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MULTI-METHOD MODEL FOR INFRASTRUCTURE PORTFOLIO MANAGEMENT

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Management practices have a direct impact on the cost of capital used for financing the operations and maintenance of existing infrastructure on a concurrent basis with planning and constructing new projects. This paper identifies best management practices that can improve credit rating, which in-turn theoretically lowers the interest paid on debt. As a result, these best management practices lower the weighted average cost of capital used to maintain existing assets on a concurrent basis with the construction of new infrastructure. As a practical example, this paper identifies the best management practices from the perspective of municipal credit rating agencies in the United States. The current research then constructs a deterministic integer programming model based on these best management practices. The deterministic model is part of multi-method model that will be mathematically embedded into a system dynamics model that can then be used as a facilities management plan. The facilities management plan aims at lowering the weighted average cost of capital for maintaining existing assets while planning and constructing new infrastructure. While the multi-method model is based on municipal credit rating in the U.S., the research goal is to nevertheless show how a system dynamics model is used to implement best management practices that are generally accepted as economically sustainable worldwide.

Keywords: Sustainability, System dynamics, Finance, Economics, Best management practices, Strategic and operational planning.

1 INTRODUCTION

The purpose of this research is to advance the economic sustainability of the infrastructure procurement process by hedging the risk of financial loss to private equity sponsors and commercial lenders. To achieve this primary goal, the objectives of the current research are threefold. The first objective is the construction of an integer programming (IP) model to optimize the management of a portfolio of infrastructure assets by meeting a set of specific economic and financial constraints while ensuring all user demands are met. The second objective is the construction of a system dynamics (SD) model to analyze and simulate the causal effects related to asset deterioration, rehabilitation processes, cost accumulation and inflexibility of resources across a portfolio of infrastructure assets. By jointly considering the first two objectives, a third and primary objective will be to present a holistic method for supporting a process to optimize decision-making during the procurement of new assets within a portfolio of existing infrastructure. The decision-making process is part of an overarching management plan that incorporates economic and financial targets while ensuring all user demands are met.

2 RESEARCH METHODOLOGY

The investigation presented in this first part of a series of research papers is intended to elucidate a methodology where SD models can be used to manage a portfolio of infrastructure assets from multiple perspectives. The methodology outlined in this paper is intended to be adaptable and used by any one of several stakeholders in the infrastructure procurement process. For practicing civil engineers and concerned governments, the SD model will be used essentially as a facility management plan. Conversely, this same methodology with a modified SD model is equally intended to be used by equity sponsors and commercial lenders for optimizing the economic return and mitigating financial risk arising from a portfolio of infrastructure investments. The methodology begins with the current research that identifies the best management practices (BMP) from the perspective of credit rating agencies in the U.S. Several of these BMPs can be mathematically modeled and are presented in an IP model in this paper. The IP model includes constraints that capture the BMPs from the perspective of credit rating agencies in the U.S. While the model is based on municipal credit rating in the U.S., the research goal is to investigate and demonstrate how IP and SD models can be constructed and used in tandem to manage an investment portfolio subject to a variety of optimizing constraints.

The IP model is presented in detail in this current research paper. The IP model includes an objective function to minimize all costs associated with managing a portfolio of infrastructure assets while ensuring all user demands are met, subject to a set of financial and economic practices that are considered highly favorable from the perspective of the credit rating agencies. This current research will be followed by an investigation that presents an illustrative case study that demonstrates how the objective function can be optimized. By doing so, the maintenance of existing assets and the procurement of new assets can be prioritized as a function of user demands, costs and the optimization constraints included in the IP model. The third and final stage of the overarching research will integrate the optimization results into a system dynamics framework similar to the "aging chain" SD model that is presented in cursory form in this current paper. Simulation results from the SD model will be used to analyze how the portfolio of infrastructure performs in meeting all user demands while satisfying the optimization constraints.

3 MANAGEMENT IMPACT ON CREDIT

For purposes of brevity, a complete discussion of management's impact on credit is precluded from this research paper. The integer programming model presented, however, is largely based on Larkin (2001) in which the BMPs have been identified as highly favorable to concerned governments and other issuers of debt. Table 1 includes those BMPs and also indicates the respective constraint(s) within the IP model that captures the mathematical representation of each practice.

4 INTEGER PROGRAMMING MODEL

The IP modeling method is concerned with optimization problems in which some of the variables are required to take on discrete values. Rather than allow a variable to assume all real values in a given range, only predetermined discrete values within a prescribed range are permitted. In most cases, these values are integers, giving rise to the name of this class of models (Jensen and Bard 2003). While a full discussion explaining the methodology of IP modeling is beyond the scope of this paper, the current research presents an IP model that mathematically represents the BMPs from the perspective of municipal credit rating agencies in the U.S.

Table 1. Management practices and integer programming model constraints.

Management Practice	Constraint No.
Fund balance reserve policy & working capital reserves	No. 4
Multiyear financial forecasting	No.'s 4, 5, 6, & 7
Contingency planning policies	No.'s 4, 5, 6, & 7
Policies regarding nonrecurring revenue	No. 5
Depreciation of general fixed assets	No. 6
Debt affordability reviews and policies	No.'s 4, 5, 6, & 7
Pay-as-you-go capital funding policies	No. 4
Five-year capital improvement plan integrating operating costs of new facilities	No. 6
Rapid debt retirement policies (greater than 65% of debt retired in 10 years)	No. 7

It is noteworthy that for academic purposes, IP models are often presented as a method for optimizing a warehouse or other facility location-type problem. There are several notable similarities and distinctions between the facility location-type problem and the application of IP modeling method in the current research. To begin, in the facility location-type problem the IP model includes constraints that are a function of the costs for building a facility at a specific location in order to meet all customer demands. Likewise, the IP model presented in this research aims to optimize the expenditure of funds while meeting all demands required of a portfolio of infrastructure assets. Furthermore, in the facility location problem constraints are related to shipping within geographical boundaries. Conversely, the IP model in the current research is bound within a range of economic and financial constraints established by credit rating agencies. In addition and as the name suggests usage of the IP model in the facility location problem is used to select a location for a facility prior to construction. In the current research the IP model is used to structure a management plan for a portfolio that consists of already existing infrastructure and other assets that have yet to be designed and/or constructed.

4.1 IP Model for BMPs

The following IP model includes constraints 1, 2 & 3 which are required to establish that all user demands are met and to account for annual operational costs for a portfolio of existing facilities on a concurrent basis with significant upgrades and the construction of new projects.

The integer programming model follows:

$$X_{ijk} = \begin{cases} 1 & \text{If calendar year } j \text{ is the } k^{th} \text{ year of upgrading or constructing an asset } i \\ 0 & \text{Otherwise} \end{cases} \quad (1)$$

where c_{ijk} equals the cost in year k for upgrading an existing infrastructure asset or a procuring new facility i in calendar year j.

Plant i take on values of A, B, C, D etc.

For a facility management plan of N years starting in year 1: $1 \leq j \leq N$.

Let S be the set of variables defined as the following:

- $X_{Aj,1}$……………………..$X_{Aj,k}$ for all j
- $X_{Bj,1}$……………………..$X_{Bj,k}$ for all j

For A, B, C, D etc.

The objective is to minimize the total cost subject to the requirements that all demands be met subject to the capacity of current and future assets contained within the infrastructure portfolio.

$$\text{Minimize} \sum_{i} \sum_{j} \sum_{k=1}^{k(i)} c_{ijk} \; X_{ijk(i)} \tag{2}$$

where *K(i)* equals the number of years to operate and maintain or upgrade existing facilities *or* construct and add new assets into the infrastructure portfolio; subject to the following constraints:

Constraint No. 1 – All demands must be met over *N* years.

$$\sum_{j}^{N} X_{ijk} = d_i \tag{3}$$

Constraint No. 2 – For upgrading and/or constructing infrastructure asset *i* in *n* number of years, the n^{th} year follows $n^{th} - 1$ year etc.

$$X_{i,j+1,2} \;\geq\; X_{i,j,+1}\,;\; X_{i,j+2,3} \;\geq\; X_{i,j,+2}\,;\; X_{i,j+3,4} \;\geq\; X_{i,j,+3}\; etc. \tag{4}$$

Constraint No. 3 – For each infrastructure asset *i* and each calendar year *j*, *j* is at most 1 year of operations and maintenance and / or new construction.

$$X_{i,j,1} + X_{i,j,2} + X_{i,j,3} + X_{i,j,k(i)} \leq 1 \tag{5}$$

Constraint No. 4 – Maintaining a fund balance reserve policy and working capital reserves.

$$\sum_{i} \sum_{j} \sum_{k=1}^{k(i)} c_{ijk} \; X_{ijk(i)} \leq \; U_j + \sum y_j \tag{6}$$

where U_j is defined as the upper bound defined by conservatively forecasted revenue less the amount placed into working capital reserves and pay-as-you-go capital funding policies and y_j is defined as the sum of allowable debt for year *j*.

Constraint No. 5 – A policy in place regarding nonrecurring revenue.

$$\sum_{j} (C_{A,j,1}X_{A,j,1} + C_{A,j,2}X_{A,j,2} + C_{A,j,3}X_{A,j,3}) \;\leq non-recurring\ revenue + \%\ U_j + \% \sum y_j \tag{7}$$

Constraint No. 6 – Implementation of a five (5) year capital improvement plan integrating operating costs.

$$\text{For each year j the} \sum c_{i,,j,k} X_{i,j,k} \;\leq\; U_j + \sum y_j \tag{8}$$

Constraint No. 7 – A policy for the rapid retirement of debt with at least 65% of debt retired in the next 10 years.

$$.65 \sum y_j \;\geq \sum y_j \;\; in\ year\ j + 10 \tag{9}$$

5 SYSTEM DYNAMICS MODELS

Of particular relevance to the current research is the work of Rashedi and Hegazy (2015), in which a SD model simulates the "aging chain" of the deterioration and rehabilitation processes as part of an infrastructure management plan. A Markovian process along with a transition probability matrix (TPM) is used to capture the nonlinear progression of infrastructure assets evolving toward worsening states of condition before receiving major rehabilitation or being completely replaced. The SD model is used to preclude budget shortfalls on a concurrent basis with the preservation of existing infrastructure. The TPM is formulated as follows:

$$\mathrm{TPM} = \begin{bmatrix} P_{11} & \mathrm{P}_{12} & 0 & 0 & 0 \\ 0 & P_{22} & \mathrm{P}_{23} & 0 & 0 \\ 0 & 0 & P_{33} & \mathrm{P}_{34} & 0 \\ 0 & 0 & 0 & P_{44} & \mathrm{P}_{45} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad \text{Eq. (10)}$$

where P_{ii} is the probability of an asset in state i remaining in state i while $\boldsymbol{P_{ij}}$ is the probability of the same asset deteriorating to state j ($P_{ii} + P_{ij} = 1$).

5.1 Developing the SD Model

The current research begins to construct the SD model (Figure 1) consistent with Rashedi and Hegazy (2015) but for purposes of brevity only a simple stock-and-flow diagram is presented. The stock-and-flow diagram presented within this research was developed with the computer software iThink 10.1.2® in order to demonstrate how a facility management plan can be developed within a SD model platform. The SD model employs the industry-accepted general structure for stock-and-flow diagrams including stocks, flows, converters, and connectors. Rectangles represent stocks and signify both physical and non-physical accumulations resulting from an activity. Flows represent activities or actions that transport quantities into or out of a stock over time. Inflows and outflows are represented by pipes or arrows pointing into (adding to) and out of (subtracting from) stocks, respectively. Unless there is a net value of zero, material stock exists at a given point in time and will remain even when the processes of inflows and outflows are complete.

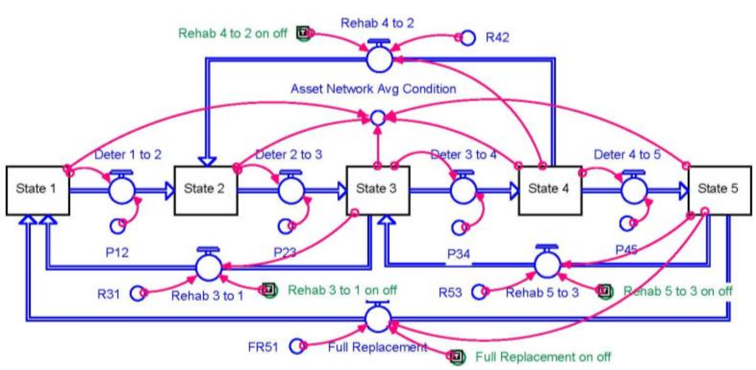

Figure 1. System dynamics model for an "Aging Chain" of infrastructure assets.

In the current research, the SD model includes the rate of deterioration based on a time constant between states that captures the nonlinear progression of infrastructure assets evolving toward worsening states of condition before receiving major rehabilitation or being completely replaced. Figure 2a shows an example for a case of 100 assets in State 1 (which could be interpreted as the "new", as built state), wherein the rate of deterioration is exponential for transitions between each successor state given the characteristic time constants for transition between these states. Figure 2b shows a reduced rate of deterioration after a rehabilitation process is introduced, which transitions assets from state #3 to the original state #1. In the follow-on research the costs for rehabilitating assets back to earlier states of condition will be constrained by the optimization results from the IP model's objective function.

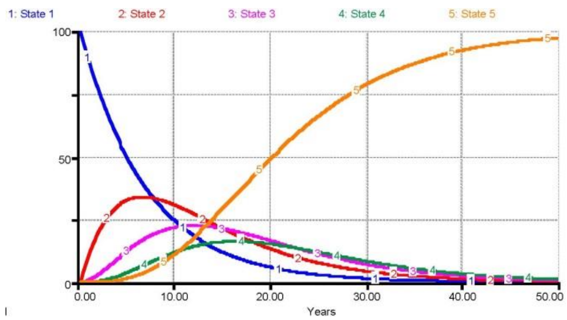

Figure 2a. Assets with no rehabilitation.

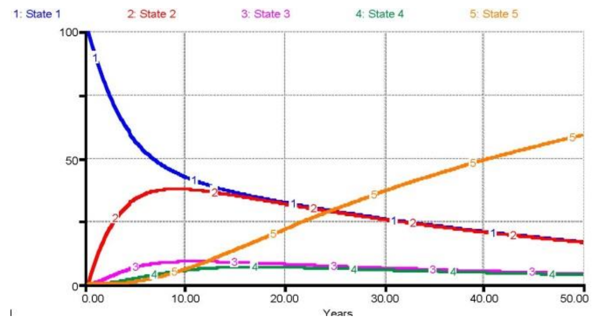

Figure 2b. Assets with rehabilitation.

6 CONCLUSION AND FURTHER RESEARCH

The research presented in this paper identifies BMPs that have been determined to improve a government credit rating. An improved credit rating translates into a lowered cost of capital, which in-turn makes future projects more feasible. The primary objective of the current research is to construct a multi-method model that can be used to manage a portfolio of infrastructure assets while meeting these BMPs. This investigation investigates a first step to facilitate a more manageable and streamline SD model. It includes the construction of an IP model in which the objective function is to minimize all costs for maintaining a portfolio of assets while meeting all user demands subject to the aforementioned BMPs. Follow-on research will include solving the IP model and optimizing the objective function at the appropriate level of abstraction to classify infrastructure assets by type while ensuring all user demands are met within the framework of the SD model. The objective of this evolving research is to develop a multi-method model to manage a portfolio of infrastructure assets.

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