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Quality Function Deployment (QFD) for Bridge Maintenance

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Abstract: Most bridge agencies have well established quality control programs with the intent of achieving effective bridge maintenance. However, consumers are becoming more involved in economic, environmental, social, etc., issues related to infrastructure. Therefore, a valid “quality” program would be definitive by involving voice of the customer in the maintenance decision-process. In this paper, an innovative approach for achieving quality in bridge maintenance is proposed by implementing the Quality Function Deployment (QFD) approach. Any non-routine major bridge maintenance can involve three outcomes for decision-making - "rehabilitate", "replace" or "no action" required scenarios. For each of these scenarios, a House of Quality is prepared for translating consumer demands (WHATs) into implementation requirements (HOWs). In the next step, the HOWs are prioritized and a decision is made based on ranking of the alternatives. The prioritization is done using QFD-based processes and the correlation between WHATs and HOWs are obtained using subjective judgment of the experts. To highlight utility of the proposed QFD approach, a case study is furnished for a bridge located in Victoria, BC, Canada.

1. INTRODUCTION

Bridge maintenance is a comprehensive process that aims at addressing various demands placed on the structure (Bolar et al. 2011; Félio et al. 2009). The demands are always coupled with constraints that are essential for evaluating and mitigating any type of potential risk. The demands can be broadly classified into engineering demands and consumer (bridge user) demands. Engineering demands are those that are deemed essential for the safe operation of the bridge, the design of which is assured by complying with design codes and regulations set by bridge or engineering standards. Once the bridge is built and under operation, in-service usage can deteriorate the bridge over time and an established inspection program can help identify deterioration and thereby control risk that would arise due to unattended maintenance (Cambridge Systematics Inc. 2006). Normally, engineering demands such as inspection program of a bridge would be under the authority of the bridge owner (a jurisdiction agency such as a Municipal, Provincial, Federal, etc., agencies). For a consumer, safety and engineering would definitely be a concern, but they may have additional demands that are much different in form such as expectations of the bridge under operation. The expectations need not just be intrinsic such as riding comfort, but lately with consumers becoming more involved in economic, environmental, social, etc., issues related to infrastructure the list of demands cannot be limited. Furthermore, the consumer need not be limited to the bridge user alone, but anyone that can get affected by the bridge operation such as corporate entities, general public, authorities such as fire rescue, airports, ports, etc. can all have interest in the bridge operation and usage. From a bridge authority's perspective, involving both engineering and consumer demands in the bridge maintenance program would be compelling and improve quality and economics by addressing exactly what is essential.

Current bridge maintenance programs address engineering issues by established maintenance and inspection practices. However, maintenance programs lack the involvement of consumer demands during maintenance decisions. Including the voice of consumer would not only be relevant for on-going maintenance, but especially during important decisions that lead to rehabilitating or replacement of a bridge. In this study, Quality Function Deployment (QFD) is introduced for bridge maintenance that is a process by which consumer demands (phrased in QFD as "voice of the customer") are included in the bridge maintenance decision-making.

2. QUALITY FUNCTION DEPLOYMENT

2.1.1 History and Areas of Application

In the year 1968, from the work of Akao, the QFD approach was developed in Kobe (Japan) and by the end of 1970s the QFD became very popular (Francisque et al., 2011; Carnevalli et al. 2008; Akao, 1988). QFD involves two fundamental aspects: *customer requirements* and *design (or production) specifications*. Customer requirements are usually expressed in terms of qualitative characteristics broadly defined (e.g., riding comfort, heritage values, comfortable stopping distances, economy in operation, etc.). Design specifications are the successive conversion of customer needs during product (design, maintenance, rehabilitation or replacement) development into internal agency requirements, usually measurable characteristics (additional weights, environmental upgrades, etc.). Although originated in manufacturing, QFD has also been widely accepted in areas such as aerospace (Kojima et al., 2007), public transportation (Hopwood II and Mazur, 2007), education (Chen et al., 2002), lifecycle analysis (Cheema and Hussain, 2007), logistics (Crostack et al., 2007), soil tillage (Barros et al 2003), construction (Gargione, 1999), environmental requirements (Gray and Bizri, 2006), oil and gas (Yang et al., 2011) and drinking water quality management (Francisque et al., 2011). The list of areas where QFD is applied has become so exhaustive that Carnevalli et al. (2008) investigated the extent of research done in QFD as a research topic itself. Sharma et al. (2008) and Chan et al. (2008) have published comprehensive literature reviews on the topic.
The application of QFD to bridges is a relatively new concept with not much research directed especially towards maintenance. Junhai et al. (2007) describe that portion of Bridge lifecycle design in China is based on QFD. Malekly (2010) has used QFD in evaluating the conceptual bridge design.

2.1.2 House of Quality (HOQ)

Quality in the context of the success of a product can be defined as a multi-attribute function involving any element that makes a product more desirable for the customer. Innovation related to quality is recognized as any intervention that can modify the market, even marginally (Francisque et al., 2011). The House of Quality (HOQ) is a term associated with QFD which is a matrix that documents and establishes all the processes in implementing QFD. The HOQ facilitates transition from a list of customer requirements or WHATs, defining HOW the WHATs can be achieved and establishing correlation of WHATs vs. HOW as well as between the various HOWs. Figure 1 shows a typical House of Quality (HOQ). The various terms are defined as follows:

- *WHATs* are the list of basic *customer demands (or requirements and needs)*, usually expressed in vague and imprecise terms (e.g., riding comfort, environmentally friendly, etc.).
- *HOWs* are the *design (or technical or product) characteristics* (e.g., no potholes, green products or construction, etc.) that serve to meet the WHATs.
- *Relationship matrix* indicates how product characteristics or decisions affect the satisfaction of each customer need. It consists of relationships existing between each WHAT and each HOW attribute.

- *Absolute weights and ranking of HOWs* contains the results of the prioritization of product characteristics to satisfy customer requirements. It represents the impact of each HOW attribute on the WHATs.
- C*orrelation matrix* is the roof of the HOQ and represents the interdependencies among HOWs. It can play an important role in deciding on the number of HOWs that directly affect the cost.

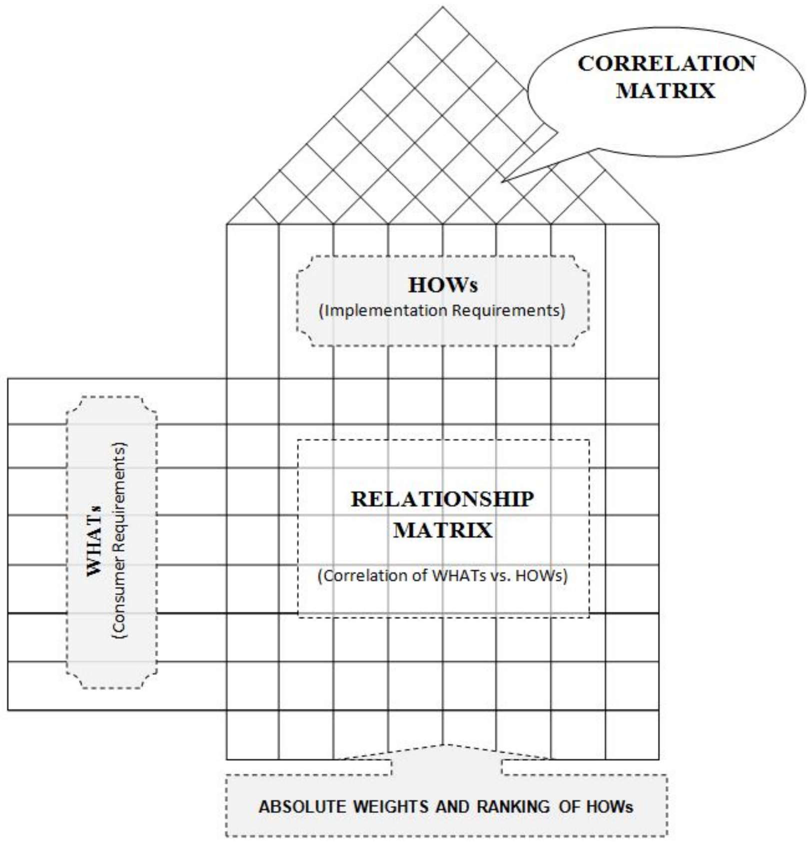


Figure 1: House of Quality (HOQ)

2.1.3 Prioritizing WHATs and HOWs

To satisfy customers, their needs must be prioritized, i.e., the level of relative importance to be attributed to the WHATs must be determined. Different approaches exist to prioritize WHATs and once WHATs are determined and prioritized, it is important to decide how to obtain the desired results, i.e., how to satisfy customers' prioritized needs. Determination of HOWs implies translating customer needs expressed in subjective terms into objective factors of a technical nature (e.g., increasing taxes, improved pedestrian safety, etc.). These characteristics are indeed a product or service description expressed in the designer's (i.e., bridge manager) language. It involves establishing a list showing the HOWs (at least one HOW for each WHAT). Product characteristics represent the quality offered demonstrated through a product or service description provided in measurable terms and should directly affect customer perception of quality (Franceschini, 2002). However, before prioritizing HOWs, it is important to indicate how these characteristics affect the satisfaction of each WHAT. The HOQ *relationship matrix* must be completed using correlations defined between each WHAT and each HOW. Three elements determine the importance of HOWs: the importance of the WHATs to which the HOW is correlated, the level of correlation (e.g., *weak*, *medium*, *strong*), and the degree of difficulty its realization entails (Franceschini, 2002). In this study, the *Independent scoring method* is adopted which is the classical method of QFD (Akao, 1988).

3. QFD FOR BRIDGE MAINTENANCE DECISION-MAKING

3.1 Methodology

Any decision-making process for structural maintenance can broadly result in three scenarios - repair/ rehabilitation (including partial replacement), complete replacement or a "No Action" required scenario. The items leading to these scenarios can involve complex assessments, technical investigations, preliminary engineering designs and most importantly community hearings or surveys conducted by municipalities or agencies that possess ownership of the entity. These surveys including any other investigations, etc. can be included in the house of quality (HOQ) for implementing the QFD approach.

3.2 Case Study

3.2.1 Introduction

The QFD approach for bridge maintenance decision-making was done using customer survey data for Johnson Street Bridge in the city of Victoria, BC, Canada. All data used in this study was available at http://www.johnsonstreetbridge.com/

The Johnson Street Bridge is a Bascule-type bridge with a counter-weight at one end facilitating the lowering of the opposite end. The bridge has two separate Bascules, the Railway section and the Highway section and was designed under the direction of Mr. F. M. Preston, City Engineer in 1920[1]. The main opening span is 148 feet in length and is balanced over a 45-foot fixed span when in open. The eastern approach has a 110' fixed girder while the western approach has a 73' fixed girder. The counter weight block on the highway span is a hollow concrete structure consisting of a number of smaller concrete weights and tips the scale at over 780-tons. It balances the 350-ton opening span.

The original Johnson Street Bridge opened in the year 1924 had a timber deck that eventually absorbed water and led to increase in weight causing machinery operation issues. By 1966, the timber deck was replaced by an open steel grid decking of constant weight. In 1979, extensive corrosion related repairs were made to the superstructure. In April 2009, the results of an overall condition assessment of the Johnson Street Bridge identified extensive corrosion in steel structural beams, obsolete instrumentation and significant seismic vulnerability. The comprehensive review concluded that substantial investment would be required by 2012 to avoid further deterioration, increasing operational costs and possible closure. The council decided to replace the bridge after considering many factors including safety, accessibility, improved pedestrian and cycling amenities, heritage values, sustainability and traffic and business disruption as well as an extensive engagement process[2]

3.2.2 QFD Consumer WHATs

The Victoria City Council decided to borrow $49.2 million to replace the Johnson Street Bridge after reviewing extensive public consultation including emails and personal contact with citizens during open houses and local markets. The input from citizens (or voice of the citizen/customer in QFD terms) is defined as a consumer WHAT in this study. The consumer can be either a resident citizen or a stakeholder such as a business entity. As such the surveys conducted included:

- Representative survey of businesses in Downtown Victoria and Victoria West[3];

[1] http://www.johnsonstreetbridge.com/the-project/history/ [Accessed 23 Jan 2012]
[2] http://www.johnsonstreetbridge.com/the-project/overview-2/ [Accessed 23 Jan 2012]
[3] http://www.johnsonstreetbridge.com/wp-content/uploads/2010/05/JSB-Business-Presentation.pdf [Accessed 23 Jan 2012]

- Representative survey of residents of Victoria and 2600 (including mail-in surveys)[4].

Table 1: Description of HOWs

HOW	Description related to the Bridge
Economic Factors	
Increase Taxes	How would an "increase in taxes" correlate with each of the WHATs
Borrowing	How would "borrowing" funds correlate with each of the WHATs
Toll	How would establishing a "toll" correlate with each of the WHATs
Social Factors	
Customer Satisfaction	How would simply accepting the requirement for customer satisfaction correlate with each of the WHATs
Aesthetics	How would Aesthetic value correlate with each of the WHATs
Heritage Value	How would Heritage value correlate with each of the WHATs
Safety Driven	
Traffic Signs	How would improved "traffic signs" correlate with each of the WHATs
Visibility	How would improved "visibility" correlate with each of the WHATs
Safety during Maintenance	How would improved "safety during maintenance" correlate with each of the WHATs
Pedestrian Safety	How would improved "pedestrian safety" correlate with each of the WHATs
Technical Factors	
Technical Investigation	How would conducting a "technical investigation" correlate with each of the WHATs
Vibration/Movement	How would limiting vibration/movement correlate with each of the WHATs
Seismic Counter-measures	How would improved "seismic counter-measures" correlate with each of the WHATs
Maintenance Efficiency Related	
Improved Access	How would "improved access" after maintenance correlate with each of the WHATs
Uneven Surface	How would improved riding surface characteristics correlate with each of the WHATs
No Potholes	How would absence of "pot-holes" correlate with each of the WHATs
Environmental Factors:	
Green Products, design or construction	How would use of green products, design or construction correlate with each of the WHATs

3.2.3 QFD Consumer HOWs

Had QFD been implemented for the Johnson Street Bridge each of the consumer WHATs would have been thoroughly investigated by a team consisting of the survey participants, stakeholders, engineers or anyone deemed to be affected by modifications to the bridge. The consumer WHATs could then be translated into implementation HOWs which simply refers to "how" each of the WHATs could be established. In the next step, in building the relationship matrix, the relationship between each HOW and WHAT is established on a scale of 1 to 9, where 9 represents strong relationship and 1 represents weak relationship. While in an actual QFD, establishing the HOWs would be result of a brainstorming process, the authors of this study established the HOWs as presented in Table 1.

3.2.4 QFD Relationship Matrix

[4] http://www.johnsonstreetbridge.com/wp-content/uploads/2010/05/JSB-Residential-Presentation.pdf [Accessed 23 Jan 2012]

For each of the WHATs, relationships if a HOW could accomplish a WHAT were determined by subjective judgment using a 5 tier scale. Table 2 shows the scale adopted to establish the relationship between each HOW and WHAT. A 5 tier scale is used starting from 1 through 9, where 1 represents weak relationship and 9 represents strong relationship. Figure 1 shows the completed QFD relationship matrix. For example, the WHAT "replacement cost related issues" was assigned a strong relationship 9 with "increasing taxes" and "borrowing money", but slightly lower at 7 for "toll" by assuming that toll would be established only if increase in taxes and borrowing money was expended.

Table 2: WHATs *vs*. HOWs Correlation Scale

	STRONG	→			WEAK
Value	**9**	**7**	**5**	**3**	**1**
Relationship	**Extremely**	**Strong**	**Moderate**	**Weak**	**Extremely**

3.2.5 QFD Correlation Matrix

Correlations are also established between each of the HOWs and are represented in the roof of the House of Quality. Similar to the relationship matrix, these correlations are established on a 3-tier scale ranging from 0 to 1, where weak is 0.1, medium 0.3 and strong 0.9.

4. DISCUSSION

The case study data adopted for this research had survey data for four categories:

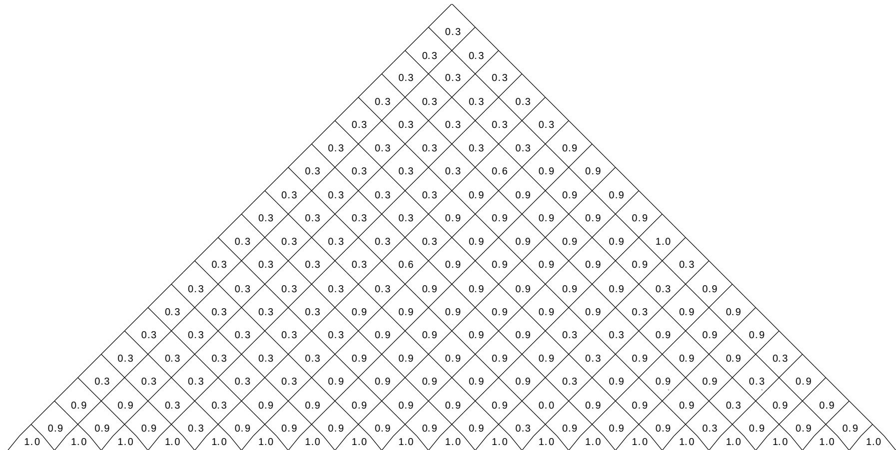
a) Replacement Option - Resident's Response (Abbreviated as RepR)
b) Rehabilitation Option - Resident's Response (Abbreviated as RehR)
c) Replacement Option - Business's Response (Abbreviated as RepB)
d) Rehabilitation Option - Business's Response (Abbreviated as RehB)

The House of Quality process described in Sections 3.2.2 to 3.2.5 was generated for each of the above cases. The absolute weight was obtained for each of the HOWs using the House of Quality and combined under the broader headings namely Economic Factors, Social Factors, Safety Driven, Technical Factors, Maintenance Efficiency and Environmental Factors. The HOQs are shown for two cases in Figures 2a and 3a. The results are plotted as pie-charts in Figures 2b and 3b and are also summarized for all cases in Table 3.

Table 3: Summary of Results from HOQ for Johnson Bridge

Independent Scoring Method

	Residential		Business	
	Replacement	**Rehabilitation**	**Replacement**	**Rehabilitation**
Economic	22	24	22	22
Social	17	19	18	18
Safety	12	12	13	12
Technical	18	17	19	18
Maintenance Efficiency	16	14	15	15
Environmental	15	14	14	16
DECISION	**REHABILITATION**		**REPLACEMENT**	
	REHABILITATION / REPLACEMENT			



	IMPLEMENTATION HOWS		Increase Taxes	Borrowing	Toll	Customer Satisfaction	Aesthetics	Heritage Value	Traffic Signs	Visibility	Safety during Maintenanc	Pedestrian Safety	Technical Investigation	Vibration/Movement	Seismic Couter-measures	Improved Access	Uneven Surface	No Potholes	Green Products	Green Design	Green Construction
			7.6	8.2	8.2	7.6	10.0	14.8	14.8	14.2	14.2	13.7	9.7	13.6	15.4	13.3	11.2	13.6	13.3	13.0	12.8
	CONSUMER WHATs	Relative Importance																			
REHABILITATION	Rehabilitate for Cost related issues	43	9	9	9	7	7	7	0	7	0	5	7	7	5	5	5	5	5	5	5
	Rehabilitate for Heritage related issues	40	9	9	9	7	3	9	0	5	0	1	5	7	5	5	5	5	5	5	5
	Rehabilitate for Construction related	21	7	7	7	7	7	9	5	7	0	5	9	7	7	5	5	5	5	5	5
	Replacement not required	19	7	7	7	7	7	5	7	7	7	7	9	7	7	7	7	7	7	7	7
	Rehabilitation budget is inflated	15	9	9	9	7	5	5	0	3	0	1	7	7	5	5	5	5	9	9	9
	Needs to be updated	6	7	7	7	7	7	7	7	7	7	7	7	9	9	9	9	9	9	9	9
	Other	13	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	Don't know	4	3	3	3	9	7	0	3	3	3	3	7	7	7	1	1	1	1	1	1
			1281	1281	1281	1109	911	1127	357	945	252	627	1101	1113	917	851	851	851	911	911	911
			22			18			12				18			15			16		

Figure 2a: Typical HOQ for Johnston Bridge: Rehabilitation Option - Business Response (RehB)

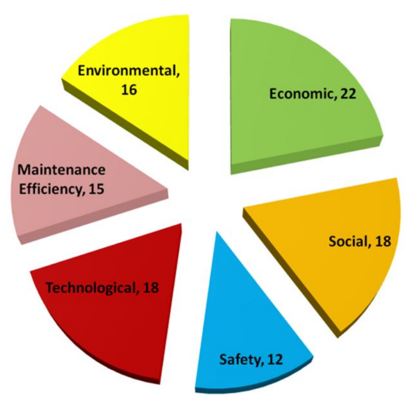
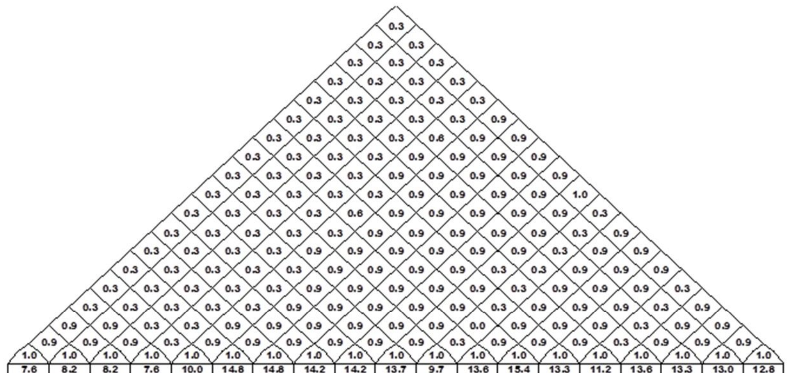


Figure 2b: Independent Scoring Results - Rehabilitation Option - Business Response (RehB)



CONSUMER WHATs / IMPLEMENTATION HOWs	Relative Importance	Increase Taxes	Borrowing	Toll	Customer Satisfaction	Aesthetics	Heritage Value	Traffic Signs	Visibility	Safety during Maintenance	Pedestrian Safety	Technical Investigation	Vibration/Movement	Seismic Couter-measures	Improved Access	Uneven Surface	No Potholes	Green Products	Green Design	Green Construction
		7.6	8.2	8.2	7.6	10.0	14.8	14.8	14.2	14.2	13.7	9.7	13.6	15.4	13.3	11.2	13.6	13.3	13.0	12.8
REPLACEMENT																				
Replacement Cost related issues	52	9	9	9	7	7	7	0	5	0	1	7	7	7	7	7	5	7	7	7
Replacement Construction related issues	36	7	7	7	7	7	9	5	7	0	5	9	7	7	5	5	5	5	5	5
Replace just to have a new bridge	15	7	7	7	7	1	7	0	1	0	1	1	1	1	0	0	0	0	0	0
Replacement will last longer / long term solution	12	7	7	7	5	1	1	0	7	0	7	7	7	7	7	7	7	7	7	7
Replacement would look better/ more attractive	11	7	7	7	7	9	3	0	3	0	3	3	3	3	5	5	5	5	5	5
Replacement for Traffic efficiency related	8	5	5	5	7	3	3	9	7	0	5	7	7	7	7	5	5	1	1	1
Replacement for Maintenance related issues	7	7	7	7	7	0	0	5	3	3	5	7	7	3	3	3	3	1	1	1
Replacement would be safer	5	7	7	7	7	5	0	5	3	9	7	7	7	7	1	1	1	1	1	1
Replacement would provide better bicycle access	4	7	7	7	7	0	0	7	0	0	7	0	7	9	9	9	9	9	9	9
Replace as old bridge will need to be replaced eventually	4	7	7	7	7	0	5	0	3	0	3	7	7	9	9	9	9	9	9	9
Replace as old bridge is in poor condition	3	7	7	7	7	7	5	7	7	7	7	7	7	7	7	7	7	7	7	7
Replace as Heritage value not important	3	7	7	7	9	7	9	0	7	0	7	7	9	9	9	9	9	9	9	9
Replacement would provide better pedestrian access	3	7	7	7	7	7	7	9	9	9	9	7	7	7	9	9	9	9	9	9
Replacement would be modern	3	7	7	7	9	9	9	7	7	7	7	7	7	7	9	9	9	9	9	9
Don't know if replacement should be done	1	3	3	3	9	7	0	3	3	3	3	7	7	7	1	1	1	1	1	1
Absolute Weight:		1250	1250	1250	1150	881	972	409	838	135	604	1072	1034	1022	939	923	819	877	877	877
		22			17			12				18			16			15		

Figure 3a: Typical HOQ for Johnston Bridge: Replacement Option - Residents Response (RepR)

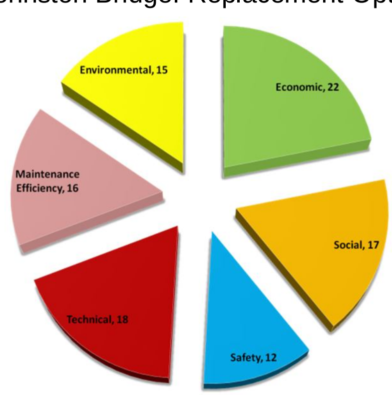


Figure 3b: Independent Scoring Results - Replacement Option - Residents Response (RepR)

All results show a higher ranking towards economic factors - RepR (22%), RehR (22%), RepB (24%), RehB (22%). This correlates well with the results of the actual survey indicating "replacement cost issues" as the highest priority. However, referring to Table 3, HOQ absolute weights based on residents' survey showed higher values for rehabilitation under economic and social factors. All other absolute weights based on residential survey showed higher values for replacement (i.e. replacement preferred). The HOQ absolute weights based on business respondents showed equal values for economic, social and maintenance efficiency factors, which could lead to a decision for either replacement, or rehabilitation, or perhaps a combination of both. Although either replacement or rehabilitation can be decided based on the results obtained - consumer requirements can be further met by following up issues of importance in order of priority every after the major maintenance is done. Social factors based on residential (RepR-17%, RehR-19%) and business surveys (RepB-18%, RehB-18%) and technical factors based on residential (RepR-18%, RehR-17%) and business surveys (RepB-19%, RehB-18%) were next on the priority list. So after the bridge is replaced/rehabilitated, adequate measures could be undertaken to address social issues (say involving Heritage value such as building a landmark close to the bridge) and continued technical investigation such as seismic monitoring and assessments. The technical factors could be adequately addressed by adopting appropriate technical investigations, replacement/rehabilitation feasibility studies, seismic countermeasures, etc. Similarly Maintenance Efficiency and Environmental Factors ranked low in the HOQ results and these could also be addressed appropriately when all other factors have been addressed.

5. CONCLUSION

QFD approach has been demonstrated for bridge maintenance decision-making involving decisions such as replacement or rehabilitation. A case study was performed by using data available for Johnson Bridge in Victoria. The results from the House of Quality are comprehensive, but yet simple for effective decision making and aid the decision maker with a prioritized summary of consumer requirements. The results can be based not only to make an immediate decision for the bridge under investigation, but to perform continued improvement by addressing needs of the consumer. Although the intent of QFD has been to involve the 'voice of the customer', implementation has normally involved participation of customer focus groups, engineering, management, construction, etc. A practical implementation of QFD for bridge maintenance would therefore require acceptance of the approach at a bridge agency. For the current study, the authors performed all the team roles in developing the House of Qualities. The results of the study are therefore not conclusive and can be further elaborated based on communication between the stakeholder's involved. This may result in, for example, enhanced HOWs, improved relationship and correlation matrices, etc. leading to optimization of maintenance needs and costs. QFD enables breaking down each customer need into a valid implementation requirement by active participation from different disciplines. Therefore, implementation of QFD for bridge maintenance would lead to improved communication between various groups involved in bridge maintenance and the customer i.e. the end user of the bridge.

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