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ENHANCED BENEFIT-COST ANALYSIS FOR INFRASTRUCTURE CORRIDOR REHABILITATION

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Abstract: Roads, water/sewer pipes, bridges, and culverts are usually co-located in the same corridor, accordingly, managing the rehabilitation of these assets requires better coordination to reduce the social costs associated with multiple disruptions for the same corridor. Yet, most of the existing municipal rehabilitation plans deal with co-located assets in isolation, thus resulting in much inefficiency. This paper, therefore, presents an enhanced benefit-cost analysis method to provide optimum funding for the rehabilitation of multiple co-located assets of different types. The proposed mechanism utilizes the equal marginal utility concept of consumer theory to achieve near-optimum fund-allocation decisions while maintaining equilibrium and balance among the different types of co-located assets. A real case study consisting of bridges and culverts co-located in the right-of-way of a pavement network has been used to demonstrate the proposed mechanism and its results. Using the case study data, the proposed mechanism proved to be able to arrive at optimum fund-allocation for corridor rehabilitation, and provide credible economic justification for spending the tax-payers money on infrastructure projects.

Keywords: LCCA; coordination; renewal; optimization; marginal utility; microeconomics.

1. INTRODUCTION

Roads and their above- and under-ground utilities (pavements, bridges, water and sewer, etc.) are infrastructure assets that are often co-located in them same corridor. Dealing with the rehabilitation work of these assets in isolation, can lead to much inefficiency, rework, and undesirable social costs (Halfawy 2008, NRC 2003). In order to implement efficient and optimized infrastructure rehabilitation strategies, coordinating the rehabilitation work among the diverse municipal departments, within each corridor, has become a necessity. For instance, while doing the rehabilitation work for structures like culverts or bridges, municipalities can study the rehabilitation of pavements to avoid the social costs associated with multiple visits for the same corridor. Similarly for the rehabilitation of an underground water system, a municipality can renew all the adjacent systems and repave the road above (Shahata and Zayed 2010, Osman 2016). Such coordination will help integrate infrastructure data, accurately manage the asset's life cycle, and eliminate fragmentation inefficiencies (Halfawy 2008). However, there are concerns regarding the loss associated with the premature replacement of some infrastructure assets, before reaching their economic life, as part of the corridor rehabilitation work. Thus, a rigorous economic analysis is needed to justify the decisions to be made in this matter.

In practice, some efforts discussed the lessons learned and requirements needed for effective coordination of infrastructure works. For example, Aldersen (2005) presented the application of InfraGuide coordinating of infrastructure works guidelines on the city of London, and the measures taken to ensure effective coordination that minimize social and environmental costs. Hafskjold (2010) discussed the requirements needed for an effective coordination of infrastructure rehabilitation works in an effort to improve Norway practices. In the literature, some research efforts have tackled coordination of infrastructure works, as well. For instance, Halfawy (2008) developed an integrated municipal infrastructure management system to integrate the distributed stand-alone software tools among the different municipal department through centralized shared data repositories. Shahata and Zayed (2010) presented a methodology to optimize corridor rehabilitation decisions by determining the best replacement interval that minimizes the renewal cost. Islam and Moselhi (2012) developed a model to determine the geo-spatial physical interdependence among infrastructure assets in a given network to avoid duplication of maintenance work during a given planning horizon. Osman (2016) developed a temporal coordination model for corridor rehabilitation decisions that takes into account level of service, risk exposure, and life cycle cost. Szimba and Rothengatter (2012), also discussed the importance of including the interdependence among infrastructure assets while analyzing the benefits and costs of infrastructure rehabilitation works.

Generally, there is a lack of literature on decision support systems that can optimally spend a predefined budget among different co-located infrastructure assets (e.g., pavement, bridges, culverts, etc.). Most of the existing efforts provide LCCA models for a single type of asset to support either project-level decisions (what rehabilitation strategy to use) or network-level decisions (when to do the rehabilitation). Example systems in various asset domains include pavements (De la Garza et al. 2011, Zhang et al. 2013, Khurshid et al. 2013); buildings (Tong et al. 2001, Hegazi and Elhakeem 2011), water networks (Alvisi and Franchini 2009, Mann and Frey 2011); bridges (Elbehairy et al. 2006, Adey and Hajdin 2011).

Moreover, most of the efforts that reported optimization results lack a satisfactory justification behind the decisions made. Typical fund-allocation problems are often formulated in the form of combinatorial optimization problems which result in a number of random combinations that can lead to solutions that are not easy to interpret/justify or identify a consistent “strategy” behind them (Hegazy and Saad 2014). In essence, there is a lack of methods and tools for providing optimum fund-allocation decision for co-located infrastructure assets supported with sound economic justification. To address this issue, this paper presents an extension to the Enhanced Benefit-Cost Analysis (EBCA) method, developed by Saad and Hegazy (2015) that optimizes fund-allocation for a single asset type. The extended method work achieves balanced fund-allocation decisions among different corridors, where different types of assets are co-located. In the next sections, the paper briefly describes the EBCA approach and discusses two strategies for extending it to corridor rehabilitation, then demonstrates the application of one of the strategies on a real case study.

2. MICOROCONOMIC-BASED EBCA METHOD

The enhanced benefit-cost analysis (EBCA) is an optimization technique inspired by the microeconomic concept of equal marginal utility per dollar of the consumer theory (Saad and Hegazy 2015; Saad 2014). The model arrives at optimum spending on different asset categories competing for funding by targeting equilibrium (equality) among the marginal utility per dollar rather than maximizing total benefit, which can be difficult to justify and interpret. As such, optimum fund-allocation is represented by an equilibrium state at which the following relationships hold:

$$[1] \quad \frac{MU}{\$})_{xth} = (\frac{MU}{\$})_{yth} = \cdot\cdot(\frac{MU}{\$})_{nth}$$

Under the condition that,

[2] $\sum RC \cong \text{Budget}$ (i.e., allocating the whole budget)

Where, the number of terms in Eq.1 represents the number of independent asset categories; MU/$ is the marginal utility (or benefit) per dollar associated with rehabilitating an asset type; and x^{th}, y^{th}, and n^{th} are the last sorted assets to be selected from each asset type, and RC is the rehabilitation cost of any given asset. More information on the derivation of the equilibrium equation (Eq. 1) and its mathematical proof is found in (Saad and Hegazy 2015)

Using the concept of equal marginal utility per dollar, the EBCA optimization technique follows 5 steps to select an optimum combination of assets from each category that maintains an equilibrium state among the asset categories while fully exhausting the budget, as schematically shown in Figure 1, where 50 assets of category 1, 30 assets of category 2, and 20 assets of category 3 have been allocated funds.

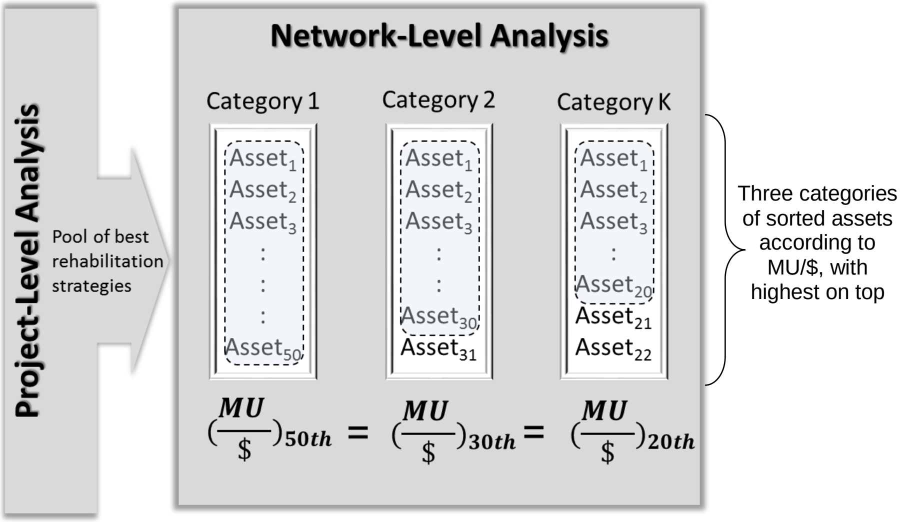


Figure 1: Network-level analysis using EBCA optimization technique

For each year in the planning horizon, the 5-step process is as follows:

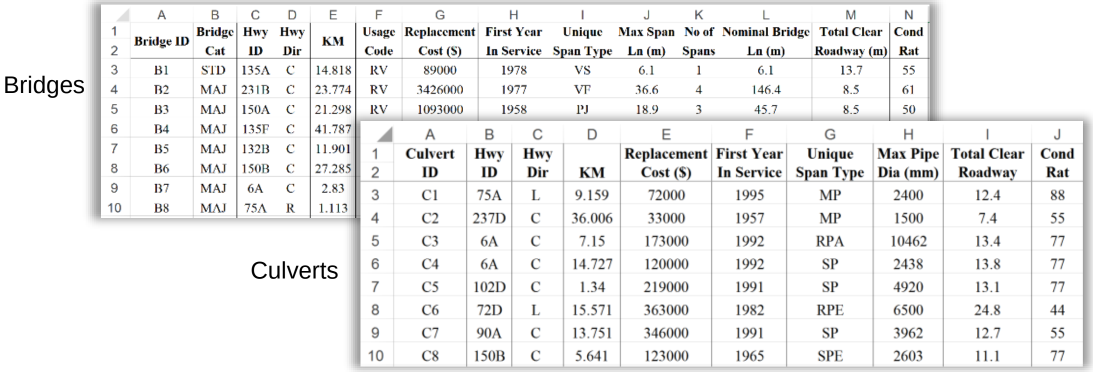
1. Group unfunded assets into their categories (Urban roads, Rural roads);
2. List the utility (benefit) and cost ($) for each asset based on the LCCA calculations, assuming all assets will be funded for renewal this year;
3. Compute the Marginal utility per dollar (MU/$) for each asset;
4. Sort assets in a descending order, according to the MU/$; and
5. Select number of assets for funding from each sorted category such that the MU/$ of the last selected asset in each category is almost equal, and the budget for this year is fully exhausted. Move unfunded to the next year. Then, proceed to step 1 for the analysis of the next year, until last year in the planning horizon.

The EBCA method has been examined on a sample pavement problem that include urban and rural roads (Saad and Hegazy 2015). The structured formulation of this technique resulted in reducing the optimization solution space dramatically, and thus it can handle large-scale problems including corridor rehabilitation projects. Accordingly, in this paper, the EBCA approach has been extended to the case of network-level fund-allocation across co-located assets of different types (e.g., bridges, culverts, roads), as described in the next section.

3. EBCA FOR CORRIDOR REHABILITATION

To demonstrate the EBCA method for allocating funds among corridors of different types of assets, a case study of a network of three types of assets (pavements, bridges, and culverts), has been used. The network consists of 24 highways that include 1293 road sections of 350 interurban and 943 rural roads, 161 bridges, and 356 culverts that are located within the right of way of the roads. The case study data was part of an asset management challenge posted at the 7th International Conference on Managing Pavements (Haas 2008). Using the case study data, the objective of this paper is to determine the optimum fund-allocation decisions across the whole network of pavements, bridges, and culverts by deciding on which assets are to be funded (network-level decision) using which rehabilitation strategy (project-level decision) in each year within a planning horizon while meeting budget constraints and achieving equilibrium among the highway corridors.

A sample of the available information for the structures (bridges and culverts) is shown in Figure 2, which includes: highway ID that shows section where the structure is located (e.g., ID of 231B means highway 231, section B), replacement cost, condition rating, etc. The condition rating for both bridges and culverts is represented in terms of an index (CI) out of 100, where CI of 0 implies very poor condition, and CI of 100 implies an excellent condition.



Bridges

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1 2	Bridge ID	Bridge Cat	Hwy ID	Hwy Dir	KM	Usage Code	Replacement Cost ($)	First Year In Service	Unique Span Type	Max Span Ln (m)	No of Spans	Nominal Bridge Ln (m)	Total Clear Roadway (m)	Cond Rat
3	B1	STD	135A	C	14.818	RV	89000	1978	VS	6.1	1	6.1	13.7	55
4	B2	MAJ	231B	C	23.774	RV	3426000	1977	VF	36.6	4	146.4	8.5	61
5	B3	MAJ	150A	C	21.298	RV	1093000	1958	PJ	18.9	3	45.7	8.5	50
6	B4	MAJ	135F	C	41.787									
7	B5	MAJ	132B	C	11.901									
8	B6	MAJ	150B	C	27.285									
9	B7	MAJ	6A	C	2.83									
10	B8	MAJ	75A	R	1.113									

Culverts

	A	B	C	D	E	F	G	H	I	J
1 2	Culvert ID	Hwy ID	Hwy Dir	KM	Replacement Cost ($)	First Year In Service	Unique Span Type	Max Pipe Dia (mm)	Total Clear Roadway	Cond Rat
3	C1	75A	L	9.159	72000	1995	MP	2400	12.4	88
4	C2	237D	C	36.006	33000	1957	MP	1500	7.4	55
5	C3	6A	C	7.15	173000	1992	RPA	10462	13.4	77
6	C4	6A	C	14.727	120000	1992	SP	2438	13.8	77
7	C5	102D	C	1.34	219000	1991	SP	4920	13.1	77
8	C6	72D	L	15.571	363000	1982	RPE	6500	24.8	44
9	C7	90A	C	13.751	346000	1991	SP	3962	12.7	55
10	C8	150B	C	5.641	123000	1965	SPE	2603	11.1	77

Figure 2: Portion of the data provided for bridges and culverts (Haas, 2008)

As opposed to bridges and culverts, the condition of roads is measured in terms of international roughness index (IRI) as a single parameter that represents pavement performance on a range from 0 to 4, where the lower the value, the better the condition. Other general information also include: annual rate of IRI increase (deterioration rate), the maximum allowed IRI values (trigger levels), IRI improvement due to five treatment types, and unit cost of these treatments, respectively. More details can be found in Haas (2007) and Hegazy and Saad (2014). In an effort to capture the importance of each road, the provided trigger values have been used to determine the relative importance factor (RIF) of each road section (RIF = maximum IRI –IRI trigger value). For example, if a road has an average annual daily traffic (AADT) between 6000 and 8000 vehicles, then the IRI trigger value is 2.1 (Haas, 2007), and accordingly the RIF is calculated as 1.9 (i.e., 4 – 2.1).

According to the case study data, the marginal utility formulated in the EBCA approach is defined in terms of the improvement in the asset's physical condition. Thus, in order to unify the scale of measurement across the different asset categories, the pavements' condition in terms of IRI is converted to a condition index (CI) out of 100 similar to the bridges and culverts' condition index, where 100 represents best condition and 0 represents extremely poor condition. Using the case study data, LCCA analysis has been carried out for all three types of assets, considering deterioration patterns, repair strategies, repair cost, condition improvement, users' vehicle operating costs (VOC), and accumulated yearly expenditures.

To enable handling extremely large scale optimization problem associated with considering hundreds of co-located assets of different types, the Multiple optimization and segmentation technique (MOST) of

Hegazy and Elhakim (2011) has been used. In MOST, standalone LCCA is first carried out for each asset type (pavement; bridge; and culvert) separately to determine the best rehabilitation method (e.g., minor, major, or full replacement) for each asset *i* in each potential repair year *j* in the planning horizon that maximizes the benefit-cost ratio in this year. This process is repeated for each potential year *j* in the planning horizon, generating a pool of best rehabilitation strategies for each asset in each possible year along with the associated benefits (Improvement Effect, IE) and costs for all assets. This pool is used as input lookup tables to the EBCA optimization to facilitate the network-level analysis that decides on the best rehabilitation year for each asset, considering the overall network utility and the budget limit (Saad and Hegazy 2015).

3.1 EBCA Optimization Strategies for Co-located Assets

In order to determine optimum fund-allocation decisions over a 5-year planning horizon using an annual budget of $50 million, across the 24 highways while achieving equilibrium among the three categories of co-located assets, in this case study, two alternative optimization strategies were developed with different adaptations of the 5 EBCA steps discussed earlier: (1) Section-level-funding and (2) Asset-level-funding. Both, however, target an equilibrium among the highways.

In the first strategy “Section-level”, as shown in Figure 3, sections within highway corridors compete for funding. If a section is selected for renewal in a given year, then the entire section, including all asset types (bridges, culverts, and roads) will be considered for renewal. For example, if section A in highway 101 (i.e., section 101A) is selected for rehabilitation, then all assets located in this section will be renewed, excluding the ones that are in acceptable level of service over the whole planning horizon. This model, thus, reduces the number of visits for each section while achieving equilibrium among highways.

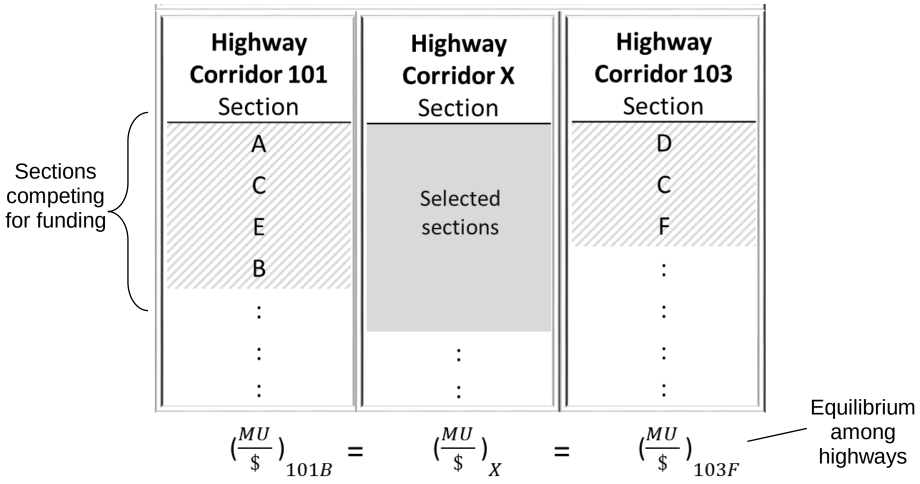


Figure 3: EBCA “Section-level-funding” optimization model

In the second strategy “Asset-level”, on the other hand, pavements; bridges; and culverts co-located within each highway compete for funding regardless of the highway sections they are located in. In this model, equilibrium is achieved by selecting number of pavements, bridges, and culverts in each highway; such that, the average marginal utility per dollar invested in each highway is almost equal, as shown in Figure 4 (e.g., selecting 70 roads, 22 bridges, and 35 culverts from highway 101, and 40 roads, 12 bridges, and 22 culverts from highway 103, and so forth). In this paper, due to size limitation, more details only about applying the “Asset-level” formulation is provided in the following subsection. However, a discussion of the section-level performance against the asset-level model is presented at the end of the case study application.

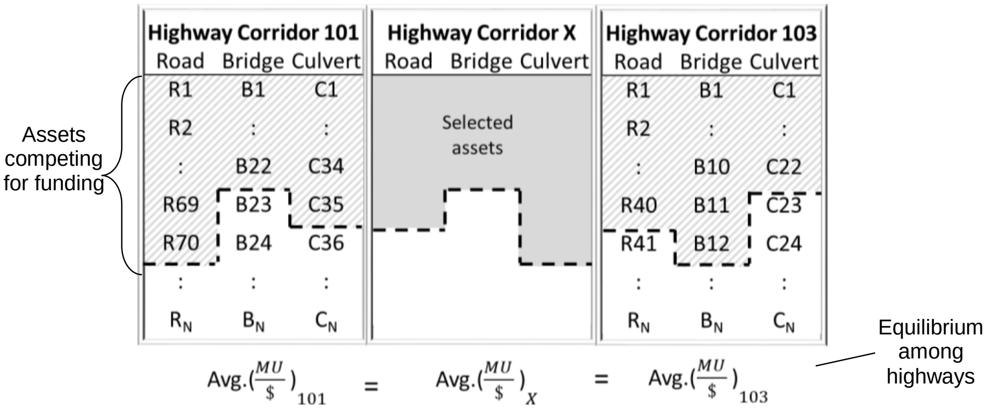


Figure 4: EBCA "Asset-level-funding" optimization model

3.2 Asset-level-funding formulation

To achieve equilibrium among highways, the EBCA steps have been modified as follows:

For each year in the planning horizon:

1. Group unfunded assets according to the highway where they are located in (e.g., 102, 105, 132, etc.), then group them according to the asset types (pavements, bridges, culverts);
2. Identify the improvement effect in the condition index (difference in condition before and after repair) and the renewal cost for each asset based on the LCCA calculations, assuming all assets will be funded this year;
3. Compute the Marginal utility per dollar (MU/$) for each asset by dividing the improvement effect by the renewal cost. To consider the differences in the asset sizes, the improvement effect of each asset, in each category, is multiplied by a scale factor (SF) from 1 to 10 (1 for small size up to 10 for large size).
4. Sort the assets in a descending order within each category, according to the MU/$; and
5. Select number of assets for funding from the top of the sorted list of each category in each highway, till the Avg.MU/$\$_{\text{Hwy}}$ of each highway in the network is almost equal (as illustrated in Figure 4), and the budget for this year is fully exhausted. Move unfunded assets beyond this equilibrium point to the next year in the planning horizon. Proceed to step 1 for the analysis of the next year, until last year in the planning horizon.

To automate this process and facilitate finding an optimum solution especially for a large-scale network, an integer programming model has been developed. The model has 72 integer variables (3 asset categories x 24 highways) which is considered very small in terms of the solution space. Each variable represents the number of assets (Y_{ix}) selected from each asset category list *i* in each highway *x*, as follows:

[3] $Y_{11,}Y_{12,}\ldots Y_{21,}Y_{22,}\ldots\ldots Y_{72}$

The objective function is set to target equality among the average marginal utility per dollar across highways (Avg. $(\frac{\text{MU}}{\$})_{\text{Hwy x}}$). To satisfy the equilibrium condition and make sure that the Avg.MU/$ values are equal, the objective function is set to minimize the variance across the Avg.MU/$ values of each highway *x*, as shown below:

[4] Minimize Variance $(\text{Avg.}\ (\frac{MU}{\$})_{\text{Hwy } 1}, \ldots\ldots, \text{Avg.}\ (\frac{MU}{\$})_{\text{Hwy } x})$, where

[5] $$\text{Avg.}(\frac{MU}{\$})_{HWYx} = \frac{\sum_{i=1}^{n} (MU/\$)_{Y_{ix}} \times S1_i \times S2_{ix}}{n}$$

Where (n) is the number of asset categories available (for roads, bridges, and culverts, $n = 3$), and $MU/\$_{Y_{ix}}$ is the marginal utility per dollar of the last selected asset in asset category (i). $S1_i$ *and* $S2_{ix}$ are scaling weight factors to capture the importance of each category. $S1_i$ accounts for the variation in the size of rehabilitation work for each asset category relative to the other categories (e.g., roads versus bridges versus culverts). While $S2_{ix}$ accounts for the variation in the size of rehabilitation work of one category within each highway relative to the other highways (i.e., pavements in highway 101, versus pavements in highway 102, etc.). Therefore, the mathematical representation of these scaling factors are as shown in Equations 6 and 7, as follows:

[6] $$S1_i = \frac{\text{Total replacement Cost of Type}_i}{\text{Total replacement cost of the whole network}}$$

[7] $$S2_{ix} = \frac{\text{Total replacement Cost of assets of category i in highway x}}{\text{Total replacement cost of assets of category i across highways}}$$

The model has two sets of constraints: the number of selected assets of any type is less than or equal the total available; and the total costs of all selected assets shall exhaust the available budget, as formulated in Equations 8 and 9.

[8] $$\sum_{x=1}^{x=24} RC_{HWYx} \leq \text{Budget}$$

[9] $$Y_{ix} \leq N_{ix}$$

Where, N is the number of assets available of asset type (i) in highway (x), and RC_{HWYx} is the replacement cost of all assets selected for funding in any highway (x).

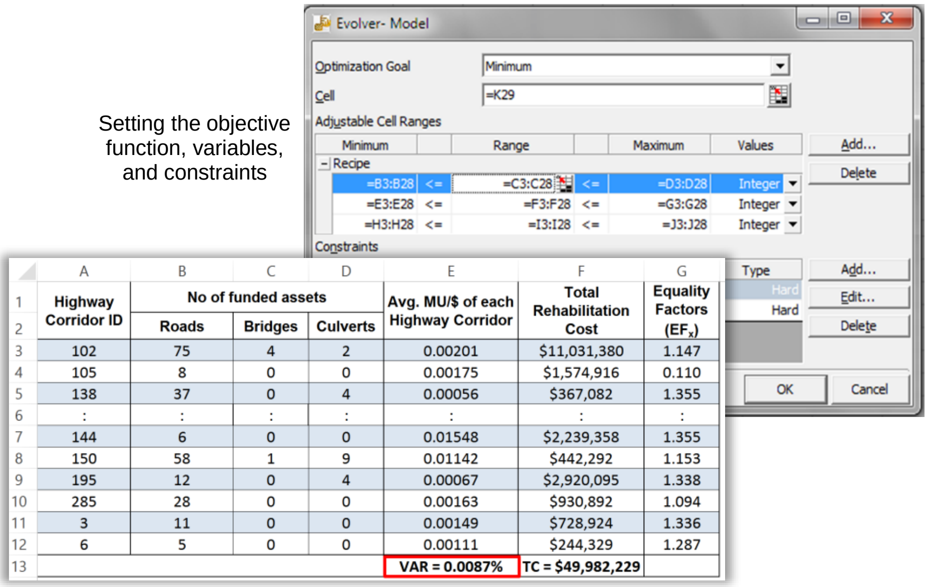
In addition to the above constraints, a set of equality-factors have been introduced as follows:

[10] $$\text{Equality Factor}(EF_{x,x+1}) = \frac{\text{Avg.}(\frac{MU}{S})_{HWYx+1}}{\text{Avg.}(\frac{MU}{S})_{HWYx}}$$

In this case, the number of equality factors is dependent on the number of highways that the model is targeting equilibrium among them; thus, if the number of highways is x, then the number of equality factors is x -1. Since the number of highways in this case study is 24, then the number of the equality factors is 23. In order to facilitate finding an optimum solution fast, the equality factors are constrained to lie in a more relaxed range between 0.7 and 1.4, as follows:

[11] $0.7 \leq EF_{x,x+1} \leq 1.4$, where $x = 1, 2, \ldots\ldots x\text{-}1$

To facilitate further experimentation with the model for the present case study, it was implemented in Excel with an add-in Evolver to setup the problem parameters and carry out the optimization using its Genetic Algorithms engine.



Setting the objective function, variables, and constraints

Optimization Goal: Minimum

Cell: =K29

Adjustable Cell Ranges

Minimum		Range		Maximum	Values
Recipe					
=B3:B28	<=	=C3:C28	<=	=D3:D28	Integer
=E3:E28	<=	=F3:F28	<=	=G3:G28	Integer
=H3:H28	<=	=I3:I28	<=	=J3:J28	Integer

Constraints

Type
Hard
Hard

	A	B	C	D	E	F	G
1	Highway Corridor ID	No of funded assets			Avg. MU/$ of each Highway Corridor	Total Rehabilitation Cost	Equality Factors (EF_x)
2		Roads	Bridges	Culverts			
3	102	75	4	2	0.00201	$11,031,380	1.147
4	105	8	0	0	0.00175	$1,574,916	0.110
5	138	37	0	4	0.00056	$367,082	1.355
6	:	:	:	:	:	:	:
7	144	6	0	0	0.01548	$2,239,358	1.355
8	150	58	1	9	0.01142	$442,292	1.153
9	195	12	0	4	0.00067	$2,920,095	1.338
10	285	28	0	0	0.00163	$930,892	1.094
11	3	11	0	0	0.00149	$728,924	1.336
12	6	5	0	0	0.00111	$244,329	1.287
13					VAR = 0.0087%	TC = $49,982,229	

Figure 5: Portion of the EBCA configuration for “Asset-level-funding” optimization in Excel

3.3 Optimization Results

The summary of the annual fund-allocation results over the 5-year planning horizon for each asset category, after running the optimization model, is presented in Table 1. Table 2 also shows the share of each asset category in the total budget, the number of assets funded from each type of assets; percentage funded in each asset category; the percentage condition improvement, and the condition before and after rehabilitation (road condition is represented in terms of IRI, while the bridges and culverts’ condition is in terms of CI). It can be noted from Table 2 that the EBCA approach arrives at near optimum fund-allocations decisions across different corridors with different asset types. Also, similar to common practice, it has allocated more money to the road sections (52%) than to bridges (45%) and culverts (3%), within the highway network, over the 5 years planning horizon.

Table 1. Results of EBCA optimization model over a 5-year plan

	Year 1	Year 2	Year 3	Year 4	Year 5
Pavements	$13,150,000	$21,150,000	$30,770,000	$40,380,000	$23,690,000
Bridges	$33,270,000	$28,590,000	$18,040,000	$9,060,000	$23,180,000
Culverts	$3,500,000	$240,000	$1,170,000	$550,000	$3,120,000
Total	$49,910,000	$49,970,000	$49,980,000	$49,990,000	$49,990,000

Table 2. Analysis of the EBCA results

	Roads	Bridges	Culverts
% allocated of the total budget	52%	45%	3%
No of funded assets	936	85	97
% funded from each category	72%	53%	27%
% Improvement	17.7%	34.3%	17.4%
Condition before repair	1.7	53.7	58.32
Condition after repair	1.4	72.14	68.49

Using the same case study, the section-level model has been formulated and examined as well. From experimenting with both models, it has been noticed that the performance of both is quite comparable; however, the asset-level model selected more assets for funding, achieved better overall performance across all the asset types, and almost fully consumed the budget available. Yet, one practical benefit of the section-level model, as opposed to the asset-level model, is that it can reduce the social and environmental costs that may potentially result from multiple visits to the same highway section to repair co-located assets during a given planning horizon. Both models, however, achieve results that are in compliance with the current practice in terms of the budget distribution among the different types of assets, yet in a structured and justifiable manner.

4. CONCLUDING REMARKS

This paper presents an extension to the Enhanced Benefit-Cost Analysis (EBCA) method to the case of coordinated infrastructure rehabilitation works. This technique relies on the concept of equal marginal utility per dollar of the consumer theory to arrive at optimum fund-allocation decisions. To examine the EBCA capability, it has been applied to a network that consists of a number of highway corridors of different types of assets (1239 pavements, 160 bridges, and 356 culverts). To address the challenge of achieving optimum fund-allocation across the highways, two alternative implementations have been presented. An “asset-level-funding” implementation where number of assets from each type is selected in each highway to achieve equilibrium among the highways. The results proved the ability of the EBCA technique to arrive at near-optimum fund-allocation decisions considering corridor rehabilitation of co-located assets, and achieving equilibrium among the different expenditure categories in structured manner. The simplicity of the method and its suitability for large-scale asset networks is an advantage over existing approaches that typically address co-located assets independently and apply sophisticated mechanisms that try random combinations of asset selections and funding levels to maximize benefits. In essence, the proposed Microeconomic-inspired EBCA approach provides optimum decision supported with enhanced benefit-cost analysis, and thus can justify the spending of the public money and improve the economics of the multi-billion dollar business of infrastructure management.

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