameters

Technical Span (ft) (65-800) 200 RC Beam

Functional Span (ft) (0-200) 200 Beam/Arch

Foundation Type Deep RC / Steel

Whats	C1	C2	C3	C4	C5	C6	C7	C8	C9	em
W1. Technical	7	5	5.75	4.75	5.75	3.75	4.75	5.5	6	0.14
W2. Functional	7.5	6.25	5.75	5.75	7	5.25	6	3.5	6	0.14
W3. Safety	6.25	6	5.25	6.25	5	5.5	6	6.25	6.25	0.14
W4. Construction	6	6.25	6.25	5.75	5.75	4.5	6	4.75	5.5	0.14
W5. Economics	6	5	4.25	6.75	6.25	4.25	5.5	6.25	6.25	0.14
W6. Aesthetics	5.25	6.5	6.75	6.25	5.75	3.5	7	5.75	5.5	0.14
W7. Material	6.25	6.25	4.5	6.25	6.5	5	5.5	6.5	5	0.14

Figure 7.8 WHATs Criterion Weights

Following the determination of the seven WHATs criterion weights, a TOPSIS matrix is developed followed by normalized decision and weighted matrices. Afterwards, the positive and negative ideal solutions are determined and set as the reference data. Towards the end, separations from positive and negative ideal solutions are obtained followed by a TOPSIS relative closeness to ideal solution decision matrix with priority rankings. Following the determination of the bridge alternatives priority ratings, the technical and functional spans and the foundation type are inputted by the user. It is important to note that the proposed system also provides a recommendation for bridge substructure and superstructure material and profile as illustrated in Figure 7.9.

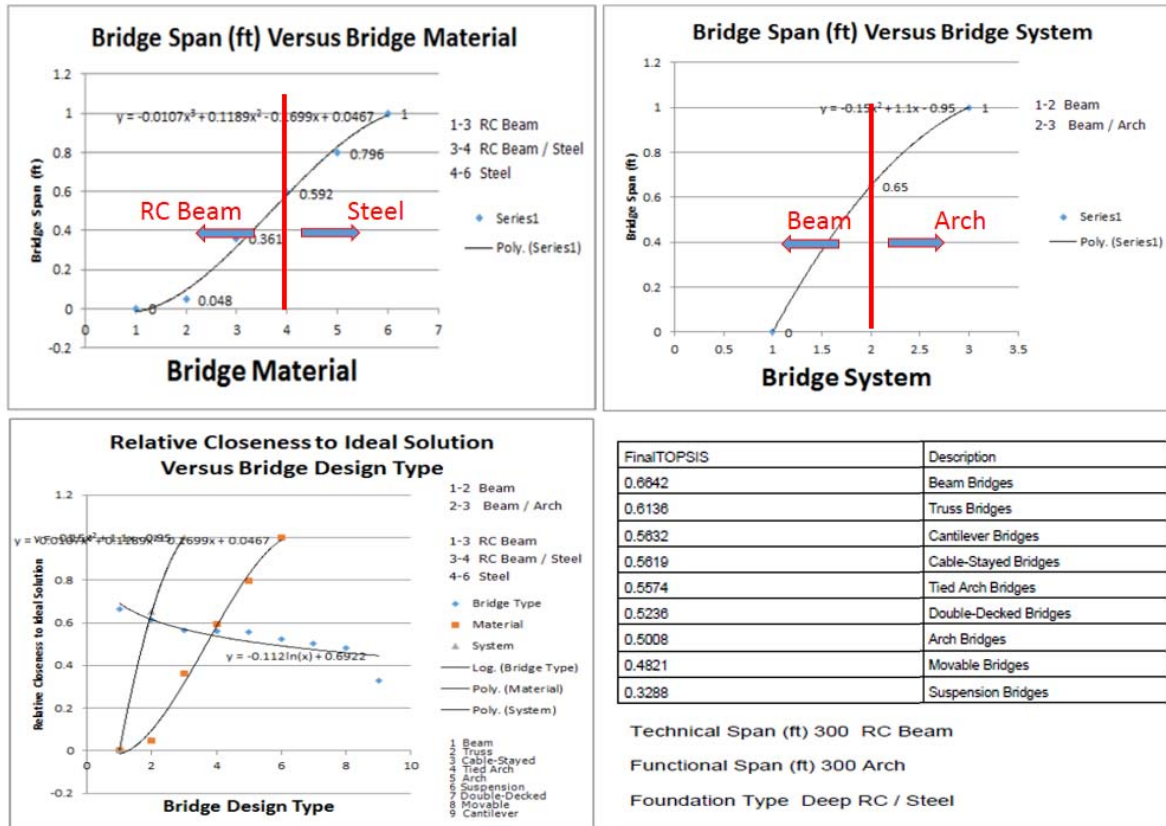


Figure 7.9 Conceptual Bridge Design Recommendations

As shown in Figure 7.9, the bridge design alternative of a beam configuration possesses the highest ranking amongst the diverse alternatives based on bridge users' relative ratings. It is important to note that the system provides the user a wider insight into bridge design alternatives, material, and system to be incorporated into the bridge information model and 'next to kin' alternatives accordingly. As part of developing the integrated system, a plug-in algorithm is hard-coded and incorporated within the BrIM tool to enable the user to instantly determine bridge total length at the conceptual design stage. The plug-in is developed within an object-oriented .NET framework while utilizing a SQLite database, which has the ability to resolve interoperability

issues among internal database applications. Upon completion of TOPSIS, the system automatically runs the BrIM tool, CSiBridge. Then, the user clicks on the advanced tab, selects tools, and proceeds with the ‘CSiBridge Plugin_Map’ option to specify the initial and final destinations of the desired bridge project. The tool then presents the user with the total bridge length as shown in Figure 7.10.

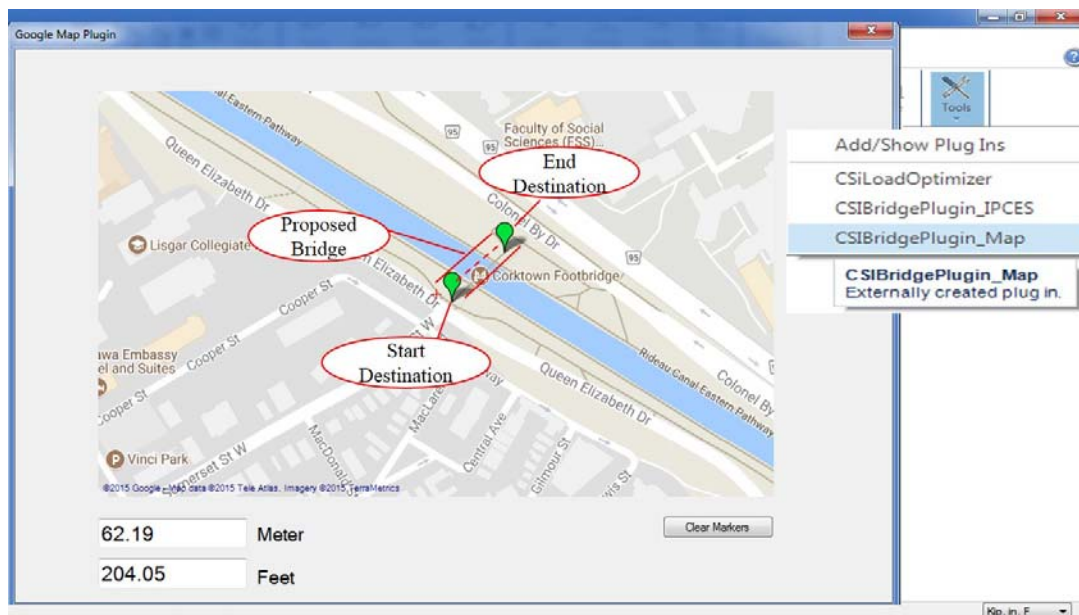


Figure 7.10 Externally Created Plug-in Tools Embedded in BrIM

As shown in Figure 7.10, it is important to note that an externally created plug-in tool ‘CSiBridge Plugin_IPCES’ is embedded into the CSiBridge in order to direct the user to ‘Module 2. Fleet Selection’ following conceptual bridge design. Once total bridge length is identified, the user inputs parameters into the bridge module design and defines geometric constraints as shown in Figure 7.11.

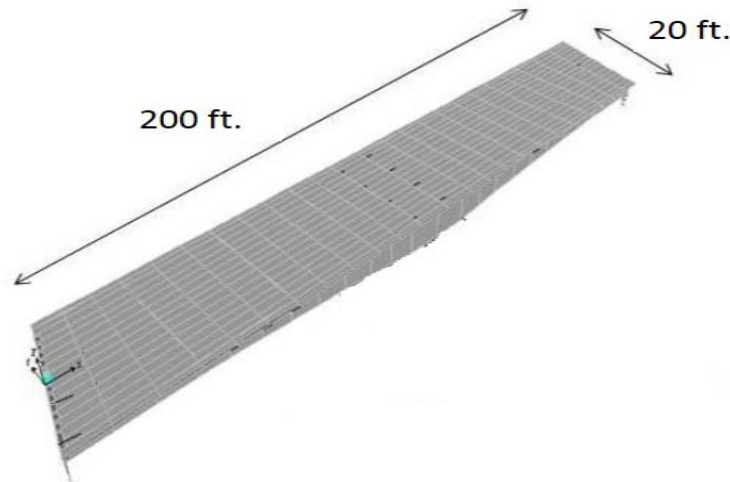


Figure 7.11 Conceptual Bridge Design Information Model

As shown in Figure 7.11, segmental bridge girder geometrical parameters are inputted by the user as follows: 200 ft. (length) and 20 ft. (width). Afterwards, the user clicks on the advanced tab, selects tools, and proceeds with the 'CSiBridge Plugin_IPCES' option. Once selected, the system extracts information from the BrIM tool via a Dynamic Link Library (DLL) - invoked Application Programming Interface (API) approach that automatically recalls the parametric enriched object-oriented model. Then, the system automatically guides the user to the fleet selection system gateway. Once the user selects the desired earthmoving operation, the proposed system displays an input form where necessary parameters related to the scope of work are inputted. Within each operation, input forms that include common variables are automatically extracted and stored in the external database in order to proceed with the numerical analysis of the earthmoving operations as shown in Figure 7.12.

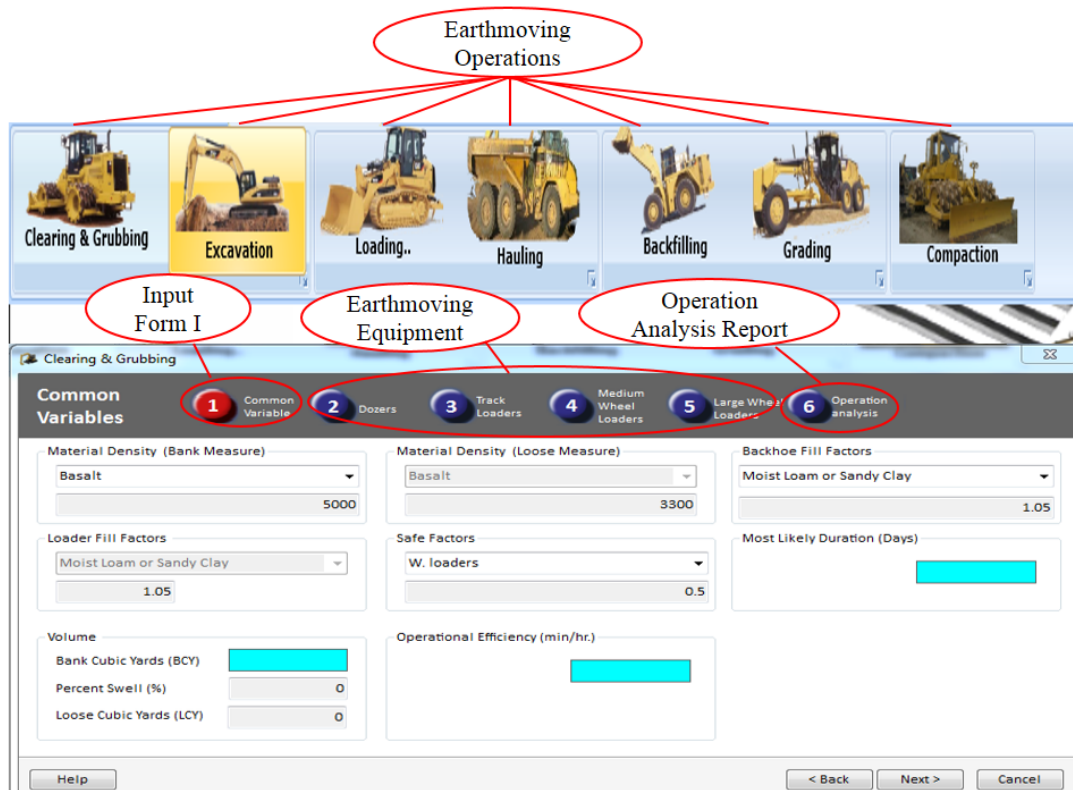


Figure 7.12 Fleet Selection Module Gateway and Input Forms

Next, the user inputs the volume of earthwork in BCY (bank cubic yards) to determine the productivity rates in LCY/hr (loose cubic yards per hour). Once completed, the system displays an output report pertaining to the numerical analysis of the earthmoving operations where productivity rates of earthmoving operations equipment are tabulated. It is important to note that a fleet is defined as a set of selected equipment that will result in the least ownership and operating costs. However, since owning and operating costs are inversely proportional to equipment operation analysis; the fleet is selected based on its productivity rate and cost. For example, if a particular equipment fleet has the maximum productivity rate, it is going to yield

the least owning and operating costs and vice versa. The fleet is obtained by using the cost minimization approach in a given mathematical model for a list of requirements and constraints represented as linear relationships. On the other hand, if the user requires a specific type and number of pieces of equipment, the user may proceed with the manual selection and modify the number of the selected equipment pieces necessary to complete the operation accompanied by corresponding productivity rates as shown in Figure 7.13.

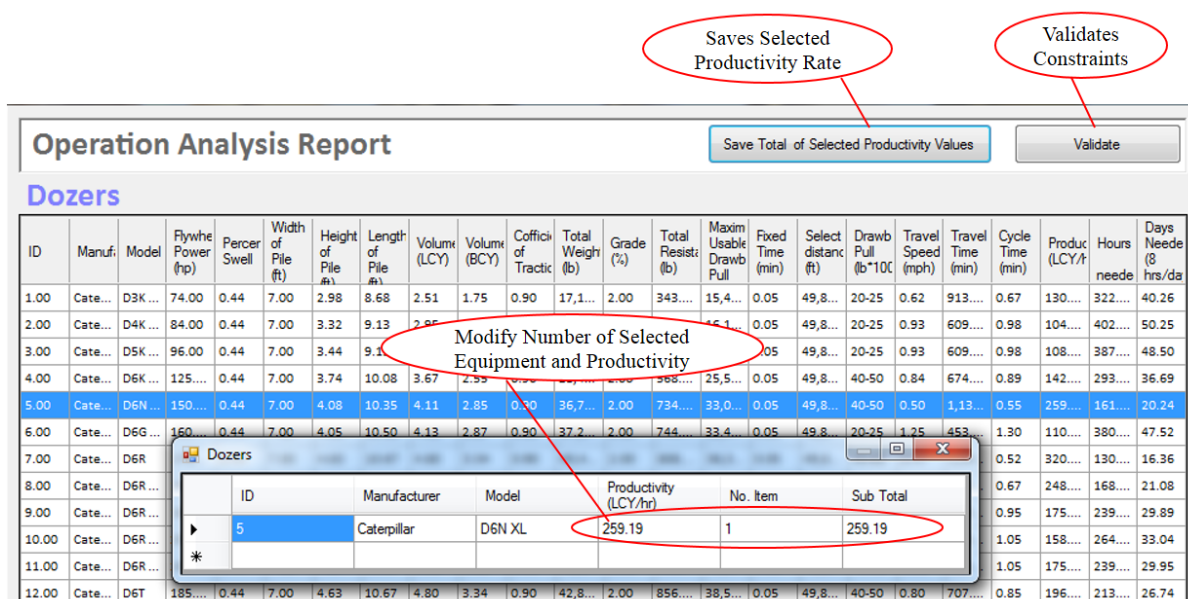


Figure 7.13 Modified Number of Selected Equipment and Corresponding Productivity

Once completed, the user proceeds with either the cost minimization or the manual selection of equipment option in order to determine total equipment owning and operating costs. If the user selects the cost minimization option, the system automatically selects equipment with minimum owning and operation costs; however, if the user selects the manual selection option, the system

determines the owning and operating costs of the selected equipment only as shown in Figure 7.14.

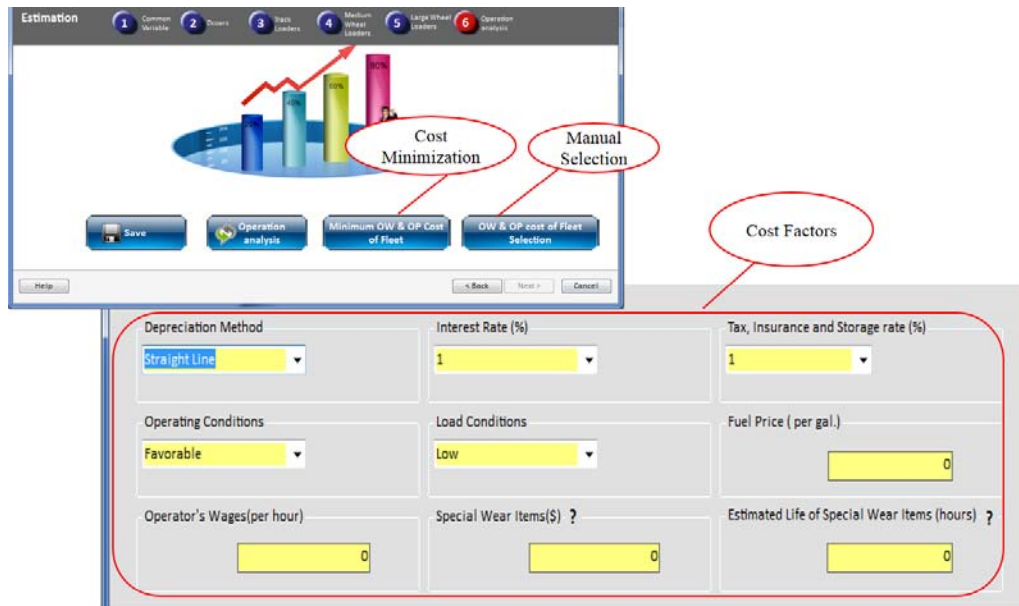


Figure 7.14 Cost Minimization of Ownership and Operating Cost Factors Module

Once completed, the system presents a generic report of owning and operating costs followed by a specific report where total costs are tabulated. Thus, the user selects the fleet needed to complete the earthmoving operation along with corresponding costs which are automatically exported and stored in the cost estimation database as shown in Figure 7.15.

General Owning and Operating Cost Report

Specific Report

Owning Cost

ID	Manufacturer	Category	Model	Delivered Price	Cost/Tire	Estimate Life (Years)	Salvage	Depreciation Costs	Interest, tax, insurance and storage cost	TOTAL OWNING COSTS
1.00	Caterpillar	Track-Type Tractors	D9K XL	89,500.00	0.00	5.00	17,900.00	14,320.00	0.82	7.98
2.00	Caterpillar	Track-Type Tractors	D9K XL	110,000.00	0.00	5.00	11,000.00	17,000.00	1.01	8.01

Specific Output Report of Minimum OW & OP Cost of Fleet

Exports to Cost Estimation Database

Owning Option

Total Owning and Operating Costs

Estimate Construction Cost

Equipment	Manufacturer	Model	Most Likely Duration (Days)	Number of Equipment	Volume (LCY)	Delivered Price	Tires Cost	Salvage Value	Depreciation Cost	Interest Tax Insurance	Total Hourly Cost	Unit Cost (\$/LCY)	Total Owning and Operating Cost
Track-Type Tract...	Caterpillar	D11T CD	20.00	1.00	37,879.00	1,681,200.00	0.00	396,240.00	268,992.00	15.47	280.18	1.13	42,830.97
Medium Wheel ...	Caterpillar	928H	20.00	6.00	37,879.00	1,074,000.00	35,852.40	214,800.00	164,668.52	9.92	347.19	8.14	308,422.26
Large Wheel Loa...	Caterpillar	990H	20.00	1.00	37,879.00	750,000.00	86,020.00	150,000.00	102,796.00	6.99	209.11	0.26	9,905.50
Track Loaders	Caterpillar	953D	20.00	1.00	37,879.00	165,906.00	0.00	33,181.20	26,544.96	1.53	62.14	0.29	10,876.90

Figure 7.15 Selected Fleet Total Owning and Operating Costs

Afterwards, the user proceeds to ‘Module 3. Preliminary Cost Estimation’ which includes the following sub-modules: i) Common Variables; ii) Substructure; iii) Superstructure; iv) Bridge Girders; and v) Concrete Waterproofing System accompanied by input forms as shown in Figure 7.16.a and Figure 7.16.b.

Common Variable	Substructure	Superstructure	Bridge Girders	Concrete waterproofing System
Enter length and width of working plot area as per demarcation				
Temporary Fencing	0	X	0	
	Length (ft)		Width (ft)	
Enter the square footage area of required barrier				
Environmental Barriers	0			
	Area (ft ^2)			
				Clearing & Grubbing (LS)
				Excavation (LS)
Site Clearance (LS)	0			
Common Variable	Substructure	Superstructure	Bridge Girders	Concrete waterproofing System
Substructure				
<i>Prestressed Concrete Piling (Furnish & Install)</i>				
Size of Piling	None			
	☐ Silica fume	☐ Heavy steel reinforcing		
Steel Piling	None			
Drilled Shaft	None			
Enter Length (LF)				

Figure 7.16.a Preliminary Cost Estimation Sub-Modules Input Form I

Common Variable	Substructure	Superstructure	Bridge Girders	Concrete waterproofing System
Superstructure				
<i>Bearing Material</i>				
Neoprene Bearing Pads (CF)		0		
Multirrotational Bearings (Kips)		251-500		
Common Variable	Substructure	Superstructure	Bridge Girders	Concrete waterproofing System
Bridge Girders				
Structural Steel (Including Coating)				
			None	
Common Variable	Substructure	Superstructure	Bridge Girders	Concrete waterproofing System
Concrete Waterproofing System				
				Type A or D
Expansion Joints				Strip Seal
<i>Retaining Walls</i>				
MSE Walls				None

Figure 7.16.b Preliminary Cost Estimation Sub-Modules Input Form II

As shown in Figure 7.16.a and Figure 7.16.b, the user inputs scope-of-work related parameters pertaining to desired bridge project. Once completed, the system automatically recalls bridge data from the BrIM tool, CSiBridge, via a Dynamic Link Library (DLL) - invoked Application Programming Interface (API) method that automatically recalls the parametric enriched object-oriented model. Once completed, total bridge construction costs are tabulated in a UNIFORMAT II elemental classification as shown in Figure 7.17.

Level 1	Level 2	Level 3			Level 4			Level 5	Details			
Major Group Elements	Group Elements	Individual Elements	% of Total Cost	Cost	Sub-Elements	% of Total Cost	Cost	Field Requirements	Unit	Quantity	Unit Cost	Amount
A Substructure	A10 Piers							A10101010 Excavation	LS	1	LOT	\$ 100,000
\$ 757,322	13.9%	\$ 734,457	12.9%		A101010 Spread Footings	11.57%	\$ 657,815	A10101020 Loadings	LS	1	LOT	\$ 150,000
Cost/sq.ft. \$ 105.17	Cost/sq.ft. \$ 102.00							A10101030 Hauling	LS	1	LOT	\$ 130,000
		A1010 Foundations	11.96%	\$ 679,622	A101030 Steel Piling	0.38%	\$ 21,807	A10101040 Cofferdam	SF	1,533	\$ 178.85	\$ 277,815
								A10103010 Temporary Casing	LF	135	\$ 95.00	\$ 12,825
		A1030 Columns	0.96%	\$ 54,835	A103010 Cast-in-Place Concrete	0.96%	\$ 54,835	A10103050 Reinforcement	LB	13,111	\$ 0.59	\$ 7,735
								A10103050 Placement	CY	1.77	\$ 703.84	\$ 1,246
		A30 Abutments			A302010 Cast-in-Place Concrete	0.40%	\$ 22,866	A10301020 Reinforcement	LB	10,097	\$ 0.59	\$ 5,957
		\$ 22,866	0.4%					A10301030 Placement	CY	69	\$ 703.84	\$ 48,878
		Cost/sq.ft. \$ 3.18						A30201010 Reinforcement	LB	5,618	\$ 0.59	\$ 3,315
								A30201020 Placement	CY	28	\$ 703.84	\$ 19,551
B Superstructure	B10 Short Span Assemblies	B1010 Flexural Members	19.44%	\$ 1,104,973	B101010 Cast-in-Place Concrete	19.44%	\$ 1,104,973	B10101010 Reinforcement	LB	1,139,729	\$ 0.59	\$ 672,440
\$ 1,626,158	28.6%	\$ 1,192,045	21.0%		B101010 Elastomeric	1.53%	\$ 87,072	B10101020 Placement	CY	501	\$ 863.81	\$ 432,533
Cost/sq.ft. \$ 225.83	Cost/sq.ft. \$ 165.53	B1010 Bearings	1.53%	\$ 87,072	B20 Long Span Assemblies			B10101020 Placement	EA	12	\$ 7,255.96	\$ 87,072
		\$ 5,359	0.1%									
		Cost/sq.ft. \$ 0.74			B2070 Segmental Box Girders	0.09%	\$ 5,359	B207020 Placement	LB	2,734	\$ 1.96	\$ 5,359
		B30 Deck										
		\$ 428,755	7.5%		B3010 Structural Surface	7.42%	\$ 421,587	B30101010 Reinforcement	LB	370,925	\$ 0.59	\$ 218,846
		Cost/sq.ft. \$ 59.54						B30101020 Placement	CY	200	\$ 863.81	\$ 172,762
					B3020 Wearing Surface	0.13%	\$ 7,168	B30101030 Finishing	SY	937	\$ 32.00	\$ 29,980
C Protection	C10 Structure Protection	C1020 Expansion Joint	0.09%	\$ 5,000	B302020 Asphalt	0.13%	\$ 7,168	B30202010 Placement	SY	800	\$ 8.96	\$ 7,168
\$ 2,396,540	42.2%	\$ 70,000	1.2%									
Cost/sq.ft. \$ 332.82	Cost/sq.ft. \$ 9.72	C1030 Drainage Systems	1.14%	\$ 65,000	C201010 Parapet Wall	1.14%	\$ 65,000					
		C20 Traffic Protection			C201010 Railing	0.57%	\$ 32,248	C20102010 Pedestrian	LF	200	\$ 72.64	\$ 14,588
		\$ 465,382	8.2%		C201050 Curb, Footways, and Paved Areas	0.20%	\$ 11,262	C20102020 Bicycle	LF	200	\$ 88.30	\$ 17,660
		Cost/sq.ft. \$ 64.63										
					C2020 Protective Shields	0.20%	\$ 11,262					
		C30 Other Protection			C2030 Traffic Controls	1.76%	\$ 100,000					
		\$ 235,000	4.1%		C3010 Lighting Controls	4.13%	\$ 235,000					
		Cost/sq.ft. \$ 32.64										
D Site Work	D10 Site Preparation	D1010 Clearing and Grubbing	2.11%	\$ 120,000	C203010 Signals and Road Markings	1.76%	\$ 100,000					
\$ 3,017,069	53.1%	\$ 170,000	3.0%									
Cost/sq.ft. \$ 419.00	Cost/sq.ft. \$ 23.61	D1020 Demolition and Relocation	0.00%	\$ -	D201010 Reinforcement	1.28%	\$ 72,949					
		D1030 Dewatering	0.00%	\$ -	D201020 Placement	1.01%	\$ 57,587					
		D1040 Temporary Shoring	0.00%	\$ -	D201030 Finishing	0.18%	\$ 9,993					
					D201040 Backfilling	1.50%	\$ 85,000					
		D1050 Environmental Restoration	0.88%	\$ 50,000	D201050 Grading	2.20%	\$ 125,000					
					D201060 Compaction	1.76%	\$ 100,000					
		D20 Approach Construction										
		\$ 450,529	7.9%									
		Cost/sq.ft. \$ 62.57										
		D2010 Approach Slab	7.93%	\$ 450,529								
E Site Overheads												
\$ 415,068	7.3%											
Cost/sq.ft. \$ 57.64												
F Mobilization/Demobilization												
\$ 415,068	7.3%											
Cost/sq.ft. \$ 57.64												
G Contingency												
\$ 222,044	3.9%											
Cost/sq.ft. \$ 30.84												
H Overhead & Profit												
\$ 444,087	7.8%											
Cost/sq.ft. \$ 61.67												
I Tax												
\$ 577,313	10.2%											
Cost/sq.ft. \$ 80.18												
TOTAL												
\$ 5,684,317	100.0%											
Cost/sq.ft. \$ 789.42												\$ 5,684,317

Figure 7.17 Bridge Preliminary Cost Estimation Output Report

Once completed, the user proceeds to ‘Module 4. Deterioration Forecast’ where the user inputs the importance rating and a set of improvement goals on bridge components. Following the input of goals, the user can proceed with TOPSIS by clicking on TOPSIS matrix to develop priority rankings of bridge components as shown in Figure 7.18.

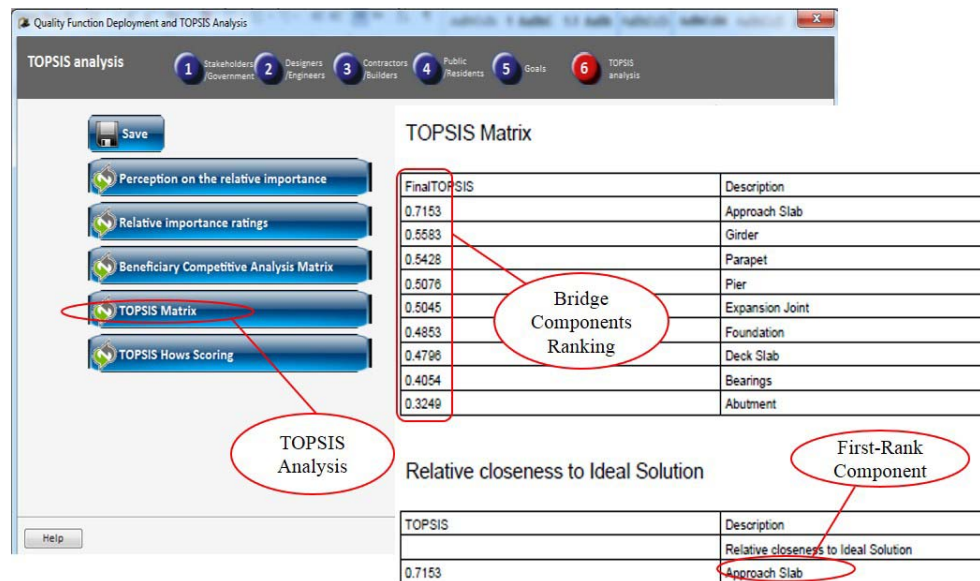


Figure 7.18 Bridge Components Final Ranking

As shown in Figure 7.18, bridge components ‘C₁.Approach Slab’; ‘C₅.Girder’; and ‘C₄.Parapet’ possess maximum weights followed by ‘C₈.Pier’; ‘C₃.Expansion Joint’; ‘C₉.Foundation’; and ‘C₂.Deck Slab’; while, ‘C₆.Bearings’ and ‘C₇.Abutment’ components possess the minimum weights. Typically, bridges are designed by taking into account the following main criteria: (1) Girder; (2) Pier; and (3) Foundation. However, by deploying the TOPSIS technique, it is determined that incorporating additional bridge users, such as contractors/builders and public/residents, influence bridge components importance weights; hence implying a more realistic and practical decision support system. With approach slab and girder components being the most expensive components, contributing significantly towards construction costs, it has

been determined that their importance weight is at the highest rank. Afterwards, the user proceeds to the final module ‘Module 5. Bridge Line of Balance’ where bridge earthmoving operations and components are plotted into a line of balance while taking into account expected bridge project construction duration as illustrated in Figure 7.19.

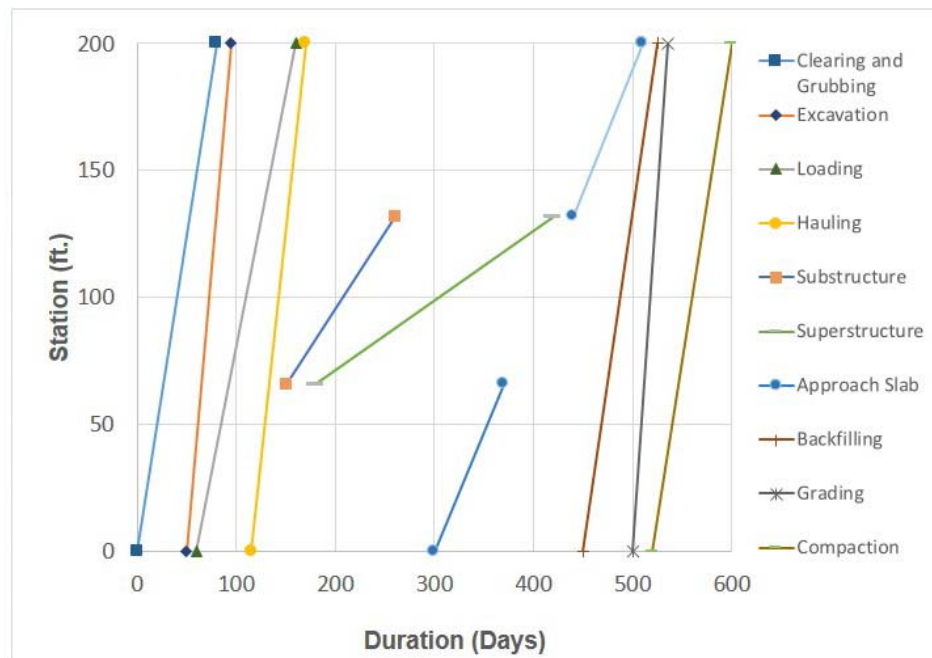


Figure 7.19 Bridge Line of Balance

As illustrated in Figure 7.19, bridge elements are categorized into two main components: ‘Substructure’; which includes: 1) foundation; 2) pier; and 3) abutment; and ‘Superstructure’; which includes: 1) bearings; 2) girder; 3) parapet; 4) expansion joint; and 5) deck slab. It is important to note that the construction of bridge substructure and superstructure starts one-third of the span between ‘station-50ft.’ and ‘station-100ft.’ and ends at two-thirds of the span between ‘station-100ft.’ and ‘station-150ft.’ On the other hand, the construction of the approach slab starts at ‘station-0ft.’ 120 days after the start of superstructure construction and resumes at

two-thirds of the span between ‘station-100ft.’ and ‘station-150ft.’ following the completion of the bridge superstructure.

7.10 Discussion of Results

The expert system presented here is capable of detecting schedule conflicts at the conceptual design stage during the reforming of earthmoving operations sequential combinations. It is important to note that the daily output (LCY) of earthmoving equipment is obtained from the actual volume of earthwork and the earthmoving operation durations. The user will then adjust the time buffers between earthmoving operations in an iterative process in order to determine the near optimum linear schedule for the total project duration. It is important to note that the size and composition of the equipment fleet recommended by the expert system differed from that used in the actual project. The variability in size of equipment fleet is due to scarcity of project site information at the conceptual design stage and availability of equipment at the operational stages. Also, the expert system is developed in such a way that a selected equipment fleet is not shared among the earthmoving operations where one type of equipment is selected to perform a single earthmoving operation. Hence, the recommended equipment fleet proposed by the expert system is based on the individual evaluation of equipment productivity rates. Therefore, the equipment fleet proposed by the expert system possesses enhanced productivity rates, which contributes towards the size and composition of the equipment fleet for a specific project duration. Furthermore, the selection of equipment fleet is directly proportional to daily productivity rates; and therefore, in order to avoid an impractical size of equipment fleet, a comprehensive list of equipment types for each earthmoving operation is organized into seven major categories as discussed earlier. Towards the end, the estimated project cost and duration

are compared to the actual cost and duration and found to be within a percentage difference ranging from approximately 10 to 15%, as illustrated in Table 7.2.

Table 7.2 Comparison of Estimated Bridge Cost (CAD) and Duration (Days) Results

Phase	Construction Cost (\$)	Pre-Construction Duration (Days)	Bridge Construction Duration (Days)	Post-Construction Duration (Days)
System Data	5,684,317	170	220	150
Actual Data	5,000,000	148	194	128

Prior to comparison of results, it is important to note that the discrepancy between the results is due to the multiple assumptions made as well as to the availability of resources at the time of construction as well as consistent productivity rates without fluctuations. For instance, fleet productivity is based on normal job site conditions. If unforeseen circumstances occur, the near-optimum line of balance would be instantly affected. Also, the productivity is estimated based on an off-site methodology. Moreover, the results are based on the combined optimization of cost and time analysis of the selected fleet without taking into consideration any constraints associated with these two parameters. The variation in project duration is due to the difference in the size and composition of the equipment fleet. The range of variation in project duration is acceptable at the conceptual design stage since the overall information pertaining to the project is neither fully defined nor detailed. The results fall within Class 3 of the AACE International Cost Estimate Classification System with an expected accuracy range of 10% to 30% which is an improvement to bridge cost estimates at the conceptual design stage that typically fall within Class 4 with an expected accuracy range of 20% to 50%. Overall results show that the accuracy of the system varies depending on the fleet productivity obtained and availability of resources and logistic considerations.

7.11 Summary and Conclusions

Integrating bridge information management systems (BrIMS) with construction technologies has inspired many researchers during the past decade. In this study, the viability of integrating a 3D computer-aided design (3D-CAD) model with bridge cost estimation system without compromising interoperability matters is discussed. An integrated system that relates a fuzzy logic decision support system with cost estimation for bridges is presented. Developing conceptual cost estimates is a multi-faceted task encountered by bridge stakeholders and infrastructure assets managers at the conceptual design stage of a bridge project. In line with conceptual cost estimation requirements, a 3D-CAD BrIM model and corresponding project-related data are necessary for obtaining reliable estimates. An integrated platform for effective exchange of project information among stakeholders results in cost-effective design alternatives. Furthermore, the deployment of an expert system for bridge type selection improves interoperability and compatibility features of the proposed platform.

In summary, this study proposes the integration of an expert system with bridge information management system (BrIMS), preliminary cost estimation, and linear scheduling of bridge projects at the conceptual design stage. The proposed system is engineered to enhance existing techniques implemented by bridge stakeholders and designers to prepare cost estimates and linear schedules at the conceptual design stage by taking into consideration a typical bridge project work break down structure that includes the following main divisions: 1) substructure; 2) superstructure; 3) protection; 4) site work; and 5) mobilization/demobilization. Furthermore, comparative analyses of diverse bridge components are conducted via TOPSIS to assist users in ranking bridge components. The proposed system is found to possess an advantage over existing

decision support algorithms and cost estimation applications known to the industry by including the following distinguishing features:

- An automated estimation tool for nine diverse bridge design type alternatives in North America.
- Integrating a BrIM with relational databases to generate multiple automated preliminary construction cost estimates.
- Ability to extract project-related parameters instantly from a BrIM and capability of implementing them with external third party data interchange applications.
- Incorporating a heavy equipment operational analysis while considering comprehensive owning and operating costs.
- Producing preliminary cost estimates by utilizing the UNIFORMAT II Elemental Classification and work breakdown structure in imperial units.
- Forecasting bridge elemental deteriorations based on gamma shock modeling and time-dependent analysis at the conceptual design stage.
- Including an all-in-one estimation tool that is capable of automating the required cost and time optimization techniques.
- Developing a bridge line of balance based on expected durations of heavy earthmoving operations and bridge main substructure and superstructure components at the conceptual design stage.

In conclusion, the results presented in this study are anticipated to be of major significance to the bridge construction industry and would be a novel contribution to BrIMS. Anticipated contributions of this study reside in the development of an integrated stand-alone all-in-one system capable of providing the user with recommendations to bridge design alternatives based on a combination of decision support, fleet selection, and cost estimation at the conceptual design stage. Besides that, the proposed system is developed in a manner that facilitates the interoperability and compatibility amongst the diverse proposed modules, sub-modules and database resources.

7.12 References

Agrawal K., Benoit A., Magnan L. and Robert Y. (2010). Scheduling algorithms for linear workflow optimization. 24th IEEE International Symposium on Parallel and Distributed Processing (IPDPS), Atlanta, Georgia, 19-23.

Arayici Y., Aouad G. (2005). Computer integrated construction: an approach to requirements engineering. *Engineering, Construction and Architectural Management*, 12(2), 194 – 215.

Association for the Advancement of Cost Engineering (AACE) International. (2016). Recommended Practice No. 18R-97, Cost Estimate Classification System, Available at: <https://web.aacei.org> [Accessed on August 6th, 2017].

Boddy S., Rezgui Y., Copper G., and Wetherill M. (2006). Computer integrated construction: A review and proposals for future direction. *Elsevier*, 38(10), 677-687.

Brown A., Rezgui Y., Cooper G., Yip J., Brandon P. (1996). Promoting computer integrated construction through the use of distribution technology. *Journal of Information Technology in Construction*, 1, 1-16.

Chan L. and Wu M. (2005). A systematic approach to quality function deployment with a full illustrative example. *Omega*, Elsevier Ltd, 33, 119-139.

Dreo J., Siarry P., Petrowski A., and Taillard E. (2006). *Metaheuristics for hard optimization: methods and case studies*. Springer, 12, France.

ElSayegh S. (1998). Linear construction planning model (LCPM): A new model for planning and scheduling linear construction projects. Ph.D. dissertation, Texas A&M University, Texas.

Fischer M. (1989). Design construction integration through constructibility design rules for the preliminary design of reinforced concrete structures. CSCE. Structural Concrete Conference, Montreal , QC, 333-346.

Fischer M., Betts M., Hannus M., Yamasaki Y., and Laitinen J. (1993). Goals, dimensions, and approaches for computer integrated construction. *Management of Information Technology for Construction*, Singapore, World Scientific Publishing Co. Ltd, 421-433.

Forrest C., and Lorenzoni A. (1997). *Applied cost engineering*. 3rd Edition, Marcel Dekker.

Gallaher M., O'Conner A., Dettbarn J. and Gilday, L. (2004). Cost analysis of inadequate interoperability in the U.S. capital facilities industry. NIST GCR 04-867, National Institute of Standards and Technology, Gaithersburg, MD.

Hinze J. (2008). *Construction planning and scheduling*. 3rd Edition, Prentice Hall, Upper Saddle River, New Jersey.

Jung Y., and Gibson G. (1999). Planning for computer integrated construction. *Journal of Computing in Civil Engineering*, 13(4), 217–225.

Kawamura K., Miyamoto A., Frangopol D., and Kimura R. (2003). Performance evaluation of concrete slabs of existing bridges using neural networks. *Engineering Structures*, 25(12), 1455-1477.

Liu W., Flood I. and Issa, R. (2005). Simulation and optimization of linear construction projects. *Proceedings of Computing in Civil Engineering*, ASCE, 1-11.

Malekly H., Mousavi S. and Hashemi, H. (2010). A fuzzy integrated methodology for evaluating conceptual bridge design. *Expert System with Applications*, Elsevier Ltd., 37(7), 4910-4920.

Otayek E., Jrade A. and Alkass, S. (2012). Integrated decision support system for bridges at conceptual design stage. *CIB W78 ‘29th*, Beirut, Lebanon, 334-343.

Peurifoy R., and Oberlender G. (2002). *Estimating construction costs*. 5th Edition, .McGraw Hill Companies.

Pinto J., (1998). *Project management handbook*. The Project Management Institute, Wiley, New York.

Shim C., Yun N. and Song, H. (2011). Application of 3D bridge information modeling to design and construction of bridges. *Procedia Engineering*, Elsevier, 14: 95-99.

Song L., Lee S-H. and Rachmat, F. (2012). Stochastic look-ahead scheduling method for linear construction projects. *Atlantis Press*, 252-260.

Srisuwanrat C. and Ioannou, P. (2007). The investigation of lead-time buffering under uncertainty using simulation and cost optimization. Proceedings of the 15th International Group for Lean Construction Conference, Ann Arbor, Michigan, 580-589.

Uppal K. (1999). Estimating past, present and 21st century. AACE 41st Annual Meeting, 1.1-1.4.

Westney R. (1997). The engineer's cost handbook: tools for managing project costs. Marcel Dekker., New York.

CHAPTER 8

CONCLUSIONS, LIMITATIONS, CONTRIBUTIONS, AND FUTURE WORK

8.1 Conclusions

Integrating bridge information management systems (BrIMS) with construction technologies has inspired many researchers during the past decade. In this thesis, the viability of integrating a 3D BrIM model with a structural analysis application and bridge cost estimation framework without compromising interoperability matters is implemented. An integrated system that relates a fuzzy logic decision support system with cost estimation for bridges was presented. Developing conceptual cost estimates is a multi-faceted task encountered by bridge stakeholders and infrastructure assets managers at the conceptual design stage of a bridge project. In line with conceptual cost estimation requirements, a 3D CAD BrIM model and corresponding project-related data are necessary for obtaining reliable estimates. An integrated platform for effective exchange of project information among stakeholders results in cost-effective design alternatives. Furthermore, the deployment of an expert system for bridge type selection improves interoperability and compatibility features of the proposed platform.

This thesis illustrates the research methodology and development process of an integrated expert system with a bridge information management system (BrIMS), cost estimation, deterioration forecasting, and linear scheduling at the conceptual design stage. The developed system is engineered to enhance existing techniques implemented by bridge stakeholders and designers to prepare cost estimates at the conceptual design stage by taking into consideration a typical bridge project work breakdown structure that includes the following main divisions: 1) site preparations; 2) substructure; 3) superstructure; and 4) site works. The developed system

possessed a great advantage over existing decision support algorithms and cost estimation applications known to the industry by including the following distinguished features:

1. Integrating BrIM model with relational databases to automatically generate preliminary construction cost estimates by utilizing the UNIFORMAT II and Work Breakdown Structure (WBS) in imperial units besides extracting project-related parameters instantly from BrIM model and capability of implementing them with external third party data interchange applications.
2. Forecasting bridge elemental deteriorations based on gamma shock modeling and time-dependent analysis at the conceptual design stage.
3. Incorporating a heavy equipment operational analysis while considering comprehensive renting, owning, and operating costs to develop a line of balance schedule based on expected durations of heavy earthmoving operations and bridge main substructure and superstructure components at the conceptual design stage.
4. Including an all-in-one bridge construction costs estimation tool that is capable of automating the required cost and time optimization techniques.

It is important to highlight, that the developed cost estimation system is developed for preparation of conceptual cost estimates for bridge projects based on the currently implemented cost database for normal average conditions. Such preliminary estimates may not be used for bidding purposes. However, the expert system serves as a foundation for future development to advanced design stages.

8.2 Limitations of the Developed System

It must be emphasized that the developed expert system may be used as a decision support tool to generate preliminary cost estimates, linear schedules, and deterioration forecasts for bridges at the project and/or network level. The developed system, however, can neither be used for preparation of life cycle assessments nor life cycle costs. The following list summarizes the developed system main limitations:

- Practitioners and experts in the field of bridge construction who participated in the interview for fuzzy logic scoring of bridge WHATs criteria are limited to three interviewees per user category. In order to generate more accurate criterion weights, the number of interviewees per user category must be increased along with the selective process of background diversity.
- Optimistic and pessimistic durations of bridge earthmoving operations are limitations of the developed system since they are mainly influenced by the scale of subjectivity involved and are highly dependent upon user experience on similar projects.
- Homogeneity of near-optimum results is one limitation of the developed system as it provides productivity rates that are suitable for undertaking work with diverse soil properties.

- Shortage of deterioration resistance data for similar bridges is one limitation of the developed system which could significantly affect the predicted regression fit and bridge component's deterioration resistance capacities.

Other system limitations are as follows:

- The developed system cannot be applied beyond the conceptual design stage of a bridge project since system databases have been developed to incorporate data commonly known to bridge stakeholders and designers at the conceptual design stage.
- Transfer of information between the BrIM tool and the developed expert system is designed to automatically extract and exchange of data which limits the user capability of customizing output data obtained from system modules.
- The developed expert system possesses a limitation pertaining to equipment suppliers, resource availability, and earth rock material. In fact, much more complex studies are required to be conducted in order to select the required fleet for this type of material work, such as earthwork involving bridge construction in mountainous terrains.
- The developed sub-modules and plug-ins are for research purposes and standard applications. A snapshot of developed plug-ins is illustrated in Appendix IV. Further enhancements to the attached hard-coding in Appendix V are required to convert the user-friendly developed system into professional use.

8.3 Contributions

The expected contributions of this thesis are the following:

- Developing an integrated stand-alone all-in-one system capable of providing the user with recommendations for bridge design alternatives based on a combination of decision support, heavy equipment selection, and cost estimation at the conceptual design stage.
- Automating the generation of cost estimation reports based on instant modification of the BrIM model and/or any of the project internal or external databases.
- Implementing the TOPSIS technique for BrIM model to assist in prioritizing preventative maintenance, repair, and replacement decisions by deploying complex cyclic gamma shock models for prediction of bridge temporal deteriorations based on historical data of similar bridges at the conceptual design stage.
- Generating a near-optimum bridge line of balance that includes both heavy earthmoving activities and bridge components at the conceptual design stage.
- Applicability of the developed system for diverse bridges design alternatives in North America and Europe regardless of the differences between the bridge design codes since the databases presented in this thesis are designed in such a way that they may be customized to suit accordingly.

8.4 Future Work

This thesis presents an integration platform that may be utilized by bridge stakeholders, infrastructure asset managers, designers, and cost estimators to assist in preparation of conceptual cost estimates. The developed system may be enhanced by the following list of future development work as listed:

- Expanding the system to include cost databases from diverse resources for simplifying its applicability in the construction industry.
- Upgrading the system for workability during construction stages while automating the generation of earned value analysis and on-time performance indices.
- Enhancing the system deterioration forecasting module capability by incorporating complex and combined bridge sub- and super-structure designs along with life cycle costing analysis.
- Incorporating complex quality functions on prioritizing maintenance, repair, and replacement decision for individual bridge components.
- Implementing an extension to the probabilistic and numerical system databases of solutions, which is an important step towards developing rational design rules for bridge components.

CHAPTER 9

REFERENCES

Alkass, S., and Harris, F. (1988). "Expert system for earthmoving equipment selection in road construction." *Journal of Construction Engineering and Management*, 114(3), 426-440.

Alshibani, A., and Moselhi, O. (2012). "Fleet selection for earthmoving projects using optimization-based simulation." *Canadian Journal of Civil Engineering*, National Research Council (NRC) Research Press, 39(6), 619-630.

Amirkhanian, S., and Baker, N. (1992). "Expert system for equipment selection for earthmoving operations." *Journal of Construction Engineering and Management*, 118(2), 318-331.

Hellmund, A., Wymelenberg, K., and Baker, K. (2008). "Facing challenges of integrated design and project delivery." *Journal of Energy Engineering*, Taylor and Francis, 105(6) 36-47.

An, S.H., Kim, G.H., and Kang, K.I. (2007). "A case-based reasoning cost estimating model using experience by analytic hierarchy process." *Building and Environment*, Elsevier, 42(7) 2573-2579.

Anderson, D., Sweeney, D., Williams, T., and Martin, K. (2008). "An introduction to management science quantitative approaches to decision making." Mason, OH: Thomson Higher Education.

Arditi, D., Kale, S., and Tangkar, M. (1997). "Innovation in construction equipment and its flow into the construction industry." *Journal of Construction Engineering and Management*, 123 (4), 371-378.

Bajaj, A., Gransberg, D., and Grenz, D. (2002). "Parametric estimating for design costs," AACE 46th Annual Meeting, 8.1-8.6.

Belegundu, A., and Chandrupatla, T. (2002). "Optimization concepts and applications in engineering." Delhi: Pearson Education.

Bode, J. (1998). "Neural networks for cost estimation." *Cost Engineering*, 40(1), 25-30.

Bradley, R., Powell, M., and Soulsby, M. (1989) "Quantifying variations in project-cost estimate." *Journal of Management in Engineering*, 6(1), 99-106.

Brito, J., Branco F., Thoft-Christensen, P., and Sorensen, J. (1997). "An expert system for concrete bridge management." *Engineering Structures*, 19(7), 519-526.

Callow, D., Lee, J., Blumenstein, M., Guan, H., and Loo, Y.C. (2013). "Development of hybrid optimization method for artificial intelligence based bridge deterioration model — feasibility study." *Automation in Construction*, Elsevier, 31, 83-91.

Caneparo, L. (2005). "Computer-integrated construction: Background and a case project." 2nd International Symposium on Automation and Robotics in Construction, ISARC 2005, 1–9.

Caterpillar[®] (2011). "Caterpillar performance handbook." Peoria: Caterpillar.

Charette, R., and Marshall, H. (1999). "UNIFORMAT II: Elemental classification for building specifications, cost estimating, and cost analysis." NISTIR 6389, Gaithersburg.

Chassiakos, A., Vagiots, P., and Theodorakopoulos, D. (2005). "A knowledge-based system for maintenance planning of highway concrete bridges." *Advances in Engineering Software*, 36(11-12), 740 - 749.

Darte, A., Khachiyan, L., and Robert, Y. (1991). "Linear scheduling is nearly optimal." *Parallel Processing Letters*, 1(2), 1-13.

Day, D., and Benjamin, N. (1991). "Construction equipment guide." New York: John Wiley & Sons.

Ding, L., Zhou, Y., and Akinici, E. (2014). "Building information modeling (BIM) application framework: The process of expanding 3D to computable nD." *Automation in Construction*, Elsevier 46, 82-93.

Elbeltagi, E., and Dawood, M., (2011). "Integrated visualized time control system for repetitive construction projects." *Automation in Construction*, Elsevier, 20(7), 940-953.

Eldin, N., and Mayfield, J. (2005). "Determination of most economical scrapers fleet." *Journal of Construction Engineering and Management*, 131 (10), 1109-1114.

Ellsworth, K. (1998). "Cost-to-capacity analysis for estimating waste-to-energy facility costs." *Cost Engineering Journal*, 40(6), 27-30.

Elmasri, R., and Navathe, S. B., (2007). "Fundamentals of database systems." 5th Edition, Pearson/Addison Wesley.

Furst, P. (2010) "Constructing integrated project delivery." *Industrial Management*, Institute of Industrial Engineers.

Gates, M., and Scarpa, A. (1975). "Optimum size of hauling units." *Journal of the Construction Division* , 101 (CO4), 853-860.

Gransberg, D., Popescu, C., and Ryan, R. (2006). "Construction equipment management for engineers, estimators, and owners." Boca Raton, FL: Taylor & Francis Group.

Haidar, A., Naoum, S., Howes, R., and Tah, J. (1999). "Genetic algorithms application and testing for equipment selection." *Journal of Construction Engineering and Management*, 125 (1), 32-38.

Halpin, D., and Woodhead, R. (1976). "Design of construction and process operations." New York, John Wiley and Sons Inc.

Halpin, D., and Woodhead, R. (1998). "Construction management." New York: John Wiley and Sons Inc.

Hammad, A., Yan, J., and Mostofi, B., (2007). "Recent development in bridge management systems in Canada." *Annual Conference of the Transportation Association of Canada*, Saskatoon, Saskatchewan.

Hasancebi, O., and Dogan, E., (2010). "Optimizing single-span steel truss bridges with simulated annealing." *Asian Journal of Civil Engineering (Building and Housing)*, 11(6), 763-775.

Hegazy, T. and Ayed, A. (1989). "Neural network model for parametric cost estimation of highway projects." *Journal of Construction Engineering and Management*, 124(3), 210-218.

Hendrickson, C. (2000). "Project management for construction." World Wide Web Publication, 2nd edition.

Hummer, J., Arocho, I., Rasdorf, W. (2017). "Approach to assessing tradeoffs between construction equipment fleet emissions and cost." *Journal of Construction Engineering and Management*, ASCE, 143(5).

Jain, K., and Bhattacharjee, B. (2012). "Application of fuzzy concepts to the visual assessment of deteriorating reinforced concrete structures." *Journal of Construction Engineering and Management*, ASCE, 138(3).

Jeong, W.S., Chang, S., and Son, J.W. (2016). "BIM-Integrated construction operation simulation for just-in-time production management." *Sustainability, Multidisciplinary Digital Publishing Institute (MDPI)*, 8(11), 1-25.

Jinsong, Z., Rucheng, X., and Lizhi, H. (2007). "Reliability assessment of large-span cable-stayed bridges based on artificial intelligence." *China Civil Engineering Journal*, China National Knowledge Infrastructure (CNKI).

Johnson, A., and Kwong, K. (2001). "Cost modeling-accurate preconstruction estimates quicker." *AACE 45th Annual Meeting*, 1.1-1.3.

Key, J. (1987). "Earthmoving and heavy equipment." *Journal of Construction Engineering and Management*, 113 (4), 611-622.

Kim, K., and Gibson Jr., G. (2003). "Interactive simulation modeling for heavy construction operations." *Journal of Automation in Construction*, 12 (1), 97-109.

Kim, K.J., Yun, W.G., Cho, N., and Ha, J. (2017). "Life cycle assessment based environmental impact estimation model for pre-stressed concrete beam bridge in the early design phase." *Environmental Impact Assessment Review*, Elsevier, 64, 47-56.

Lucko, G., and Vorster, M. (2003). "Predicting the residual value of heavy construction equipment." Proceedings of the 2003 4th Joint International Symposium on Information Technology in Civil Engineering, Nashville: American Society of Civil Engineers, 1-11.

Makovsek, D. (2014). "Systematic construction risk, cost estimation mechanism and unit price movements." Transport Policy, Elsevier, 35, 135-145.

Marti, J., Alcala, J., Garcia-Segura, T., and Yepes, V. (2016). "Heuristic design of a precast-prestressed concrete U-beam and post-tensioned cast-in-place concrete slab road bridges." WIT Transactions on the Built Environment, Institute of Concrete Science and Technology (ICITECH), 166, 17-28.

Marzouk, M., and Moselhi, O. (2003). "Object-oriented simulation model for earthmoving operations." Journal of Construction Engineering and Management, 129(2), 173-181.

Marzouk, M., and Moselhi, O. (2004). "Multiobjective optimization of earthmoving operations." Journal of Construction Engineering and Management, 130(1), 105-113.

McGuire, B., Atadero, R., Clevenger, C., and Ozbek, M. (2016). "Bridge information modeling for inspection and evaluation." Journal of Bridge Engineering, ASCE, 21(4).

Melin, J. (1994). "Parametric estimation." Cost Engineering Journal, 36(1), 19-24.

Messner, J. (2005). "Computer integrated construction research program." Available at: <http://www.engr.psu.edu> [Accessed on June 6th, 2015].

Meyer, R., and Burns, J. (1999). "Facility parametric cost estimating." AACE 43rd Annual Meeting, 2.1-2.6.

Moselhi, O., and Marzouk, M. (2000). "Automated system for cost estimating of earthmoving operations." Proceedings of the 17th International Symposium on Automation and Robotics in Construction (ISARC), Taipei, Taiwan, 1053-1058.

Moselhi, O., and Siqueira, I. (1998). "Neural networks for cost estimating of structural steel buildings." AACE 42nd Annual Meeting, 6.1-6.4.

O'Brien, J., Havers, J., and Stubbs, Jr, F. (1996). "Standard handbook of heavy construction." New York: McGraw-Hill.

Oberlender, D., and Trost, M. (2001). "Predicting accuracy of early cost estimates based on estimate quality." Journal of Construction Engineering and Management, ASCE, 127, 173-182.

Ostwald, P. (1984). "Cost estimating." 2nd Edition, Engle-wood Cliffs, New Jersey: Prentice Hall.

Peurifoy, R., and Schexnayder, C. (2002). "Construction planning, equipment, and methods." New York: McGraw-Hill.

Phelps, R. (1977). "Equipment costs." Working Paper, Oregon State University, Corvallis, Oregon.

Rast, J., and Peterson, M. (1999). "Parametric cost estimating for environmental remediation projects." AACE 43rd Annual Meeting, 9.1-9.11.

Rashidi, M., and Lemass, B. (2011). "A decision support methodology for remediation planning of concrete bridges." Journal of Construction Engineering and Project Management, Korea Science, 1(2), 1-10.

Reda, R. (1990). "RPM: Repeitive Project Modeling." *Journal of Construction and Engineering and Management*, ASCE, 116(2), 316-330.

Ringwald, R. (1987). "Bunching theory applied to minimize cost." *Journal of Construction Engineering and Management*, ASCE, 113(2), 321-326.

Rossi, F., Van Beek, P., and Walsh, T. (2006). "Handbook of constraint programming." Elsevier, USA.

R.S. Means® (2012). "R. S. means heavy construction cost data." Reed Construction Data Construction Publishers & Consultants, Norwell, MA, U.S.A.

Sanders, S., Maxwell, R., and Glagola, C. (1992). "Preliminary estimating models for infrastructure projects." *Cost Engineering Journal*, 34(8), 7-13.

Schexnayder, C., and David, S. (2002). "Past an future of construction equipment-part IV." *Journal of Construction Engineering and Management*, 128(4), 279-286.

Shapira, A., and Goldenberg, M. (2005). "AHP-based equipment selection model for construction projects." *Journal of Construction Engineering and Management*, 131 (12), 1263-1273.

Srinivas, V., Sasmal, S., and Karusala, R. (2016). "Fuzzy based decision support system for condition assessment and rating of bridges." *Journal of the Institution of Engineers (India): Series A*, Springer, 97(3), 261-272.

Sun, X.Y., Dai, J.G., Wang, H.L., and Dong, W.W. (2015). "Decision support system for optimizing the maintenance of RC girder bridge superstructures in consideration of the carbon footprint." *Journal of Bridge Engineering*, ASCE, 20(12).

Su, Y., and Lucko, G. (2016). "Linear scheduling with multiple crews based on line-of-balance and productivity scheduling method with singularity functions" *Automation in Construction*, Elsevier, 70, 38-50.

Tang, Y., Liu, R., Wang, H.L., and Sun, Q. (2014). "Schedule control model for linear projects based on linear scheduling method and constraint programming." *Automation in Construction*, Elsevier, 37, 22-37.

Tatum, C., Vorster, M., Klingler, M., and Paulson, B. (2006). "Systems analysis of technical advancement in earthmoving equipment." *Journal of Construction Engineering and Management*, 132 (9), 976-986.

Tavakoli, A. (1985). "Productivity analysis of construction operations." *Journal of Construction Engineering and Management*, 111 (1), 31-39.

Tavakoli, A., and Taye, E. (1989). "Equipment policy of top 400 contractors: a survey." *Journal of Construction Engineering and Management*, 115 (2), 317-329.

Thompson, P., Merlo, T., Kerr, B., Cheetham, and A., Ellis, R. (2000). "The new Ontario bridge management system." 8th International Bridge Management Conference, TRB Transportation Research Circular 498, 1, F-6/1 – F-6/15.

Vojinovic, Z., Seidel, R., and Kecman, V. (2000). "Advanced cost estimating and strategic planning." AACE 44th Annual Meeting, 6.1-6.8.

Wagter, H. (1992). "Computer integrated construction." Elsevier Science Publishers B.V., Netherlands.

Yao, I.(1980). "Damage assessment of existing structures." Journal of the Engineering Mechanics Division, 106(4), 785-799.

Yeh, I. (1989). "Quantity estimating of building with logarithm-neuron networks." Journal of Construction Engineering and Management, 24(5), 374-380.

Zadeh, A., (1965). "Fuzzy sets." Information and Control, 8(3), 338-353.

Zuk, W., (1991). "Expert system for determining the disposition of older bridges."Transportation Research Board, Washington, D.C., 145-148.

APPENDIXES

APPENDIX I

Bridge Experts' Interview Questionnaire

Dear Participant,

Thank you for participating in this interview questionnaire. This questionnaire is intended to evaluate your perception/opinion on diverse criteria for constructing a new bridge in our city/region. In this questionnaire, you will be required to submit your score on bridge selection 'WHATs' criteria according to a 9-point scale scoring system. This questionnaire is part of a research conducted by Nizar Markiz and lead by Dr. Ahmad Jrade whom are members of the Faculty of Postgraduate and Postdoctoral Studies (FGPS). As part of this questionnaire, background information for each participant is required. All of the information collected shall be kept strictly confidential and are intended solely for research purposes.

Name:

Organization:

Position:

Experience:

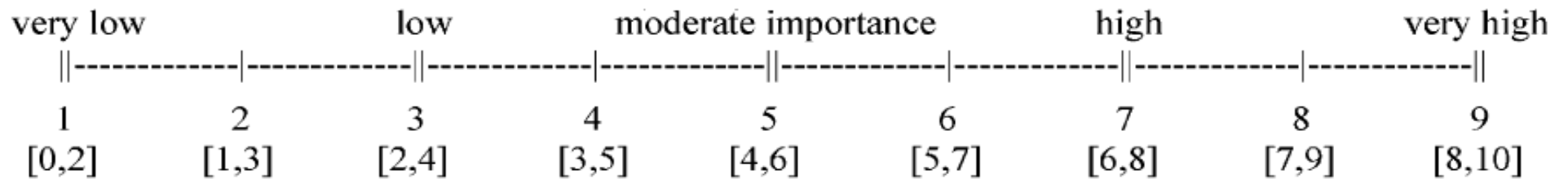
Age:

Academic Qualification:

Experience with Decision Support Systems:

'WHATs' Criteria	'WHATs' Sub-Criteria	Bridge Design Type								
		C1. Beam	C2. Truss	C3. Cantilever	C4. Arch	C5. Tied-Arch	C6. Suspension	C7. Cable-Stayed	C8. Movable	C9. Double-Decked
W1. Technical	Design Requirements									
	Code Compliance									
	Load-Bearing Capacity									
W2. Functional	Traffic Capacity									
	Freight Efficiency									
	Sustainability									
W3. Safety	Parapet Wall									
	Protective Shields									
	Traffic Barriers									
W4. Construction	Methodology									
	Inspection Accessibility									
	Traffic Diversification									
W5. Economics	Direct/Indirect Costs									
	Fund Allocation									
	Benefit/Cost Ratio									
W6. Aesthetics	Architectural Design									
	Urban/Sub-Urban Perspective									
	Touristic Attraction									
W7. Material	Aggressive Environment Durability									
	Environmental Impact									
	Maintainability									

Scoring System (9-Point Scale):



Source: Chan and Wu (2005)

Relative Importance Perception on WHATs Un-Weighted Criteria Matrix

Whats	C1.Crisp	C1.Fuzzy	C2.Crisp	C2.Fuzzy	C3.Crisp	C3.Fuzzy	C4.Crisp	C4.Fuzzy	C5.Crisp	C5.Fuzzy
W1. Technical	7	[6,8]	9	[8,10]	1	[0,2]	5	[4,6]	7	[6,8]
W2. Functional	7	[6,8]	7	[6,8]	9	[8,10]	9	[8,10]	9	[8,10]
W3. Safety	7	[6,8]	5	[4,6]	5	[4,6]	7	[6,8]	5	[4,6]
W4. Construction	7	[6,8]	7	[6,8]	3	[2,4]	1	[0,2]	3	[2,4]
W5. Economics	5	[4,6]	9	[8,10]	7	[6,8]	5	[4,6]	7	[6,8]
W6. Aesthetics	3	[2,4]	5	[4,6]	5	[4,6]	7	[6,8]	5	[4,6]
W7. Material	5	[4,6]	7	[6,8]	5	[4,6]	5	[4,6]	7	[6,8]

Whats	C6.Crisp	C6.Fuzzy	C7.Crisp	C7.Fuzzy	C8.Crisp	C8.Fuzzy	C9.Crisp	C9.Fuzzy
W1. Technical	3	[2,4]	5	[4,6]	1	[0,2]	3	[2,4]
W2. Functional	5	[4,6]	9	[8,10]	9	[8,10]	1	[0,2]
W3. Safety	3	[2,4]	5	[4,6]	3	[2,4]	3	[2,4]
W4. Construction	1	[0,2]	3	[2,4]	1	[0,2]	3	[2,4]
W5. Economics	3	[2,4]	5	[4,6]	1	[0,2]	1	[0,2]
W6. Aesthetics	9	[8,10]	9	[8,10]	5	[4,6]	5	[4,6]
W7. Material	5	[4,6]	7	[6,8]	5	[4,6]	7	[6,8]

Normalized Bridge Type Competitive Matrix Analysis

Whats	C1	C2	C3	C4	C5	C6	C7	C8	C9	em
W1. Technical	5.5	6	4.5	6	6	5.5	5.5	3	4.5	0.14
W2. Functional	7.5	8.5	8	7.5	7	8	9	7	5	0.15
W3. Safety	6.5	5.5	6	7	6	4.5	5.5	4.5	4.5	0.15
W4. Construction	6.5	5.5	1.5	1	3	1	3	1	3	0.13
W5. Economics	4.5	6	5	4	5.5	3.5	5	2.5	3.5	0.14
W6. Aesthetics	3.5	4.5	5	7.5	7.5	8.5	7.5	5	5	0.14
W7. Material	6	6	5	5	5.5	4	6	5	6	0.15

Normalized Weighted TOPSIS Decision Matrix

0.35	0.33	0.39	0.64	0.33	0.19	0.37
0.38	0.37	0.33	0.54	0.44	0.24	0.37
0.29	0.35	0.36	0.15	0.37	0.27	0.31
0.38	0.33	0.42	0.10	0.30	0.40	0.31
0.38	0.31	0.36	0.29	0.41	0.40	0.34
0.35	0.35	0.27	0.10	0.26	0.46	0.25
0.35	0.40	0.33	0.29	0.37	0.40	0.37
0.19	0.31	0.27	0.10	0.18	0.27	0.31
0.29	0.22	0.27	0.29	0.26	0.27	0.37

Normalized Weighted TOPSIS Positive Ideal Solution

0.049	0.049	0.058	0.083	0.047	0.026	0.055
0.053	0.056	0.049	0.070	0.062	0.034	0.055
0.040	0.053	0.053	0.019	0.052	0.037	0.046
0.053	0.049	0.062	0.013	0.041	0.056	0.046
0.053	0.046	0.053	0.038	0.057	0.056	0.051
0.049	0.053	0.040	0.013	0.036	0.064	0.037
0.049	0.059	0.049	0.038	0.052	0.056	0.055
0.027	0.046	0.040	0.013	0.026	0.037	0.046
0.040	0.033	0.040	0.038	0.036	0.037	0.055

Normalized Weighted TOPSIS Negative Ideal Solution

0.049	0.049	0.058	0.083	0.047	0.026	0.055
0.053	0.056	0.049	0.070	0.062	0.034	0.055
0.040	0.053	0.053	0.019	0.052	0.037	0.046
0.053	0.049	0.062	0.013	0.041	0.056	0.046
0.053	0.046	0.053	0.038	0.057	0.056	0.051
0.049	0.053	0.040	0.013	0.036	0.064	0.037
0.049	0.059	0.049	0.038	0.052	0.056	0.055
0.027	0.046	0.040	0.013	0.026	0.037	0.046
0.040	0.033	0.040	0.038	0.036	0.037	0.055

Normalized Weighted TOPSIS Separation from Positive Ideal Solution

$(0.049 - 0.053)^2$	$(0.049 - 0.059)^2$	$(0.058 - 0.062)^2$	$(0.083 - 0.083)^2$	$(0.047 - 0.026)^2$	$(0.026 - 0.064)^2$	$(0.055 - 0.055)^2$	0.001971	0.0441
$(0.053 - 0.053)^2$	$(0.056 - 0.059)^2$	$(0.049 - 0.062)^2$	$(0.070 - 0.083)^2$	$(0.062 - 0.026)^2$	$(0.034 - 0.064)^2$	$(0.055 - 0.055)^2$	0.002560	0.051
$(0.040 - 0.053)^2$	$(0.053 - 0.059)^2$	$(0.053 - 0.062)^2$	$(0.019 - 0.083)^2$	$(0.052 - 0.026)^2$	$(0.037 - 0.064)^2$	$(0.046 - 0.055)^2$	0.005776	0.076
$(0.053 - 0.053)^2$	$(0.049 - 0.059)^2$	$(0.062 - 0.062)^2$	$(0.013 - 0.083)^2$	$(0.041 - 0.026)^2$	$(0.056 - 0.064)^2$	$(0.046 - 0.055)^2$	0.005360	0.073
$(0.053 - 0.053)^2$	$(0.046 - 0.059)^2$	$(0.053 - 0.062)^2$	$(0.038 - 0.083)^2$	$(0.057 - 0.026)^2$	$(0.056 - 0.064)^2$	$(0.051 - 0.055)^2$	0.003270	0.057
$(0.049 - 0.053)^2$	$(0.053 - 0.059)^2$	$(0.040 - 0.062)^2$	$(0.013 - 0.083)^2$	$(0.036 - 0.026)^2$	$(0.064 - 0.064)^2$	$(0.037 - 0.055)^2$	0.005884	0.077
$(0.049 - 0.053)^2$	$(0.059 - 0.059)^2$	$(0.049 - 0.062)^2$	$(0.038 - 0.083)^2$	$(0.052 - 0.026)^2$	$(0.056 - 0.064)^2$	$(0.055 - 0.055)^2$	0.002889	0.054
$(0.027 - 0.053)^2$	$(0.046 - 0.059)^2$	$(0.040 - 0.062)^2$	$(0.013 - 0.083)^2$	$(0.026 - 0.026)^2$	$(0.037 - 0.064)^2$	$(0.046 - 0.055)^2$	0.007033	0.084
$(0.040 - 0.053)^2$	$(0.033 - 0.059)^2$	$(0.040 - 0.062)^2$	$(0.038 - 0.083)^2$	$(0.036 - 0.026)^2$	$(0.037 - 0.064)^2$	$(0.055 - 0.055)^2$	0.004141	0.064

Normalized Weighted TOPSIS Separation from Negative Ideal Solution

$(0.049 - 0.027)^2$	$(0.049 - 0.033)^2$	$(0.058 - 0.040)^2$	$(0.083 - 0.013)^2$	$(0.047 - 0.062)^2$	$(0.026 - 0.027)^2$	$(0.055 - 0.037)^2$	0.006542	0.081
$(0.053 - 0.027)^2$	$(0.056 - 0.033)^2$	$(0.049 - 0.040)^2$	$(0.070 - 0.013)^2$	$(0.062 - 0.062)^2$	$(0.034 - 0.027)^2$	$(0.055 - 0.037)^2$	0.004988	0.071
$(0.040 - 0.027)^2$	$(0.053 - 0.033)^2$	$(0.053 - 0.040)^2$	$(0.019 - 0.013)^2$	$(0.052 - 0.062)^2$	$(0.037 - 0.027)^2$	$(0.046 - 0.037)^2$	0.001106	0.033
$(0.053 - 0.027)^2$	$(0.049 - 0.033)^2$	$(0.062 - 0.040)^2$	$(0.013 - 0.013)^2$	$(0.041 - 0.062)^2$	$(0.056 - 0.027)^2$	$(0.046 - 0.037)^2$	0.002890	0.054
$(0.053 - 0.027)^2$	$(0.046 - 0.033)^2$	$(0.053 - 0.040)^2$	$(0.038 - 0.013)^2$	$(0.057 - 0.062)^2$	$(0.056 - 0.027)^2$	$(0.051 - 0.037)^2$	0.002825	0.053
$(0.049 - 0.027)^2$	$(0.053 - 0.033)^2$	$(0.040 - 0.040)^2$	$(0.013 - 0.013)^2$	$(0.036 - 0.062)^2$	$(0.064 - 0.027)^2$	$(0.037 - 0.037)^2$	0.002960	0.054
$(0.049 - 0.027)^2$	$(0.059 - 0.033)^2$	$(0.049 - 0.040)^2$	$(0.038 - 0.013)^2$	$(0.052 - 0.062)^2$	$(0.056 - 0.027)^2$	$(0.055 - 0.037)^2$	0.003261	0.057
$(0.027 - 0.027)^2$	$(0.046 - 0.033)^2$	$(0.040 - 0.040)^2$	$(0.013 - 0.013)^2$	$(0.026 - 0.062)^2$	$(0.037 - 0.027)^2$	$(0.046 - 0.037)^2$	0.001696	0.041
$(0.040 - 0.027)^2$	$(0.033 - 0.033)^2$	$(0.040 - 0.040)^2$	$(0.038 - 0.013)^2$	$(0.036 - 0.062)^2$	$(0.037 - 0.027)^2$	$(0.055 - 0.037)^2$	0.001957	0.044

Normalized Weighted TOPSIS Relative Closeness to Ideal Solution (Priority Rankings)

$0.081/(0.044 + 0.081)$	0.646	Beam
$0.071/(0.051 + 0.071)$	0.583	Truss
$0.033/(0.076 + 0.033)$	0.304	Cantilever
$0.054/(0.073 + 0.054)$	0.423	Arch
$0.053/(0.057 + 0.053)$	0.482	Tied – Arch
$0.054/(0.077 + 0.054)$	0.415	Suspension
$0.057/(0.054 + 0.057)$	0.515	Cable – Stayed
$0.041/(0.084 + 0.041)$	0.329	Movable
$0.044/(0.064 + 0.044)$	0.407	Double – Decked

APPENDIX II

Equipment Specifications and Mathematical Formulations

According to Schaufelberger (1999), rim-pull is the power available to move a wheeled piece of equipment and its associated load which is calculated by using Equation A.1.

$$RP = \frac{375 (HP)(e)}{V} \quad (A.1)$$

Where; RP is the maximum rim-pull; HP is the horsepower of the engine; e is the gear efficiency which ranges from 0.75 to 0.85; and V is the speed (mph); however, both methods differ in calculating cycle time for the hauling system. Peurifoy and Schexnayder's (2002) method includes loading, traveling, and delay times as illustrated in Equation A.2.

$$C = L + T + D \quad (A.2)$$

Where; C is the cycle time (min); L is the loading time (min); T is the travel time (min); and D is the delay time (min), whereas Phelps's (1977) method includes fixed, variable, and loading times as shown in Equation A.3.

$$C = F_i + V + L \quad (A.3)$$

Where; C is the cycle time (min); F_i is the fixed time (min); V is the variable time (min); and L is the loading time (min). The fixed time in Phelps's method includes all time components except wasted time (Gransberg et al., 2006). Variable time, however, is calculated for a piece of equipment while loaded or empty and is obtained using Equations A.4 to A.6:

$$V_H = \frac{375(HP)(e)}{W_F(RR + 20(\pm S))}; \quad \text{while loaded} \quad (A.4)$$

$$V_R = \frac{375(HP)(e)}{W_E(RR + 20(\pm S))}; \quad \text{while empty} \quad (A.5)$$

$$V = \frac{60d}{V_H} + \frac{60d}{V_R} \quad (A.6)$$

Where; V_H is the travel speed while loaded (mph); V_R is the travel speed while empty (mph); V is the total variable time; W_F is the weight loaded (tons); W_E is the weight empty (tons); RR is the rolling resistance (lb/ton); S is the segment slope (%); and d is the travel distance (miles). For both methods, the required number of units is determined using Equation A.7; however, an apparent pitfall is that the optimum size of hauling units is not considered. According to Gates and Scarpa (1975), Equation (A.7) is as consistently reliable as other more complex relationships.

$$n = \frac{C}{L} \quad (A.7)$$

Where; n is the number of haul units; C is the total hauling cycle time (min); L is the loading time per equipment (min). The first model to include the cost function in system optimization is the one developed by Gates and Scarpa (1975). Their model utilizes Equation A.7 to estimate the required number of units and then employs Equation (A1.8) to optimize hauling unit size.

$$S_{opt} = \sqrt{\frac{DPT}{k}} \quad (A.8)$$

Where; S_{opt} is the optimum size of hauling unit (yd³); D is the total out-of-pocket hourly cost (\$); P is the production rate of loading (yd³); T is the cycle time except loading time (min); and k is the hourly cost per unit of capacity (\$). It is noticed that Equation A.8 is adopted from the bunching (queue's) theory. Although bunching theory equations are verified in the construction field, it has been found that they under predict production by 3%, which is not the

preference of contractors (Ringwald, 1987). The original equation is based on the probability that no haul unit or one or more haul units is available as indicated in Equation A.9:

$$P_t = 1 - \left[\sum_{i=0}^n \frac{n!}{(n-i)!} (r)^i \right]^{-1} \quad (\text{A.9})$$

Where; P_t is the probability that one or more haul units is available; n is the number of hauler units; i is the integer from 0 to n ; and r is the ratio of arrival rate to loading rate. After determining the probability, results are stored into tables. By using Equation A.10, the ratio of arrival rate to loading rate is calculated. Then, the result value is used to determine the optimum hauling units. After that, the number of optimum hauling units is calculated as per the ratio $1/r$.

$$r = \frac{T_C}{L_p \times T} \quad (\text{A.10})$$

Where; r is the ratio of arrival rate to loading rate; T_C is the truck capacity; L_p is the loader production rate; and T is the travel time. Equations A.11 to A.15 are used to determine the magnitude of the rolling resistance factor, grade resistance factor, and total resistance:

$$\text{Rolling Resistance Factor} \left(\frac{\text{lb}}{\text{ton}} \right) = 40 \frac{\text{lb}}{\text{ton}} + \left[\left(30 \frac{\text{lb}}{\text{ton/in.}} \right) (\text{in. of tire penetration}) \right] \quad (\text{A.11})$$

$$\text{Rolling Resistance Force (lb)} = \left[\text{Rolling Resistance Factor} \left(\frac{\text{lb}}{\text{ton}} \right) \right] [\text{Total Weight (ton)}] \quad (\text{A.12})$$

$$\text{Grade Resistance Factor} \left(\frac{\text{lb}}{\text{ton}} \right) = \left(20 \frac{\text{lb}}{\text{ton}} \text{ per } \% \text{ slope} \right) (\% \text{ slope}) \quad (\text{A.13})$$

$$\text{Grade Resistance Force (lb)} = \left[\text{Grade Resistance Factor} \left(\frac{\text{lb}}{\text{ton}} \right) \right] [\text{Total Weight (ton)}] \quad (\text{A.14})$$

$$\text{Total Resistance (lb)} = \text{Rolling Resistance Force (lb)} + \text{Grade Resistance Force (lb)} \quad (\text{A.15})$$

The maximum usable tractive force is then calculated using Equation A.16:

$$TF_{\max} = W * C_r \quad (\text{A.16})$$

Where; $TF_{\max}$ is the maximum tractive force; W is the weight on driving wheels or tracks (lb);

and C_r is the coefficient of traction. The deratign factor is calculated using Equation (A.17):

$$\text{Derating Factor} = \frac{(0.3) * (\text{Altitude (ft.)} - 1000 \text{ (ft.)})}{1000 \text{ (ft.)}} \quad (\text{A.17})$$

The total construction cost of the project is estimated based on Equation A1.18, as follows:

$$TC = DC + IC \quad (\text{A.18})$$

Where; TC is the project total estimated construction cost; DC is the total direct construction cost; and IC is the total indirect construction cost. Direct costs are calculated based on Equation A.19 below:

$$\text{Direct Constructi on Cost (\$)} = \text{Quantity of Work} * \text{Unit Cost (\$)} \quad (\text{A.19})$$

Where Unit Cost is the cost of a unit of work extracted from the preliminary cost estimation module database. Indirect costs are then calculated using Equations A.20 through A.22 below:

$$\text{OH \& P (\$)} = \text{Direct Constructi on Cost (\$)} * \text{OH \& P Input (\%)} \quad (\text{A.20})$$

$$\text{Contingency (\$)} = \text{Direct Cosntruction Cost (\$)} * \text{Contingency Input (\%)} \quad (\text{A.21})$$

$$\text{Sales Tax (\$)} = \text{Direct Constructi on Cost (\$)} * \text{Sales Tax Input (\%)} \quad (\text{A.22})$$

Where $\text{OH \& P}$ is the anticipated overhead and profit cost; and $\text{OH \& P (\%)}$, $\text{Contingency (\%)}$, and $\text{Sales Tax (\%)}$ are the corresponding user input percentages for overhead and profit, contingency, and sales tax. At the end, total project construction costs are calculated based on Equation A.23.

$$\text{Total Construction Cost(\$)} = \text{Direct Cost(\$)} + \text{Indirect Cost(\$)} \quad (\text{A.23})$$

Table A.1 illustrates an example of hauler capacity and specification data incorporated into the system.

Table A.1 Hauler Capacity and Specifications

Model	Flywheel Power (hp)	Weight Distribution Empty (Loaded)			Maximum Weight (lb)	Heaped Capacity (yd ³)
		(%)				
		Front	Center	Rear		
725	309	58.5 (32.8)	21.7 (34.1)	19.8 (33.1)	101,082	19
770	511	48.0 (33.0)	-	52.0 (67.0)	157,000	33
772	598	48.0 (33.0)	-	52.0 (67.0)	181,000	41

Source: Caterpillar[®] Performance Handbook, 2011

Table A.2 presents an example of a transformed chart for a Caterpillar[®] 621G Elevating Scraper.

Table A.2 Elevating Scraper 621G Transformed Chart (Empty)

Distance-One Way (ft.)	Total Resistance (%)	Travel Speed (mph)
0.000-1,000	0	0.438
1,000-2,000	2	0.750
2,000-3,000	4	1.250
3,000-4,000	6	2.125
4,000-5,000	8	3.375
5,000-6,000	12	5.500
6,000-7,000	14	5.500

Source: Caterpillar[®] Performance Handbook, 2011

Table A.3 summarizes the types of material and their corresponding densities.

Table A.3 Earth Material Properties

Material	Loose Density (lb/yd ³)	Bank Density (lb/yd ³)
Basalt	3,300	5,000
Caliches	2,100	3,800
Cinders	950	1,450
Clay	2,800	3,400
Dry	2,500	3,100
Wet	2,800	3,500
Coal	2,000	2,700
Washed	1,850	2,200
Top Soil	1,600	2,300
Loam	2,100	2,600

Percent swell is the increase in volume or reduction in density (Schaufelberger, 1999) and is calculated using Equation A.24:

$$\text{Percent Swell}(\%) = \frac{(V_L - V_B)(100\%)}{V_B} \quad (\text{A.24})$$

Where; V_L is the loose volume, and V_B is the bank volume. Load factor is the ratio between bank measure and loose measure and is used to convert from loose to bank and vice versa and calculated using Equation A.25 (O'Brien et. al., 1996):

$$\text{Load Factor} = \frac{V_L}{V_B} \quad (\text{A.25})$$

Shrinkage factor is the decrease in volume after the soil is compacted and is calculated using Equation A.26 (Schaufelberger, 1999):

$$\text{Percent Shrinkage}(\%) = \frac{(V_c - V_B)(100\%)}{V_B} \quad (\text{A.26})$$

Where V_c is the compacted volume.

Table A.4 illustrates typical coefficients of traction for common types of surfaces.

Table A.4 Typical Coefficients of Traction

Material	Rubber Tires	Crawler Tracks
Concrete	0.90	0.45
Clay load, dry	0.55	0.90
Clay loam, wet	0.45	0.70
Dry sand	0.20	0.30
Wet sand	0.40	0.50
Quarry pit	0.65	0.55
Packed snow	0.20	0.27
Firm earth	0.55	0.90
Loose earth	0.45	0.60
Coal, stockpiled	0.45	0.60

Source: (Caterpillar[®] Performance Handbook, 2011)

▪ **Excavators**

Table A.5 illustrates examples of the selected excavators and corresponding specifications.

Table A.5 Excavators Specifications

Model	Flywheel Power (hp)	Bucket Capacity (yd ³)	Cycle Time (min.)
301.6 C	18	0.073	0.210
302.5 C	25	0.120	0.210
312 D	90	0.970	0.210
315 DL	115	1.150	0.240
324 D	166	1.960	0.250
336 D	268	2.490	0.270
365 CL	404	4.290	0.300
390 D	523	6.100	0.350
M316 D	160	1.650	0.180
M318 D	169	1.650	0.200
M322 D	167	2.050	0.230

Source: (Caterpillar® Performance Handbook, 2011)

Table A.6 presents backhoe and front shovel bucket fill factors while the heaped capacity is calculated using Equation A.27:

$$\text{Heaped Capacity} = \text{Rated Capacity} * \text{Bucket Fill Factor} \quad (\text{A.27})$$

Table A.6 Backhoe and Front Shovel Bucket Fill Factors

Equipment	Material	Bucket Fill Factor
Backhoe	Moist Loam or Sandy Clay	0.75
	Sand and Gravel	1.10
	Hard, Tough Clay	1.50
	Rock – Well Blasted	2.50
	Rock – Poorly Blasted	3.50
Front Shovel	Bank clay; earth	1.05
	Rock-earth mixtures	1.10
	Poorly blasted rock	0.95
	Well blasted rock	1.05
	Shale; sandstone	0.95

Source: (Caterpillar® Performance Handbook, 2011)

The productivity of excavators and front shovels is then calculated using Equation A.28:

$$Productivity = \frac{Heaped\ Capacity * E}{Cycle\ Time\ (min.)} \quad (A.28)$$

Where E is operating minutes per hour, which represent the percentage of use.

▪ **Dozers**

Table A.7 presents a sample of selected dozers and corresponding specifications.

Table A.7 Dozers Specifications

Model	Flywheel Power (hp)
D8R	305
D9R	405
D9T	410
D10T	580
D11T	850

Source: (Caterpillar[®] Performance Handbook, 2011)

Correction factors are classified into five groups: (1) job condition; (2) material type; (3) job efficiency; (4) material weight; and (5) blade type. The first four groups are listed in Table A.8.

Table A.8 Dozers Correction Factors

Job Condition	
Excellent	1.00
Average	0.75
Poor	0.60
Material Type	
Loose stockpile	1.20
Hard to cut	0.8
Very sticky material	0.8
Rock, ripped or blasted	0.7
Job Efficiency	
50 min/hr	0.83
40 min/hr	0.67
Weight Factor	
2300 lb/LCY (ideal) / (actual)	

Source: (Caterpillar[®] Performance Handbook, 2011)

Table A.9 summarizes the maximum production of selected dozers for illustrative purposes.

Table A.9 Maximum Production of Dozers (LCY/hr)

Distance (ft.)	Semi-U Blade				
	D8R	D9R	D9T	D10T	D11T
0.00-100	625	1,100	1,100	1,600	2,200
100-200	400	600	600	900	1,250
200-300	275	450	450	625	900
300-400	200	350	350	500	700
400-500	190	300	300	400	575
500-600	175	225	225	350	450

Source: (Caterpillar[®] Performance Handbook, 2011)

- On-the-job Estimating: This method involves calculating the volume of earth that can be moved during each operating cycle using Equation A.29:

$$Productivity = \frac{Volume\ of\ Earthwork}{Cycle\ Time\ (min.)} \quad (A.29)$$

- Off-the-job Estimating: This method obtains the maximum productivity of a dozer from production curves provided by the manufacturer. Because the maximum production is based on certain conditions, contractors must correct its value by applying correction factors using Equation A.30:

$$Production = Maximum\ Production * Correction\ Factors \quad (A.30)$$

▪ **Scrapers**

Tables A.10 and A.11 present scrapers and corresponding specifications.

Table A.10 Scrapers Specifications

Model	Flywheel Power (hp)	Heaped Capacity (BCY)
621G	365	22
623G	365	23
627G	365	22
631G	500	34
637G	500	34
657G	600	44

Source: (Caterpillar® Performance Handbook, 2011)

Table A.11 Scrapers Weight Distribution

Model	Distribution Empty (%)		Distribution Loaded (%)	
	Front	Rear	Front	Rear
621G	67	33	52	48
623G	63	37	52	48
627G	59	41	50	50
631G	64	36	52	48
637G	59	41	50	50
657G	58	42	50	50

Source: (Caterpillar® Performance Handbook, 2011)

Table A.12 Scrapers Fixed Time (min.)

Job Conditions	Loading Time	Spot and Delay Time	Turning and Dumping Time
Favorable	0.8	Negligible	0.3
Average	1.1	Negligible	0.5
Unfavorable	1.5	0.2	0.8

Source: (Schaufelberger, 1999)

Table A.13 illustrates an example of a retarder chart.

Table A.13 Scraper 621G (Empty) Travel Time (minutes)

Distance (ft.)	Total Resistance (%)								
	0	2	4	6	8	10	12	14	16
0.00-1,000	0.438	0.500	0.563	0.625	0.750	0.875	1.000	1.250	1.375
1,000-2,000	0.800	0.800	0.900	1.125	1.375	1.625	1.875	2.250	2.500
2,000-3,000	1.125	1.125	1.300	1.625	2.125	2.500	3.000	3.375	3.875
3,000-4,000	1.500	1.500	1.625	2.125	2.7500	3.250	3.875	4.500	5.125
4,000-5,000	1.875	1.950	2.000	2.750	3.375	4.000	4.875	5.500	5.500
5,000-6,000	2.250	2.250	2.375	3.250	4.000	4.875	5.500	5.500	5.500
6,000-7,000	2.500	2.625	2.875	3.750	31	5.500	5.500	5.500	5.500

Source: (Caterpillar[®] Performance Handbook, 2011)

In order for the user to be able to select the proper value of total resistance, the effective grade is calculated using Equation A.31:

$$\text{Effective Grade (\%)} = \text{Actual Grade (\%)} + \frac{\text{Rolling Resistance Factor (lb/ton)}}{20 \text{ lb/ton per \% slope}} \quad (\text{A.31})$$

The productivity of a scraper is estimated by using Equations A.32 and A.33, based on the assumption that a scraper does not require a dozer to assist in performing the work, which is one limitation of the work.

$$\text{Productivity} = \frac{\text{Rated Capacity (BCY)} * \text{Operational Efficiency}}{\text{Cycle Time (min)}} \quad (\text{A.32})$$

$$\text{Cycle Time (min)} = \text{Fixed Time (min)} + \text{Travel Time (min)} \quad (\text{A.33})$$

The fixed time (min) includes loading time, spot and delay time, and turning and dumping time and is estimated by using Equation A.34.

$$\text{Fixed Time (min)} = \text{Loading Time (min)} + \text{Spot Time (min)} + \text{Turning Time (min)} \quad (\text{A.34})$$

▪ **Loaders**

There are particular constraints that must be checked when conducting the operation analysis for loaders. The first constraint is the maximum weight a particular loader can handle per cycle. Table A.14 presents examples of the selected loaders and corresponding specifications. The maximum weight is determined by using Equation A.35:

$$\text{Maximum Weight} = \text{Safe Factor} * \text{Static Tipping Load} \quad (\text{A.35})$$

Where the safe factor is determined from Table A.15 and the static tipping load is determined from Table A.14.

Table A.14 Loaders Specifications

Size	Model	Flywheel Power (hp)	Static Tipping Load (lb)	Bucket Capacity (BCY)
Medium	904 H	55	5,657	0.78
	924 H	132	9,858	2.20
	972 H	307	32,894	5.00
Large	990 H	687	82,018	11.00
	993 K	1,050	124,494	15.70
	994 F	1,577	241,032	18.50
Tracked	939 C	90	14,560	1.50
	973 D	263	46,700	3.74

Source: (Caterpillar[®] Performance Handbook, 2011)

Table A.15 Loader Safe Factors

Type of Loader	Safe Factor (%)
Wheeled Loader	50
Crawler Loader	35

Source: (Schaufelberger, 1999)

The second constraint is the load weight, which should always be less or equal to than the maximum weight and is calculated using Equation A.36:

$$\text{Load Weight} = \text{Fill Factor} * \text{Heaped Capacity} \quad (\text{A.36})$$

Where the fill factor is determined from Table A.16 and the heaped capacity is calculated using Equation A.27.

Table A.16 Loader Bucket Fill Factors

Material	Fill Factor
Mixed Moist Aggregates	1.05
Uniform Aggregates	
Up to 3 mm (1/8 in.)	1.05
3 mm-9 mm (1/8 in.-3/8 in.)	0.95
12 mm-20 mm (1/2 in.-3/4 in.)	0.90
24 mm and over (1 in.)	1.0

Source: (Caterpillar[®] Performance Handbook, 2011)

Table A.17 illustrates the performance chart for loader travel time

Table A.17 Loader 904H Travel Time (min)

Loaded			Empty		
Select Distance (ft)	Total Resistance (%)	Travel Time (min)	Select Distance (ft)	Total Resistance (%)	Travel Time (min)
0.00-100	8	0.188	0-100	8	0.163
100-200	8	0.375	100-200	8	0.261
200-300	8	0.438	200-300	8	0.375
300-400	8	0.510	300-400	8	0.500
400-500	8	0.688	400-500	8	0.563
500-600	8	0.813	500-600	8	0.688
600-700	8	0.938	600-700	8	0.813
700-800	8	1.063	700-800	8	0.750

Source: (Caterpillar[®] Performance Handbook, 2011)

Then, the productivity is estimated using Equation A.37

$$Productivity = \frac{(Heaped\ Capacity) * (Operational\ Efficiency)}{Cycle\ Time\ (min)} \quad (A.37)$$

Where cycle time is the sum of loader fixed and travel times (min) and determined by using Equation A.33.

▪ **Haulers**

Tables A.18 and A.19 present examples of selected haulers and corresponding specifications.

Table A.18 Haulers Specifications

Model	Flywheel Power (hp)	Rated Heaped Capacity (BCY)
735B	452	26
740B	489	31
773F	740	46
777D	1,000	79
785D	1,450	102
789C	1,900	137
793D	2,415	195
797F	4,000	333

Source: (Caterpillar® Performance Handbook, 2011)

Table A.19 Haulers Weight Distribution

Model	Distribution Empty (%)			Distribution Loaded (%)		
	Front	Center	Rear	Front	Center	Rear
735B	61.9	20.2	18.0	36.0	33.0	32.0
740B	60.1	21.0	18.9	35.0	33.0	32.0
773F	51.0	-	49.0	35.0	-	65.0
777D	47.0	-	53.0	33.0	-	67.0
785D	46.0	-	54.0	33.0	-	67.0
789C	46.9	-	53.1	33.6	-	66.4
793D	47.0	-	53.0	33.0	-	67.0
797F	43.5	-	56.5	33.3	-	66.7

Source: (Caterpillar® Performance Handbook, 2011)

Equation A.38 is used to determine the load weight:

$$Load \ Weight \ (lb) = \left(\frac{Heaped \ Capacity}{1 + Percent \ Swell} \right) \times Material \ Density \quad (A.38)$$

The maximum rim-pull for the loaded truck is calculated using Equation A.39:

$$\text{Maximum Rimpull (lb)} = (\text{Coefficient of Traction}) * (\text{Weight on Driving Axle}) \quad (\text{A.39})$$

Where the coefficient of traction is obtained from Table A.4 and the weight on driving axles is obtained from multiplying the total weight by the weight distribution on the center and rear axles. The distribution values are obtained from Table A.18.

Table A.20 is used to estimate the dumping and spotting times. For the loading time, a table is created to contain all the data for all sixteen selected loaders. Equation A.40 is used to calculate the loading time for each hauler.

$$\text{Loading Time (min)} = \left(\frac{\text{Hauler Heaped Capacity}}{\text{Loader Heaped Capacity}} \right) \times \text{Loader Cycle Time (min)} \quad (\text{A.40})$$

Table A.20 Haulers Fixed Time (min.)

Job Conditions	Turning and Dumping Time	Spotting Time
Favorable	1.00	0.15
Average	1.30	0.30
Unfavorable	1.75	0.80

Source: (O'Brien et al., 1996)

Table A.21 illustrates an example of the user input data.

Table A.21 Hauling Road Segments

No.	Distance (ft.)	Grade (%)
1	1,000	4
2	2,000	9
3	2,000	6
4	1,000	8

Equations A.41 and A.42 are used to determine the average speed (mph) in each segment, which is the maximum speed corrected using the speed factors in Table A.22. The travel time is determined using Equation A.43

$$\text{Maximum Speed (mph)} = \frac{\text{Net Horsepower} \times 375}{\text{Total Resistance (lb)}} \quad (\text{A.41})$$

$$\text{Average Speed (mph)} = \text{Maximum Speed (mph)} * \text{Speed Factor} \quad (\text{A.42})$$

$$\text{Travel Time} = \frac{\text{Total Distance}}{\text{Average Speed}} \quad (\text{A.43})$$

Table A.22 Speed Factors

Length of Segment (ft)	Starting from Standstill or Coming to a Stop
100	0.45
150	0.55
200	0.62
300	0.68
400	0.74
500	0.77
700	0.83
1,000	0.86
2,000	0.92
3,000	0.94
4,000	0.95
5,000	0.96

Source: (Day and Benjamin, 1991)

After determining all constraints and the total cycle time, the hauler productivity is estimated using Equation A.44:

$$\text{Productivity} = \frac{(\text{Volume Hauled}) * (\text{Operational Efficiency})}{\text{Cycle Time (min)}} \quad (\text{A.44})$$

- **Graders**

Table A.23 presents selected graders and their corresponding specifications. The average grading speed and moldboard length, which is the length of the moveable blade mounted to the grader are determined from Table A.23.

Table A.23 Grader Specifications

Model	Flywheel Power (hp)	Moldboard Length (ft)	Average Grading Speed (mph)
140M	183	12	4
160K	206	14	5
14M	259	14	5
16M	297	16	5
24M	533	24	5

Source: (Caterpillar® Performance Handbook, 2011)

In order to estimate the productivity of the graders, Equation A.45 is used:

$$Productivity = \frac{(V) * (W) * (OF)}{P} \quad (A.45)$$

Where; V is the average grading speed, W is the effective grading width, OF is the operating factor, P is the number of passes required.

▪ **Compactors**

Equation A.46 is used in order to determine the optimum moisture content:

$$\text{Optimum Moisture Content (\%)} = \frac{(\text{Wet Unit Weight} - \text{Dry Unit Weight}) * (100)}{\text{Dry Unit Weight}} \quad (\text{A.46})$$

Table A.24 lists selected compactors and their specifications.

Table A.24 Compactors Specifications

Model	Compaction Dump Width (ft)	Average Speed (mph)
CS-323C	4.2	4
CS-433E	5.5	4
CS-533E	7.0	4
CS-64	7.0	4
815F2	10.7	4
825H	12.0	4

Source: (Caterpillar® Performance Handbook, 2011)

Equation A.47 is used to estimate the productivity of compactors:

$$\text{Productivity} = \frac{(W)(S)(L)(OF)}{P} \quad (\text{A.47})$$

Where W is the effective compaction width, S is the average compactor speed, L is the thickness of the lift to be compacted, OF is the operating factor, P is the number of passes required.

Equation A.48 is used to obtain the time needed to complete a certain earthwork operation:

$$\text{Time Required (days)} = \frac{\text{Volume}}{\text{Productivity per day}} \quad (\text{A.48})$$

After determining all related costs, the unit cost for selected equipment is estimated based on

Equation A.49:

$$\text{Unit Cost} = \frac{\text{Total Hourly Costs}}{\text{Productivity per hour}} \quad (\text{A.49})$$

Equation A.50 is then used to select the equipment with minimum unit cost:

$$MIN = \sum_{i=1}^n EU_i \quad (A.50)$$

Where i is the number of pieces of equipment and EU is the equipment unit cost.

APPENDIX III

XML Index Algorithm for Converting System Databases into Digital Table Formats

```
CREATE TABLE [dbo].[Division](
[Id] [int] NOT NULL,
[Name] [nvarchar](max) NOT NULL,
[Budget] [decimal](18, 2) NOT NULL,
CONSTRAINT [PK_Division] PRIMARY KEY CLUSTERED
(
[Id] ASC
)WITH (PAD_INDEX = OFF, STATISTICS_NORECOMPUTE = OFF,
IGNORE_DUP_KEY = OFF, ALLOW_ROW_LOCKS = ON, ALLOW_PAGE_LOCKS =
ON) ON [PRIMARY]
) ON [PRIMARY] TEXTIMAGE_ON [PRIMARY]
CREATE TABLE [dbo].[Element](
[Id] [int] NOT NULL,
[Name] [nvarchar](max) NOT NULL,
[Quantity] [decimal](18, 2) NOT NULL,
CONSTRAINT [PK_Element] PRIMARY KEY CLUSTERED
(
[Id] ASC
)WITH (PAD_INDEX = OFF, STATISTICS_NORECOMPUTE = OFF,
IGNORE_DUP_KEY = OFF, ALLOW_ROW_LOCKS = ON, ALLOW_PAGE_LOCKS =
ON) ON [PRIMARY]
) ON [PRIMARY] TEXTIMAGE_ON [PRIMARY]
CREATE TABLE [dbo].[Item](
[ID] [int] NOT NULL,
[ElementID] [int] NOT NULL,
[Description] [nvarchar](max) NULL,
[Quantity] [decimal](18, 2) NULL,
[UnitCost] [decimal](18, 2) NULL,
[Unit] [nvarchar](10) NULL,
CONSTRAINT [PK_Element_Item] PRIMARY KEY CLUSTERED
(
[ID] ASC,
[ElementID] ASC
)WITH (PAD_INDEX = OFF, STATISTICS_NORECOMPUTE = OFF,
IGNORE_DUP_KEY = OFF, ALLOW_ROW_LOCKS = ON, ALLOW_PAGE_LOCKS =
ON) ON [PRIMARY]
) ON [PRIMARY] TEXTIMAGE_ON [PRIMARY]
CREATE TABLE [dbo].[Project_Division](
[ProjectID] [int] NOT NULL,
```

```

[DivisionID] [int] NOT NULL,
CONSTRAINT [PK_Project_Division] PRIMARY KEY CLUSTERED
(
[ProjectID] ASC,
[DivisionID] ASC
)WITH (PAD_INDEX = OFF, STATISTICS_NORECOMPUTE = OFF,
IGNORE_DUP_KEY = OFF, ALLOW_ROW_LOCKS = ON, ALLOW_PAGE_LOCKS =
ON) ON [PRIMARY]
) ON [PRIMARY]
CREATE TABLE [dbo].[Project_Element](
[ProjectID] [int] NOT NULL,
[ElementID] [int] NOT NULL,
CONSTRAINT [PK_Project_Element] PRIMARY KEY CLUSTERED
(
[ProjectID] ASC,
[ElementID] ASC
)WITH (PAD_INDEX = OFF, STATISTICS_NORECOMPUTE = OFF,
IGNORE_DUP_KEY = OFF, ALLOW_ROW_LOCKS = ON, ALLOW_PAGE_LOCKS =
ON) ON [PRIMARY]
) ON [PRIMARY]
CREATE TABLE [dbo].[Projects](
[ID] [int] NOT NULL,
[Description] [nvarchar](max) NOT NULL,
[Area] [decimal](18, 2) NOT NULL,
[Unit] [nvarchar](10) NOT NULL,
[TotalCost] [decimal](18, 2) NOT NULL,
CONSTRAINT [PK_Projects] PRIMARY KEY CLUSTERED
(
[ID] ASC
)WITH (PAD_INDEX = OFF, STATISTICS_NORECOMPUTE = OFF,
IGNORE_DUP_KEY = OFF, ALLOW_ROW_LOCKS = ON, ALLOW_PAGE_LOCKS =
ON) ON [PRIMARY]
) ON [PRIMARY] TEXTIMAGE_ON [PRIMARY]
CREATE TABLE [dbo].[User](
[Id] [int] NOT NULL,
[DivisionID] [int] NOT NULL,
[Name] [nvarchar](max) NOT NULL,
[UserType] [nvarchar](max) NOT NULL,
CONSTRAINT [PK_User] PRIMARY KEY CLUSTERED
(
[Id] ASC,
[DivisionID] ASC
)WITH (PAD_INDEX = OFF, STATISTICS_NORECOMPUTE = OFF,
IGNORE_DUP_KEY = OFF, ALLOW_ROW_LOCKS = ON, ALLOW_PAGE_LOCKS =
ON) ON [PRIMARY]
) ON [PRIMARY] TEXTIMAGE_ON [PRIMARY]

```

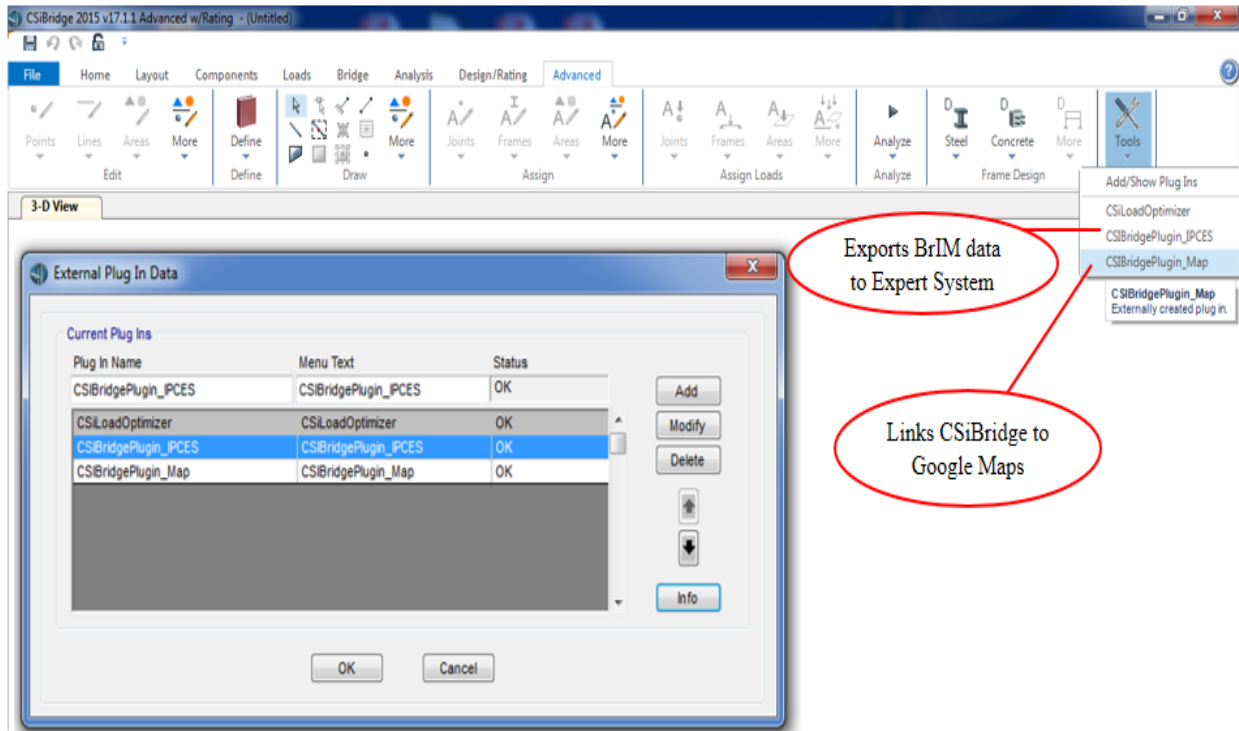
```

ALTER TABLE [dbo].[Item] WITH CHECK ADD CONSTRAINT [FK_Item_Element]
FOREIGN KEY([ElementID])
REFERENCES [dbo].[Element] ([Id])
ALTER TABLE [dbo].[Item] CHECK CONSTRAINT [FK_Item_Element]
ALTER TABLE [dbo].[Project_Division] WITH CHECK ADD CONSTRAINT
[FK_Project_Division_Division] FOREIGN KEY([DivisionID])
REFERENCES [dbo].[Division] ([Id])
ALTER TABLE [dbo].[Project_Division] CHECK CONSTRAINT
[FK_Project_Division_Division]
ALTER TABLE [dbo].[Project_Division] WITH CHECK ADD CONSTRAINT
[FK_Project_Division_Projects] FOREIGN KEY([ProjectID])
REFERENCES [dbo].[Projects] ([ID])
ALTER TABLE [dbo].[Project_Division] CHECK CONSTRAINT
[FK_Project_Division_Projects]
ALTER TABLE [dbo].[Project_Element] WITH CHECK ADD CONSTRAINT
[FK_Project_Element_Element] FOREIGN KEY([ElementID])
REFERENCES [dbo].[Element] ([Id])
ALTER TABLE [dbo].[Project_Element] CHECK CONSTRAINT
[FK_Project_Element_Element]
ALTER TABLE [dbo].[Project_Element] WITH CHECK ADD CONSTRAINT
[FK_Project_Element_Projects] FOREIGN KEY([ProjectID])
REFERENCES [dbo].[Projects] ([ID])
ALTER TABLE [dbo].[Project_Element] CHECK CONSTRAINT
[FK_Project_Element_Projects]
ALTER TABLE [dbo].[User] WITH CHECK ADD CONSTRAINT [FK_User_Division]
FOREIGN KEY([DivisionID])
REFERENCES [dbo].[Division] ([Id])
ALTER TABLE [dbo].[User] CHECK CONSTRAINT [FK_Role_Division]

```

APPENDIX IV

Snapshot of Developed Plug-ins



APPENDIX V

Hard-Code of Developed Plug-Ins

Plug-in that automatically exports BrIM data into the developed system via Dynamic Link Library (DLL) -invoked Application Programming Interface (API)

```
Imports CSiBridge17

<ComClass(cPlugin.ClassId, cPlugin.InterfaceId, cPlugin.EventsId)> _
PublicClasscPlugin

#Region"COM GUIDs"
' These GUIDs provide the COM identity for this class
' and its COM interfaces. If you change them, existing
' clients will no longer be able to access the class.
PublicConst ClassId AsString = "6e652ec7-a2c4-4b8b-b749-c8a61a0d4f65"
PublicConst InterfaceId AsString = "48e9cd50-4b08-457a-9e79-16936d16083e"
PublicConst EventsId AsString = "9592ae92-4ac4-426b-8fdf-520d607b5646"
#EndRegion

' A creatable COM class must have a Public Sub New()
' with no parameters, otherwise, the class will not be
' registered in the COM registry and cannot be created
' via CreateObject.
PublicSubNew()
MyBase.New()
EndSub

PublicFunction Info(ByRef Text AsString) AsInteger

Try
    Text = "This external PlugIn is supplied by Computers and Structures, Inc.,
"
    Text = Text &"as a simple example for developers of new PlugIns for
SAP2000. "
    Text = Text &"It starts a new model, then converts a line of text into "
    Text = Text &"frame objects and adds them your model. If you enter the "
    Text = Text &"text ""crash"" an error will be generated for testing
purposes. "
    Text = Text &"Version 3."
Catch ex AsException
EndTry

Return 0

EndFunction

PublicSub Main(ByRef SapModel AscSapModel, ByRef ISapPlugin AscPluginCallback)

Dim aForm AsNewFleetOptimizationSystem
```

```

Try
    aForm.setParentPluginObject(Me)
    aForm.setSapModel(SapModel, ISapPlugin)

' Non-modal call, allows graphics referesh operations in SAP2000,
' but Main will return to SAP2000 before the form is closed.
    aForm.Show()

' Modal forms will not return to SAP2000 until form is closed,
' but causes errors when refreshing the view.
''' aForm.ShowDialog()

' It is very important to call ISapPlugin.Finish(iError) when form closes, !!!
' otherwise, SAP2000 will wait and be hung !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
' this must be done inside the closing event for the form itself, not here !!!

' if you simply have algorithmic code here without any forms,
' then call ISapPlugin.Finish(iError) here before returning to SAP2000

' if your code will run for more than a few seconds, you should exercise
' the Windows messaging loop to keep the program responsive. You may
' also want to provide an opportunity for the user to cancel operations.

Catch ex AsException
    MsgBox("The following error terminated the Plug-In:"& vbCrLf & ex.Message)

' call Finish to inform SAP2000 that the PlugIn has terminated
Try
    ISapPlugin.Finish(1)
Catch ex1 AsException
EndTry
EndTry

Return

EndSub

ProtectedOverridesSub Finalize()
MyBase.Finalize()
EndSub
EndClass

Imports System.Windows.Forms
Imports CSiBridge17
Imports System.IO

PublicClassFleetOptimizationSystem

Protected ParentPluginObject AscPlugin
Protected SapModel AscSapModel
Protected ISapPlugin AscPluginCallback
Private ExportedDatabase AsString = ""

PublicSub setParentPluginObject(ByRef inParentPluginObject AscPlugin)

    ParentPluginObject = inParentPluginObject

EndSub

```

```

PublicSub setSapModel(ByRef inSapModel AsC SapModel, ByRef inISapPlugin
AsC PluginCallback)

    SapModel = inSapModel
    ISapPlugin = inISapPlugin

EndSub

PrivateSub FramesFromTextForm_Closing(ByVal sender AsObject, ByVal e As
System.ComponentModel.CancelEventArgs) Handles MyBase.Closing

' It is very important to call ISapPlugin.Finish(0) when form closes, !!!
' otherwise, SAP2000 will wait and be hung !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

    ISapPlugin.Finish(0)

EndSub

PrivateSub FleetOptimizationSystem_Load(sender AsObject, e AsEventArgs)
Handles MyBase.Load
Dim procInfo As System.Diagnostics.ProcessStartInfo = New
System.Diagnostics.ProcessStartInfo()
    procInfo.FileName = My.Application.Info.DirectoryPath.ToString() +
"/FleetOptimizationSystem/debug/" + "FleetOptimizationSystem.exe"
    procInfo.Arguments = My.Application.Info.DirectoryPath.ToString() +
"/FleetOptimizationSystem/debug/"
    System.Diagnostics.Process.Start(procInfo)
EndSub
EndClass

Public Class cVectorFont
    Public Enum TextAlignment
        kTA_HLeft = 0
        kTA_HCenter
        kTA_HRight
        kTA_VBottom
        kTA_VCenter
        kTA_VTop
    End Enum

    Protected Const VF_CHARACTERS As Integer = 96
    Protected Const VF_MOVES_PER_CHARACTER As Integer = 20
    Protected Const VF_ASPECT_RATIO As Double = 0.5

    Structure VFData
        Dim XI As Double
        Dim YI As Double
        Dim pen As Integer
    End Structure

    'std::vector<std::vector<VFData>> vf;
    Protected vf(,) As VFData

```

```

Public Sub New()
    ReDim vf(VF_CHARACTERS + 1, VF_CHARACTERS + 1)

    Initialize()
End Sub

Protected Sub Initialize()
    Dim VectorChar(97) As String, tmpString As String
    Dim i As Integer, j As Integer, k As Integer
    VectorChar(1) = "923 000"
    VectorChar(2) = "323 422 343 442 462 572 482 382 272 362 342 923 000"
    VectorChar(3) = "383 272 262 162 172 272 683 572 562 462 472 572 923 000"
    VectorChar(4) = "133 172 573 532 643 042 063 662 923 000"
    VectorChar(5) = "133 532 642 552 152 062 172 572 383 322 923 000"
    VectorChar(6) = "163 262 372 282 182 072 162 573 132 423 522 632 542 442 332 422 923 000"
    VectorChar(7) = "623 172 282 482 472 052 032 122 422 532 632 923 000"
    VectorChar(8) = "483 372 362 262 272 372 923 000"
    VectorChar(9) = "683 472 252 232 412 602 923 000"
    VectorChar(10) = "283 472 652 632 412 203 923 000"
    VectorChar(11) = "333 372 563 142 053 652 543 162 923 000"
    VectorChar(12) = "333 372 053 652 923 000"
    VectorChar(13) = "213 322 332 232 222 322 923 000"
    VectorChar(14) = "053 652 923 000"
    VectorChar(15) = "223 322 332 232 222 923 000"
    VectorChar(16) = "682 923 000"
    VectorChar(17) = "123 522 632 672 582 182 072 032 122 133 572 923 000"
    VectorChar(18) = "323 522 423 482 372 923 000"
    VectorChar(19) = "173 282 582 672 662 032 022 622 923 000"
    VectorChar(20) = "033 122 522 632 642 552 352 553 662 672 582 282 172 923 000"
    VectorChar(21) = "423 622 523 582 042 642 923 000"
    VectorChar(22) = "033 122 522 632 642 552 152 182 582 923 000"
    VectorChar(23) = "583 262 152 042 032 122 522 632 642 552 152 923 000"
    VectorChar(24) = "023 682 182 072 923 000"
    VectorChar(25) = "123 522 632 642 452 252 162 172 282 482 572 562 452 253 042 032 122 923 000"
    VectorChar(26) = "023 442 662 672 582 182 072 062 152 552 923 000"
    VectorChar(27) = "223 322 332 232 222 253 352 362 262 252 923 000"
    VectorChar(28) = "213 322 332 232 222 322 253 352 362 262 252 923 000"
    VectorChar(29) = "533 152 572 923 000"
    VectorChar(30) = "143 542 563 162 923 000"
    VectorChar(31) = "043 452 062 352 042 923 000"
    VectorChar(32) = "223 322 243 342 352 562 572 482 182 072 923 000"
    VectorChar(33) = "553 542 342 352 552 662 572 272 062 032 222 522 632 923 000"
    VectorChar(34) = "052 382 652 622 043 642 923 000"
    VectorChar(35) = "082 482 572 562 452 552 642 632 522 022 053 452 923 000"
    VectorChar(36) = "573 482 182 072 032 122 522 632 923 000"
    VectorChar(37) = "082 582 672 632 522 022 923 000"
    VectorChar(38) = "082 582 353 052 023 622 923 000"
    VectorChar(39) = "082 682 453 052 923 000"
    VectorChar(40) = "353 552 642 632 522 122 032 072 182 482 572 923 000"
    VectorChar(41) = "082 053 652 683 622 923 000"
    VectorChar(42) = "123 522 323 382 183 582 923 000"
    VectorChar(43) = "033 122 422 532 582 383 682 923 000"
    VectorChar(44) = "082 053 352 683 352 622 923 000"

```

```

VectorChar(45) = "083 022 622 923 000"
VectorChar(46) = "082 352 682 622 923 000"
VectorChar(47) = "082 622 682 582 923 000"
VectorChar(48) = "033 072 182 582 672 632 522 122 032 923 000"
VectorChar(49) = "082 582 672 662 552 052 923 000"
VectorChar(50) = "033 072 182 582 672 632 522 122 032 343 432 622 923 000"
VectorChar(51) = "082 582 672 662 552 052 453 442 622 923 000"
VectorChar(52) = "033 122 522 632 642 552 152 062 072 182 482 572 923 000"
VectorChar(53) = "323 382 083 682 923 000"
VectorChar(54) = "083 032 122 522 632 682 923 000"
VectorChar(55) = "083 052 322 652 682 923 000"
VectorChar(56) = "083 022 352 622 682 923 000"
VectorChar(57) = "682 083 622 923 000"
VectorChar(58) = "323 352 082 683 352 923 000"
VectorChar(59) = "083 682 022 622 253 452 923 000"
VectorChar(60) = "423 222 282 482 923 000"
VectorChar(61) = "083 622 923 000"
VectorChar(62) = "223 422 482 282 923 000"
VectorChar(63) = "153 372 552 923 000"
VectorChar(64) = "013 612 923 000"
VectorChar(65) = "453 362 372 272 262 362 923 000"
VectorChar(66) = "623 532 422 122 032 042 152 452 542 652 543 532 923 000"
VectorChar(67) = "072 043 252 552 642 632 522 122 032 923 000"
VectorChar(68) = "553 152 042 032 122 522 632 923 000"
VectorChar(69) = "623 672 643 452 152 042 032 122 522 632 923 000"
VectorChar(70) = "623 122 032 042 262 462 642 042 923 000"
VectorChar(71) = "223 262 372 472 562 143 342 923 000"
VectorChar(72) = "103 402 512 542 652 543 452 152 042 032 122 422 532 923 000"
VectorChar(73) = "072 043 252 552 642 622 923 000"
VectorChar(74) = "373 472 353 322 422 923 000"
VectorChar(75) = "373 472 453 402 202 923 000"
VectorChar(76) = "072 043 442 552 443 622 923 000"
VectorChar(77) = "273 222 422 923 000"
VectorChar(78) = "052 152 332 552 652 622 923 000"
VectorChar(79) = "052 043 252 552 642 622 923 000"
VectorChar(80) = "123 032 042 152 552 642 632 522 122 923 000"
VectorChar(81) = "002 023 052 043 252 552 642 632 522 222 032 923 000"
VectorChar(82) = "653 642 452 152 042 032 122 522 632 643 602 702 923 000"
VectorChar(83) = "052 043 252 552 642 923 000"
VectorChar(84) = "522 632 542 242 152 362 562 923 000"
VectorChar(85) = "423 322 372 263 562 923 000"
VectorChar(86) = "053 032 122 422 522 552 533 622 923 000"
VectorChar(87) = "053 222 552 652 923 000"
VectorChar(88) = "052 023 122 342 522 622 652 923 000"
VectorChar(89) = "122 342 552 652 053 152 342 522 622 923 000"
VectorChar(90) = "053 032 122 422 632 652 633 602 402 923 000"
VectorChar(91) = "652 052 023 622 923 000"
VectorChar(92) = "483 372 362 252 342 332 422 923 000"
VectorChar(93) = "323 342 363 382 923 000"
VectorChar(94) = "223 332 342 452 362 372 282 923 000"
VectorChar(95) = "073 182 282 462 562 672 923 000"
VectorChar(96) = "123 152 052 382 652 552 522 122 923 000"
For i = 1 To VF_CHARACTERS

```

```

For j = 1 To VF_MOVES_PER_CHARACTER
    k = (4 * j) - 4 'k = (4 * j) - 3;
    tmpString = VectorChar(i).Substring(k + 2, 1)
    vf(i, j).pen = Integer.Parse(tmpString)
    If vf(i, j).pen = 0 Then Exit For
    tmpString = VectorChar(i).Substring(k, 1)
    vf(i, j).XI = Double.Parse(tmpString)
    vf(i, j).XI *= VF_ASPECT_RATIO
    tmpString = VectorChar(i).Substring(k + 1, 1)
    vf(i, j).YI = Double.Parse(tmpString)
Next j
Next i

```

End Sub

Public Sub FillTextVertices(ByVal inStr As String, ByVal CharHeight As Double, ByVal HAlignment As Integer, ByVal VAlignment As Integer, ByRef tX() As Double, ByRef tY() As Double)

```

Dim i, j, NumChars, NumPts, pos As Integer
Const CharWidth As Double = VF_ASPECT_RATIO * 9 ' 9 is initial height

NumPts = 0
NumChars = inStr.Length()

For pos = 0 To NumChars - 1
    If Microsoft.VisualBasic.Asc(inStr.Substring(pos, 1)) = 13 Then
        'do nothing
    ElseIf Microsoft.VisualBasic.Asc(inStr.Substring(pos, 1)) = 10 Then
        'do nothing
    Else
        i = Microsoft.VisualBasic.Asc(inStr.Substring(pos, 1)) - 31
        For j = 1 To VF_MOVES_PER_CHARACTER
            If vf(i, j).pen = 2 Then NumPts += 2
        Next j
    End If
Next pos

```

```

ReDim tX(NumPts)
ReDim tY(NumPts)

```

```

Dim LineStart As Integer = 0, LineEnd As Integer = 1
Dim YOffset As Double = 0.0
Dim CharStartX As Double = 0.0
Dim XCurrent As Double = 0.0
Dim YCurrent As Double = 0.0
Dim XStart As Double, YStart As Double

```

```

For pos = 0 To NumChars - 1
    If Microsoft.VisualBasic.Asc(inStr.Substring(pos, 1)) = 13 Then
        YOffset -= 9.0 + 2.0 '9.0 is initial char height, 2.0 is spacing
        CharStartX = 0.0
    ElseIf Microsoft.VisualBasic.Asc(inStr.Substring(pos, 1)) = 10 Then
        'do nothing
    End If
Next pos

```

```

Else
    i = Microsoft.VisualBasic.Asc(inStr.Substring(pos, 1)) - 31 ' ASCII 32 is VectorFont(1)

    If vf(i, 1).pen = 2 Then
        XStart = CharStartX
        YStart = 2.0 + YOffset
    End If

    For j = 1 To VF_MOVES_PER_CHARACTER

        If vf(i, j).pen = 0 Then Exit For

        If vf(i, j).pen = 2 Then ' pen down finishes a line
            XCurrent = vf(i, j).Xl + CharStartX
            YCurrent = vf(i, j).Yl + YOffset

            tX(LineStart) = XStart : tX(LineEnd) = XCurrent
            tY(LineStart) = YStart : tY(LineEnd) = YCurrent

            LineStart += 2 : LineEnd += 2
            XStart = XCurrent
            YStart = YCurrent
        ElseIf vf(i, j).pen = 3 Then ' pen up starts a new line
            XStart = vf(i, j).Xl + CharStartX
            YStart = vf(i, j).Yl + YOffset
        End If
    Next j
    CharStartX += CharWidth
End If
Next pos
Dim ScaleFactor As Double = CharHeight / 9.0
Dim OffsetX As Double = 0.0, OffsetY = 0.0

Select Case HAlignment
    Case TextAlignment.kTA_HCenter
        OffsetX = -NumChars * CharWidth / 2.0
    Case TextAlignment.kTA_HRight
        OffsetX = -NumChars * CharWidth
End Select
Select Case VAlignment
    Case TextAlignment.kTA_VCenter
        OffsetY = -9 / 2.0
    Case TextAlignment.kTA_VTop
        OffsetY = 0.0
    Case TextAlignment.kTA_VBottom
        OffsetY = -9.0
End Select
For i = 0 To NumPts - 1
    tX(i) += OffsetX : tY(i) += OffsetY
    tX(i) *= ScaleFactor : tY(i) *= ScaleFactor
Next i
End Sub
End Class

```

Plug-in that automatically links BrIM tool to Google Maps

```

Protected ParentPluginObject AscPlugin
Protected SapModel AscSapModel
Protected ISapPlugin AscPluginCallback
Private ExportedDatabase AsString = ""

PublicSub setParentPluginObject(ByRef inParentPluginObject AscPlugin)

    ParentPluginObject = inParentPluginObject

EndSub

PublicSub setSapModel(ByRef inSapModel AscSapModel, ByRef inISapPlugin
AscPluginCallback)

    SapModel = inSapModel
    ISapPlugin = inISapPlugin

EndSub

PrivateFunction distance(ByVal lat1 AsDouble, ByVal lon1 AsDouble, ByVal lat2 AsDouble,
ByVal lon2 AsDouble) AsDouble
Dim theta AsDouble = (lon1 - lon2)
Dim dist AsDouble = ((Math.Sin(deg2rad(lat1)) * Math.Sin(deg2rad(lat2))) _
    + (Math.Cos(deg2rad(lat1)) _
        * (Math.Cos(deg2rad(lat2)) * Math.Cos(deg2rad(theta)))))
    dist = Math.Acos(dist)
    dist = rad2deg(dist)
    dist = (dist * (60 * 1.1515))

    dist = (dist * 1.609344)

Return dist
EndFunction

'::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
':: This function converts decimal degrees to radians ::
'::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
PrivateFunction deg2rad(ByVal deg AsDouble) AsDouble
Return (deg * Math.PI / 180)
EndFunction

'::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
':: This function converts radians to decimal degrees ::
'::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
PrivateFunction rad2deg(ByVal rad AsDouble) AsDouble
Return (rad / Math.PI * 180)
EndFunction

PrivateSub gMapControl1_Click(sender AsObject, e AsMouseEventArgs) Handles
GMapControl1.MouseDoubleClick
If (MarkersNum <> 2) Then
Dim lat AsDouble = GMapControl1.FromLocalToLatLng(e.X, e.Y).Lat

```

```

Dim lng AsDouble = GMapControl1.FromLocalToLatLng(e.X, e.Y).Lng
Dim markersOverlay AsGMapOverlay = NewGMapOverlay("markers")
Dim marker AsGMarkerGoogle = NewGMarkerGoogle(NewPointLatLng(lat, lng),
GMarkerGoogleType.green)
    markersOverlay.Markers.Add(marker)
    GMapControl1.Overlays.Add(markersOverlay)
Dim TempZoom = GMapControl1.Zoom
    GMapControl1.Zoom = 1
    GMapControl1.Zoom = TempZoom
If (MarkersNum = 0) Then
    Lat1 = lat
    Lng1 = lng

    MarkersNum = (MarkersNum + 1)
ElseIf (MarkersNum = 1) Then
    Lat2 = lat
    Lng2 = lng

    MarkersNum = (MarkersNum + 1)
    TextBox1.Text = Math.Round(distance(Lat1, Lng1, Lat2, Lng2) * 1000,
2).ToString()
    TextBox2.Text = Math.Round(distance(Lat1, Lng1, Lat2, Lng2) * 3280.84,
2).ToString

EndIf

EndIf
EndSub

PrivateSub Button1_Click_1(sender AsObject, e AsEventArgs) Handles Button1.Click
    GMapControl1.Overlays.Clear()
Dim TempZoom = GMapControl1.Zoom
    GMapControl1.Zoom = 1
    GMapControl1.Zoom = TempZoom
    MarkersNum = 0
    TextBox1.Text = "0.0"
    TextBox2.Text = "0.0"
EndSub

PrivateSub frmMap_Load(sender AsObject, e AsEventArgs) Handles MyBase.Load
    GMapControl1.MapProvider = GMap.NET.MapProviders.GoogleMapProvider.Instance
    GMap.NET.GMaps.Instance.Mode = GMap.NET.AccessMode.ServerOnly
EndSub

PrivateSub frmMap_Closing(sender AsObject, e AsFormClosingEventArgs)
Handles MyBase.FormClosing
' It is very important to call ISapPlugin.Finish(0) when form closes, !!!
' otherwise, SAP2000 will wait and be hung !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

    ISapPlugin.Finish(0)
EndSub
EndClass

```