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Optimum Infrastructure Spending: A Microeconomic Perspective

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Abstract: Municipalities and public agencies are currently facing tremendous pressures to sustain the safety and operability of their deteriorating infrastructure assets while being able to justify the associated expenditures. Infrastructure asset management involves detailed life cycle cost analysis (LCCA) to optimally allocate limited rehabilitation (renewal) funds among many competing assets. LCCA analysis, however, represents a complex optimization problem Moreover, no mechanisms exist to test the optimality of results or to provide economic reasoning behind the decisions made. In an effort to introduce such mechanisms, this research imports theories from Microeconomics that offer simple heuristics to maximize the return (utility) from consumer spending on multiple goods. To test the applicability of microeconomic concepts on the infrastructure fund-allocation problem, a real case study of 1293 pavement sections was used. An optimization model for the case study was developed to determine the optimum fund-allocation decisions. Afterwards, an analysis mechanism was developed to test the optimum results from a consumer theory perspective. The analysis proved that the optimum results can be explained as an equilibrium state in which fair and equitable allocations are made so that the utility per dollar is equalized for all asset categories. In essence, this research provides a novel approach for testing the results of LCCA models, as well as a solid economic basis that can justify fund allocation decisions.

1 INTRODUCTION

Civil infrastructure assets require continuous rehabilitation actions to sustain its safety and operability. In general, rehabilitation is a large process that involves detailed life cycle cost analysis (LCCA) of the whole network of assets to facilitate the allocation of the limited funds (Ugarelli and Di Federico 2010, Vanier 1999, FHWA 1999). Optimizing rehabilitation actions, however, is not a simple task due to the limited budgets available and the strict constraints that should be taken into account. Several research efforts in the literature have introduced optimization models for life cycle analysis and rehabilitation planning in different asset domains. Among these models are: pavement maintenance (De la Garza et al. 2011, Ng et al. 2009); renewal of sewer networks (Halfawy 2008); rehabilitation of water networks (Dridi et al. 2008, Mann and Frey 2011); life cycle cost optimization of steel structures (Sarma and Adeli 2001, 2002); bridge maintenance (Elbehairy et al. 2006, Morcous and Lounis 2005, Liu and Frangopol 2002, Itoh et al. 1997, Liu et al. 1997); building asset management (Tong et al. 2001, Hegazy and Elhakeem 2011); mixed municipal assets (Shahata and Zayed 2010); and groundwater remediation (Zou et al. 2009). While these efforts provided useful LCCA models, none has reported satisfactory optimization results for large scale rehabilitation problems. Moreover, they suffer from many drawbacks, such as the difficulty that the decision maker has in formulating complex functions and constraints. In addition, optimization is often looked at by many industry professionals as a black box that provides no economic reasoning to support rehabilitation decisions. In essence, there is a lack of methods and tools for testing the quality of LCCA models and for providing sound economic justification of fund allocation decisions.

This paper aims at improving fund-allocation practices for infrastructure rehabilitation. It tests the applicability of consumer theory principles to the infrastructure funding problem, through a real case study related to pavements. An optimization model was developed using mathematical programming, then the optimality results were analyzed with respect to the "law of Equi-Marginal Utility per dollar" concept which is one of the main principles of consumer theory. The potential of using microeconomic concepts, to facilitate and justify the fund-allocation decisions, is then discussed.

2 MICROECONOMIC PRINCIPLES FOR OPTIMIZING CONSUMER CHOICES

Basic microeconomic principles, such as consumer theory, have been used since the middle of the 20th century for understanding how consumers optimally spend their limited budgets on multiple goods (Khan and Hildreth 2002), which resembles the situation of a municipality trying to spend limited funds on multiple assets. The basic assumption in consumer theory is that consumers are rational and look for affordable combinations of goods that maximize their total utility (satisfaction) (Lipsey et al. 1997, Fozzard 2001, Rahman and Vanier 2004, Parkin and Bade 2009).

Microeconomic textbooks describe the consumer situation as an optimization problem that has an objective of maximizing total utility, under budget constraints. To demonstrate this basic concept, a simple example from (Parkin and Bade 2009) is used. The example is of a consumer who would like to optimally spend his limited income of $40 on two products: Movies ($8/unit) and Soda cases ($4/unit). Before determining the optimum combination of both products that consumes the $40 budget and achieves the highest satisfaction, basic information about the consumer's utility from both products is shown in Figure 1. In this figure, the 3rd column of each product shows the consumer's total utility gained from the consumption of different amounts of each product (more consumption gives more total utility). The 2nd column of each product shows the marginal utility (MU) which is the change in the consumer's total utility that results from a one unit increase in the consumed quantity from each product. It can be noted that as the consumed quantity from a product increases, the marginal utility decreases (e.g., the consumer's marginal utility from the 2nd movie is 40 which is less than his/her marginal utility from the 1st movie which is 50). This phenomenon of decreasing marginal utility is called *diminishing marginal utility* (Parkin 2009).

To facilitate the total utility maximization, Figure 1 lists six combinations of both movies and soda cases that fully consume the $40 budget (e.g., 1 movie and 8 soda cases; or 3 movies and 4 soda cases, etc.) along with the sum of the total utility associated with each combination. Accordingly, it is possible to immediately determine the optimum combination that has the maximum total utility, which is a combination of 2 movies and 6 soda cases, giving a total utility of 315. While Figure 1 represented this example in an easy-to-solve manner, larger problems would need an integer optimization tool to determine the decision variables (amount to be purchased from each product) with the objective of maximizing the sum of total utility, under the budget constraints. Therefore, it is expected in large problems, particularly when the example is mapped to the infrastructure domain, it will involve high degree of complexity (Sanad, et al. 2008, Liao, et al. 2011), and inability to justify the optimum decisions.

Marginal utility exhibits a diminishing pattern.

Optimum combination (2+6) has highest total utility

Movies $8/unit			Soda $4/unit			Total Utility from both
Quantity	Marginal Utility (MU)*	Total Utility	Quantity	Marginal Utility (MU)	Total Utility	
0	0	0	10	5	260	260
1	50	50	8	10	248	298
2	40	90	**6**	20	225	**315**
3	32	122	4	24	183	305
4	28	150	2	48	123	273
5	26	176	0	0	0	176

Six possible combinations of movies and soda cases that fully consume the $40 budget.

*Marginal Utility= level of satisfaction per unit increase in the consumed quantity

Figure 1: Optimum spending using total utility maximization

As an alternative to solving the above example using total utility maximization, microeconomics provides an interesting heuristic approach to arrive at the optimum decision. In this approach, the consumer chooses the combination of products that achieves an equilibrium state at which the marginal utility gained per dollar spent on the last unit consumed from each product is equal (Khan and Hildreth 2002), as shown in Equation 1, and illustrated in Figure 2.

Marginal Utility per dollar for Movies = Marginal utility per dollar for Soda cases

[1] $(MU/\$)_{movies} = (MU/\$)_{soda}$

Movies $8/unit			Soda $4/unit		
Quantity	Marginal Utility (MU)	MU per dollar	Quantity	Marginal Utility (MU)	MU per dollar
0	0	0	10	5	1.25
1	50	6.25	8	10	2.50
2	40	5.00	**6**	20	5.00
3	32	4.00	4	24	6.00
4	28	3.50	2	48	12.00
5	26	3.25	0	0	0

Optimum combination (2+6) has equal MU/$ in all categories

$(MU/\$)_{movies} = (MU/\$)_{soda}$

The combination that equates MU per dollar for all categories, achieves same optimum results reached in Figure 1.

Figure 2: Optimum spending using the Equi-Marginal Utility approach

In Figure 2, the 3rd column of each product shows the marginal utility gained per dollar (MU/$) from consuming different quantities from both products. Using this approach, the optimum combination is determined to be a combination of 2 movies and 6 soda cases where the MU/$ gained from the 6th unit of soda = MU/$ gained from the 2nd unit of movies = a value of 5. This result is the same as the one obtained by total utility maximization. The logical process to arrive at this optimum combination starts by the consumer evaluating the MU/$ from each product, and successively selects the ones with the highest MU/$, one-by-one, till the budget is exhausted. For example, looking at Figure 2 and starting with the highest values of MU/$, the consumer would do the following:

- Buys 2 soda cases (MU/$ =12); remaining budget is $32;
- Buys 1 movie (MU/$ = 6.25); remaining budget is $24;
- Buys 2 more soda cases (total is 4; MU/$ = 6); remaining budget is $16;
- Buys 1 more movie (total is 2; MU/$ = 5); remaining budget is$8; and
- Buys 2 more soda cases (total is 6; MU/$ = 5); no remaining budget; end of process.

By the end of this process, the money is fully spent and the consumer accumulated the choices with the highest returns (2 movies and 6 soda cases), thus reaching to a balanced satisfaction from both products. Since the optimum combination using the law of Equi-Marginal Utility per dollar (MU/$) is identical to the one obtained from total utility maximization; therefore, this law can reach optimum solution through balanced and fair allocation of money over different categories of spending. This consumer situation is almost similar to the infrastructure fund-allocation case, where the decision maker is deciding on how much to allocate to the different categories of assets that compete for limited rehabilitation funds. Therefore, microeconomic concepts have the potential to properly allocate rehabilitation funds while achieving equity and optimality, considering the utility gained from the money spent.

3 TESTING MICROECONOMIC PRINCIPLES IN THE INFRASTRUCTURE DOMAIN

To verify the applicability of adopting microeconomic concepts in the infrastructure domain a two-step process has been followed (Figure 3): 1) Developing an optimization model for a given case study and determining the optimum fund-allocation decisions; and 2) Performing a microeconomic analysis on the optimum results with respect to the law of equi-marginal utility per dollar. In this paper, the fund-allocation decisions are made based on the condition improvement of assets within the given case study. The next subsection discusses the development of the optimization technique used in step 1 of the process. Afterwards, experimenting on a case study is discussed in the subsections to follow.

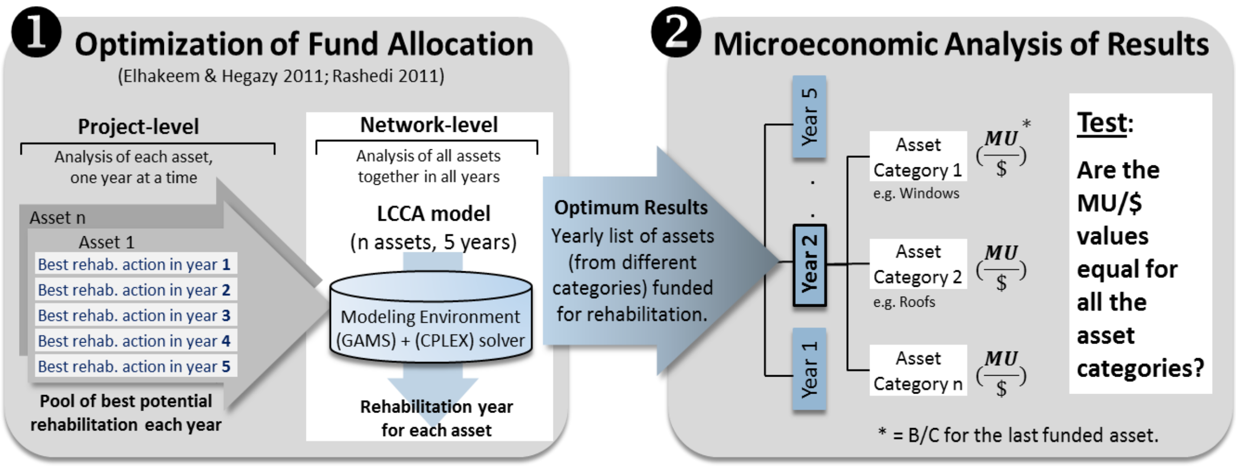


Figure 3: Two-step process to test microeconomic concepts on infrastructure case studies

3.1 Network-level Optimization Model

LCCA models that optimize infrastructure fund-allocation include two levels of decisions: 1) project-level to decide on the rehabilitation type for each asset, and 2) network-level to decide on the rehabilitation year for each asset within the planning horizon. To optimize decisions considering both levels, the authors' previous work on developing the MOST optimization model (Hegazy and Elhakeem 2011) has been utilized. In the MOST technique, project-level decisions are first optimized separately through small individual optimizations for each asset to determine the best rehabilitation method associated with each year in the planning horizon. The project-level optimization yielded a pool of best rehabilitation scenarios for all assets (with corresponding costs and condition improvement) at each optional year in the planning horizon). Afterwards, this pool is used as an input to optimize network-level decisions. The optimization model at the network level was designed to be generic and determines for each asset the optimum rehabilitation year within the planning horizon that improves the overall network condition. The model's objective is to maximize the overall network condition index CI_N, which is an aggregation of one or more performance parameters of all individual assets. The life cycle analysis is assumed to be along a planning horizon of 5 years, therefore each asset can be selected in year 1, 2…, 5, or zero (no action). A Binary decision variable X_{ij} is used to represent the 2-dimension solution space of n-assets and j years. If X_{ij} for a certain asset i and year j is equal to 1, then the asset is selected for rehabilitation at this year, and the associated rehabilitation cost and condition improvement would be plugged in the model. The model's variables, constraints, and objective function are as follows:

Decision Variables:
(Matrix of rehabilitation timing decisions)

$$\begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} \\ . & . & . & . & . \\ . & . & X_{ij} & . & . \\ . & . & . & . & . \\ X_{i1} & X_{i2} & X_{i3} & X_{i4} & X_{i5} \end{bmatrix}$$

Where, if X_{ij}= 1, then asset (i) is selected for rehabilitation in year (j), otherwise X_{ij}= 0 and the asset is not selected.

Objective function: maximize the overall condition index (CI_N) for the whole network of assets, which is a function of the matrix (combination) of rehabilitation timing decisions, as follows:

[2] CI_N = weighted sum of asset conditions w/o rehab + weighted sum of asset improvements due to rehab

$$= \frac{\sum_i (\text{Ave.}\,(\text{CI})_{i0} \times \text{RIF}_i)}{\sum_i \text{RIF}_i} + \frac{\sum_{i=1}^{i} [\sum_{j=1}^{j} (\text{IE}_{ij} \times \text{X}_{ij}) \times \text{RIF}_i]}{\sum_i \text{RIF}_i}$$

Where, RIF_i is the relative importance factor (0 – 100) of asset i;
IE_{ij} is the improvement effect of renewing an asset (i) in year (j);
Ave. $(CI)_{i0}$ is the average of CI values of asset (i) at all years (j) in case of no rehabilitation.

It is important to note that the objective function, which is an additive function of the assets' improvements (IEs), uses the relative importance factor RIF to represent these improvements on the same scale.

Constraint: The total rehabilitation cost (TC_j), which is the sum of all assets' costs (IRC_{ij}) in any year *j*, should not exceed the available budget for that year, as shown in Equation 6. Also each asset can only be selected once for rehabilitation within the planning horizon or not selected. As shown in Equation 3.

[3] $\text{TC}_j = \sum_i (\text{IRC}_{ij} * X_{ij}) \le \text{B}_j, \quad (\sum_j \text{X}_{ij}) \le 1$

The network-level optimization model of this study, based on an earlier work by Rashedi (2011), utilized General Algebraic Modeling System (GAMS) which is suitable to model large-scale optimization problems. GAMS consists of an array of integrated high-performance built-in solvers. The present model used the CPLEX internal solver (IBM-ILOG 2009), which is one of GAMS most powerful solvers.

3.2 Microeconomic Analysis: Pavement Case Study

This case study is a pavement network which was part of an asset management challenge posted at the 7th International Conference on Managing Pavements (ICMP7) (ICMPA 2007). The pavement network consists of a total of 1293 road sections of two types: interurban and rural roads. The available budget per year is assumed to be $10 million with an annual interest rate of 6%. The information given on each road section include: length, width, AADT, year of construction, and surface condition assessments (International Roughness Index, IRI, and others). Other general information was also given, as shown on the left of Figure 4, regarding the annual rate of increase of IRI, the max allowed IRI values (trigger levels) which are function of the traffic volume, the unit cost of various types of treatments, and IRI values before-and-after treatment (the right of Figure 4). The trigger values are then used to determine the relative importance factor of each road.

Having the information about the pavement network, the previously described optimization model was applied to the case study data. First, project-level analysis was carried out separately using the MOST technique of *(*Hegazy and Elhakeem 2011) to determine the best rehabilitation type for each road section, and the results were exported to the network-level optimization model. It is important to note in this model, the international roughness index IRI was used to reflect the condition of the road sections; therefore, the objective function in Equation 2 was adjusted to minimize the overall CI_N of the network, since lower values of IRI indicate better condition.

Road Class	AADT	Rate of Increase in IRI (m/km/yr)
Interurban	> 8000	0.069
	< 8000	0.077
Rural	> 1500	0.091
	< 1500	0.101

AADT	IRI Trigger Value (mm/m)	Rel. Importance Factor (RIF)
<400	3.0	1.0
400-1500	2.6	1.4
1500-6000	2.3	1.7
6000-8000	2.1	1.9
>8000	1.9	2.1

Intervention Type	Cost ($)
1. Preventive Maintenance	6.45
2. 40mm Overlay	6.75
3. Cold Mill & 40mm Overlay	10.50
4. 75mm Overlay	15.75
5. 100mm Overlay	16.50

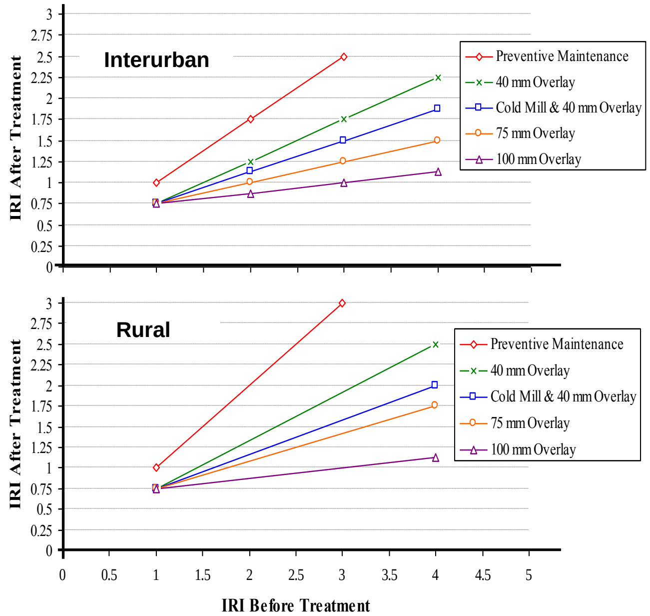
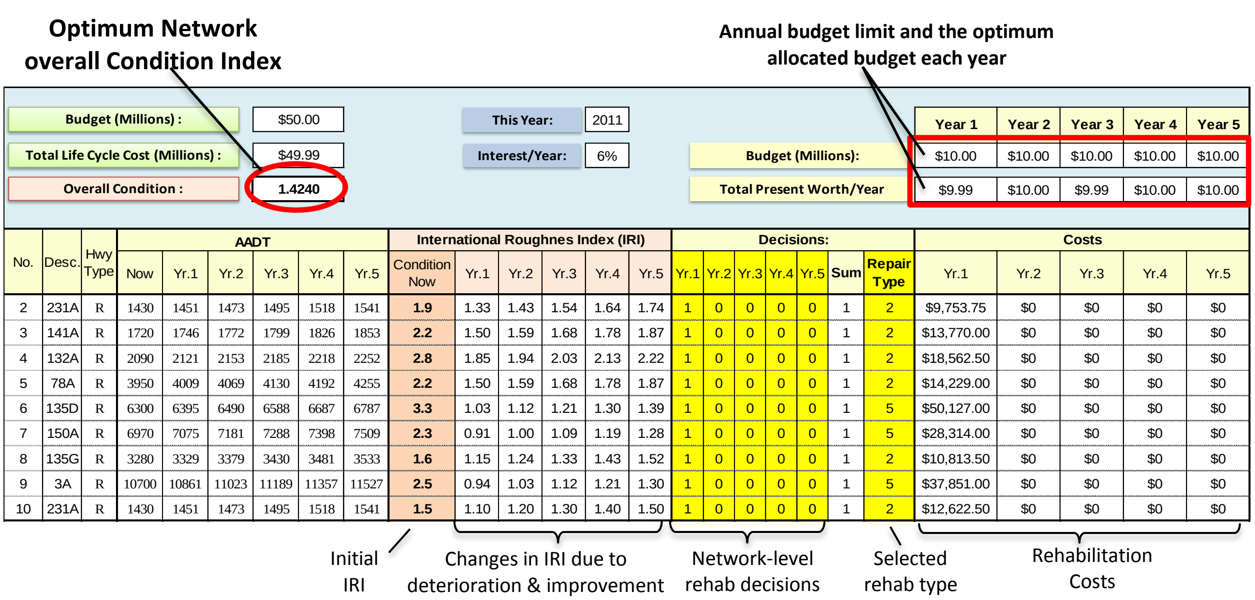


Figure 4: IRI after treatment for urban and rural roads

After applying the optimization model, the optimum rehabilitation year of each road section was determined and the overall network condition was maximized while meeting the annual budget limits ($10M). The optimization model reached a near-optimum solution value of 1.424 for the overall network CI_N, which represents a huge improvement from the original CI_N of 1.7 without any rehabilitation. The screen capture in Figure 5 shows a portion of the optimization results represented in a spreadsheet to facilitate further analysis. Each row in the figure represents one road section and the corresponding network-level decision regarding the rehabilitation year for each road, and the resulting IRI and cost in each year. Also it shows the accumulated annual spending (top right of the figure) and the overall optimum result (top left).



Budget (Millions) :	$50.00	This Year:	2011		
Total Life Cycle Cost (Millions) :	$49.99	Interest/Year:	6%		
Overall Condition :	1.4240				

	Year 1	Year 2	Year 3	Year 4	Year 5
Budget (Millions):	$10.00	$10.00	$10.00	$10.00	$10.00
Total Present Worth/Year	$9.99	$10.00	$9.99	$10.00	$10.00

No.	Desc.	Hwy Type	AADT Now	AADT Yr.1	AADT Yr.2	AADT Yr.3	AADT Yr.4	AADT Yr.5	IRI Condition Now	IRI Yr.1	IRI Yr.2	IRI Yr.3	IRI Yr.4	IRI Yr.5	Decisions Yr.1	Decisions Yr.2	Decisions Yr.3	Decisions Yr.4	Decisions Yr.5	Sum	Repair Type	Costs Yr.1	Costs Yr.2	Costs Yr.3	Costs Yr.4	Costs Yr.5
2	231A	R	1430	1451	1473	1495	1518	1541	**1.9**	1.33	1.43	1.54	1.64	1.74	1	0	0	0	0	1	2	$9,753.75	$0	$0	$0	$0
3	141A	R	1720	1746	1772	1799	1826	1853	**2.2**	1.50	1.59	1.68	1.78	1.87	1	0	0	0	0	1	2	$13,770.00	$0	$0	$0	$0
4	132A	R	2090	2121	2153	2185	2218	2252	**2.8**	1.85	1.94	2.03	2.13	2.22	1	0	0	0	0	1	2	$18,562.50	$0	$0	$0	$0
5	78A	R	3950	4009	4069	4130	4192	4255	**2.2**	1.50	1.59	1.68	1.78	1.87	1	0	0	0	0	1	2	$14,229.00	$0	$0	$0	$0
6	135D	R	6300	6395	6490	6588	6687	6787	**3.3**	1.03	1.12	1.21	1.30	1.39	1	0	0	0	0	1	5	$50,127.00	$0	$0	$0	$0
7	150A	R	6970	7075	7181	7288	7398	7509	**2.3**	0.91	1.00	1.09	1.19	1.28	1	0	0	0	0	1	5	$28,314.00	$0	$0	$0	$0
8	135G	R	3280	3329	3379	3430	3481	3533	**1.6**	1.15	1.24	1.33	1.43	1.52	1	0	0	0	0	1	2	$10,813.50	$0	$0	$0	$0
9	3A	R	10700	10861	11023	11189	11357	11527	**2.5**	0.94	1.03	1.12	1.21	1.30	1	0	0	0	0	1	5	$37,851.00	$0	$0	$0	$0
10	231A	R	1430	1451	1473	1495	1518	1541	**1.5**	1.10	1.20	1.30	1.40	1.50	1	0	0	0	0	1	2	$12,622.50	$0	$0	$0	$0

Figure 5: Portion of the network-level optimization results for the pavement case study

The fund allocation decisions obtained from the network-level optimization model were then further analyzed with respect to the law of equi-marginal utility per dollar to test the applicability of using microeconomic concepts (consumer theory) in the infrastructure domain using this case study. Hence, the principles applied in the soda-movies case are tested in the pavement network case (one year at a time). The consumer's decision of spending money between soda cases and movies under limited income is mapped to the decision problem of allocating limited funds among different asset categories (Interurban and Rural pavement sections). The optimum solution in the soda-movies case was achieved by equating the marginal utility per dollar spent on the last unit consumed from each product. Therefore, the marginal utility per dollar spent on renewing the last asset from each category in the case study is computed to check the equality of values. The marginal utility per dollar is determined by computing, for each asset, the condition improvement (marginal utility) per rehabilitation cost (dollar). As such the rehabilitation cost of one asset resembles the cost incurred to purchase one unit of a product. The condition improvement, resulting from renewing, that each asset adds to the overall network condition resembles the marginal utility that each additional unit of a product adds to the consumer's satisfaction. Generally, utility can represent, in the infrastructure domain, a combination of social, economic, environmental improvements gained from a given rehabilitation decision. Since in this paper, fund-allocation decisions consider only the condition improvement; therefore, the utility will be only in terms of condition improvement. The condition improvement (Marginal utility) of an asset in a given rehabilitation year is computed using the following equations:

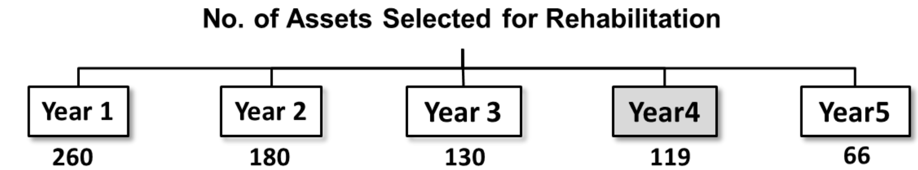
[4] Condition Improvement (MU) = Average of IRI values $_{(\text{No Rehab})}$ – Average of IRI values $_{(\text{Rehab})}$

[5] Marginal Utility per dollar (MU/$) = Condition Improvement / Cost of rehabilitation

In essence, the optimum fund-allocation results of each year were analyzed separately with respect to the two road categories: Interurban, and Rural. The analysis involved computing Marginal utility per dollar (MU/$) for each allocated asset in each year. The general steps of the analysis are as follows:

1. Export the optimum results of GAMS/CPLEX to an Excel spreadsheet
2. For each year in the analysis:
    - Consider only the assets selected for funding in the optimum solution in this year;
    - Group the assets according to their asset category (e.g., interurban, and rural);
    - Calculate the marginal utility (MU) in terms of condition improvement and costs ($) of each asset;
    - Sort the assets within each group in a descending order according to (MU/$); and
    - Examine the equality of the (MU/$) values among the last assets selected for funding of each category;
3. Proceed to step 2 for the analysis of the next year, until last year in the planning horizon.

Figure 6 shows the analysis results for each year. For example at year 4, the optimum number of assets with allocated funds is 119 (35 interurban and 84 rural). The analysis also shows that the marginal utility per dollar (MU/$) spent on the last interurban and rural road sections selected are 0.24 and 0.23, respectively which are very close. This approximate equality of marginal utility per dollar proves that optimal results are consistent with the law of equi-marginal utility per dollar among different asset categories. Therefore, it proves the applicability of Consumer Theory in the infrastructure domain. This paper, thus, proved that, from a microeconomics perspective, optimum fund allocation is an equilibrium state in which fair and equitable allocations are made so that the utility per dollar is equalized for all asset categories. Such an equilibrium condition is perhaps easier to achieve through an easy-to-explain microeconomic approach than to use complex optimization models that choose combinations of funding levels at random.



Category	No.	MU/$*	No.	MU/$	No.	MU/$	No.	MU/$	No.	MU/$
Interurban	64	1.63	40	0.89	40	0.53	35	0.24	30	0.09
Rural	196	1.61	140	0.86	90	0.34	84	0.23	36	0.08

*MU/$ = Marginal Utility per dollar

Figure 6: Microeconomic analysis of optimal results for the pavement case study

4 SUMMARY AND CONCLUDING REMARKS

This paper examined the applicability of microeconomic concepts that explain the spending behaviour of consumers, in the infrastructure fund allocation problem. To facilitate this investigation, a real case study of 1293 pavement sections has been used. The research successfully developed a mathematical life cycle cost optimization model for the case study and obtained optimum fund allocation solution. The next step analyzed the optimality results from the equi-marginal utility concept of microeconomics to develop a better understating of the rationale behind optimum solutions. The Analysis results proved that, from a microeconomics perspective, optimum fund allocation is an equilibrium state in which fair and equitable allocations are made so that the marginal utility per dollar is equalized for all asset categories. Accordingly, this microeconomic analysis provides sound economic justification for funding decisions. The proposed microeconomic analysis can be readily used as a benchmark test to examine the quality of any budgeting/funding mechanism. The integration of microeconomic and asset management concepts proposed in this paper is very promising and with continued research can lead to new innovative decision support tools for improving the economics of the multi-billion dollar business of infrastructure management.

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