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A COMPREHENSIVE ASSET MANAGEMENT SYSTEM FOR SEWER INFRASTRUCTURES

A Dissertation in

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by

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ABSTRACT

As critical components of infrastructure management systems, after enforcement of the Government Accounting Standards Board's statement 34 (GASB 34), development of a valuation approach and optimal rehabilitation and replacement polices (R&R policies) for infrastructure assets become overriding concerns to governmental agencies. To comply with GASB 34 requirements, governments must report the value of their infrastructures' assets by using a depreciation method or a modified approach. However, most existing valuation approaches, including these two, do not properly account for the change of assets' conditions and time-value of money. This may lead to inappropriate asset values, especially for infrastructures that have significantly longer service life than other capital assets.

This study proposes an asset valuation model, combined with a Markov chain-based, condition prediction and a regression-based, construction cost index prediction, to capture the change of asset condition and time value of money. The model not only will assist in predicting the future value of the asset but also will play an important role in constructing the optimal R&R policies and the timing of their application.

This study also describes the development of a two-step optimization process for R&R policies that include project and network levels optimizations. In project-level optimization, probabilistic dynamic programming analyzes the life cycle cost of a system. In network-level optimization, fuzzy logic theory optimizes the allocation of limited funds and prioritization polices for the infrastructure system.

Finally, by describing the potential applicability of the prediction model to real option theory, this study assists government agencies in implementing a comprehensive infrastructure management system to further assist in making satisfactory financial decisions.

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Chapter 1

INTRODUCTION

1.1 Background

Despite the importance of civil infrastructure as a driving factor in economic growth, the most recent American Society of Civil Engineers (ASCE) report-card showed that overall U.S. civil infrastructures are now graded D (on a scale of A to F and I) and need a $1.6 trillion investment for upgrades (ASCE 2005). This D-grade means that most infrastructure systems are aging and about to reach the end of their useful lives. In the case of sewer infrastructure, the U.S. should spend $390 billion over the next 20 years to improve current systems and construct new ones to respond to increasing demands. Under this circumstance, the question is how to establish a long-term investment plan to more effectively and efficiently fund projects to maximize benefits. By this reasoning, comprehensive asset management systems are receiving closer attention than ever before, as are asset valuation approaches.

Asset valuation is one of the major components of asset management systems for civil infrastructure. The Government Accounting Standard Board's statement 34 (GASB 34) established new requirements for financial statements for local and state agencies, mandating that the governing entities should include the value of infrastructure in their financial statements. An additional influence is the growing trend toward privatization and transfer of ownership of municipal assets between governing agencies and private entities. Although financial accounting guidelines have been developed and adopted to guide public agencies in valuing and reporting public assets, these methodologies often lack a reflection of the performance of assets and the time-value of money. Such guidelines may not properly provide the basis for financial decisions. Thus, this study presents a valuation method that incorporates structural condition and time-value of money to determine the current and future values of sewer infrastructure in this study.

Another issue in existing sewer management systems is the reactive approaches in rehabilitation and replacement policies. Unlike other infrastructures, a sewer system is often neglected until critical problems arise, because sewer lines are underground and rarely inspected regularly. Thus, in most cases, sewer infrastructure systems are managed on a worst-first basis, and this leads to ineffective funding allocations and more frequent system failures. For these reasons, establishment of optimal Rehabilitation and Replacement (R&R) policies significant challenges facing governmental agencies that manage comprehensive sewer management systems.

1.2 Problem Discussion

As discussed earlier, two critical transitions exist for the delivery of infrastructure systems. First, due to privatization within infrastructure systems that had traditionally been owned and operated by public government, an increased need has arisen for a systematic valuation approach to ensure equitable transactions. The second reason is the new GASB 34 accounting requirements for state and local agencies. These requirements mean that for the first time agencies must show the value of their infrastructures’ assets through annual reporting.

Considering the influence of infrastructure on the public, whatever valuation method is used, the formulated value should include accurate information about the condition and performance of the infrastructure’s assets. Further, a consistently derived asset value is a basis for comparison and reference for the decision making process within a comprehensive asset management system. Although some efforts to develop the performance model and valuation method for sewer infrastructure systems have been undertaken, no widely accepted condition rating system and valuation method exists. This is one of biggest problems in the reliable estimation of asset value. Without a consistent practice and methodology for valuation, comparison of asset value for different agencies may result in misleading data.

Another problem existing in this area is the lack of scientific knowledge regarding deterioration mechanisms for underground structures. The reasons include lack of a nation-wide inventory of sewer systems, lack of well-defined performance parameters, lack of long-term inspection data, and lack of a minutely classified condition rating system. These deficiencies for existing sewer systems produce issues like inefficient budget allocation, costly emergency repairs, frequent service failures, public health problems, etc. On the other hand, significant investigation regarding prediction models and condition rating systems has been done in pavement infrastructures, and government agencies still consider performance modeling as a significant task for the next several decades in order to optimize funding allocation and maximize benefit for their infrastructures.

1.3 Research Goal and Scope

The main purpose of this research is to develop a performance based asset valuation method that incorporates time-value of money and a deterioration model to provide an assessment tool for determining the serviceability of the sewer infrastructure system. This study also presents two-step optimization approach to help establish long-term investment plans for optimal R&R policies. The approach employs probabilistic dynamic programming of life cycle cost analysis for project level of optimization and applies fuzzy logic model for network levels of optimization. Consequently, this study provides a basis for financial decisions in comprehensive sewer infrastructure management systems as shown Figure 1-1.

This work includes:

- Development of a deterioration model using the expected value method
- Examination of the linkage between this performance prediction model and the valuation method
- Comparison of the developed valuation model with other existing valuation models
- Development of project and network levels of optimal R&R policies and budget allocations by a two-step optimization process
- Demonstration of the impact of asset valuation on the investment decision

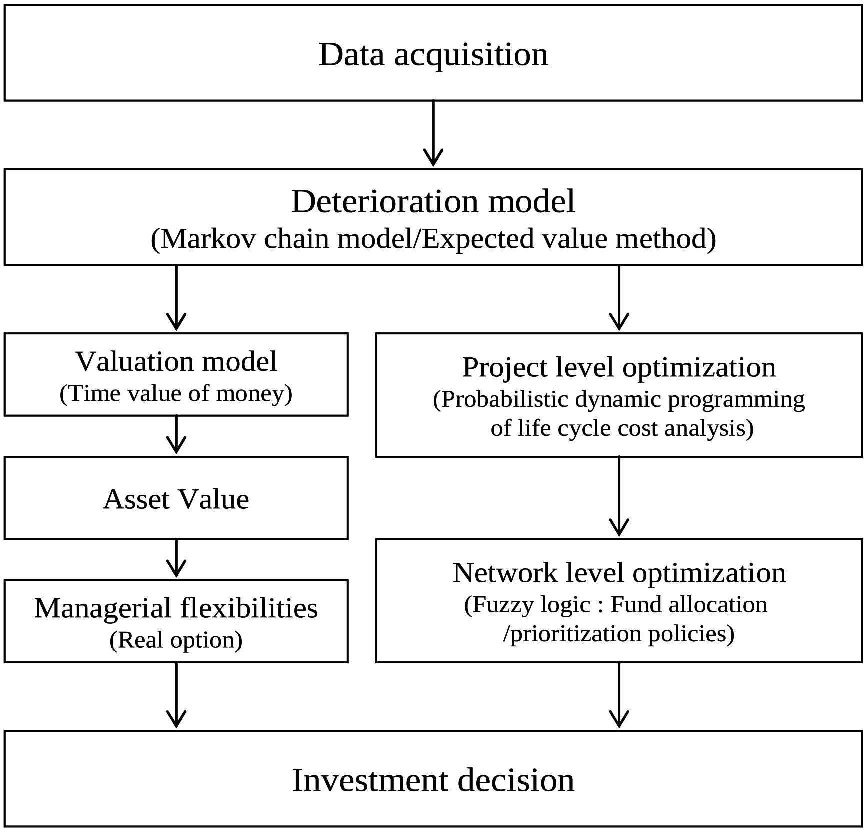


Figure 1-1: Research framework

Key aspects to consider in the development of a valuation model include:

- Impact of maintenance, rehabilitation and replacement on the asset value and service life
- Application of the concept of “time-value of money”
- Applicability of a valuation model for the prediction of future value
- Application of the model to other infrastructures

Key aspects to consider in the development of the two-step optimization process include:

- Manipulation of transition probabilities based on renewal technologies
- Involvement of engineering judgment and experience in optimal rehabilitation and replacement policies
- Formulation of reasonable membership function for each parameter in fuzzy logic modeling
- Presentation of guidelines for optimal R&R policies

1.4 Organization of the Thesis

This thesis includes seven chapters. Chapter 1 presents background information, problem discussion, and research objectives. Prior research regarding asset management systems, GASB34, asset valuation and life cycle cost analysis are discussed in Chapter 2. Chapter 3 reviews existing prediction models and the fundamental idea of Markov chain-based deterioration model and methods to estimate transition probabilities. Chapter 3 also includes a description of data used for deterioration modeling and comparison of deterioration models based on sizes, materials and locations. Chapter 4 describes the concept and method of two-step optimization for R&R policies, along with illustrative examples, application of dynamic programming and fuzzy logic theory in the development of optimum R&R policies. Chapter 5 presents a new valuation approach reflecting condition and price and a comparison with other existing valuation methods. In Chapter 6, new emerging real option theory is introduced and the potential application of transition probabilities and the proposed valuation model to the investment decision is discussed. Finally, Chapter 7 summarizes contributions and limitations of the study and presents some recommendations for future study and improvement to the research direction.

Chapter 2

REVIEW OF THE EXISTING INFRASTRUCTURE MANAGEMENT SYSTEM

As indicated previously, due to implementation of new accounting requirements and limited available funds, the idea of asset management systems is receiving more attention. This chapter mainly addresses an overview of a comprehensive asset management system and its contributing components. The first section presents the key concepts and the implementation of an asset management system. Some supporting concepts for an asset management system, such as GASB34, asset valuation, and life cycle cost analysis are described.

2.1 Asset Management System

2.1.1 Background

Asset management is a systematic approach that guides the maintenance, operation, preservation and improvement of infrastructure assets to obtain optimum service delivery and resource allocation throughout the asset's service life (FHWA 1999). The idea of an asset management system is most widely used in the transportation area. and the fundamental framework can be expressed as shown in Figure 2-1

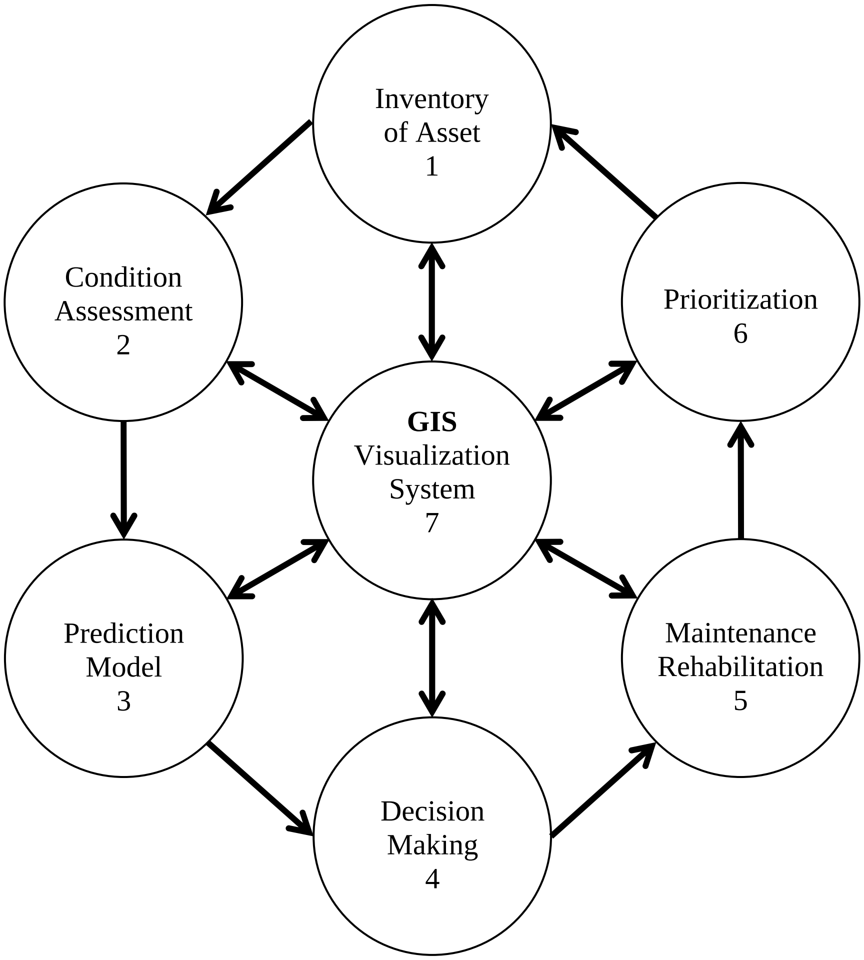


Figure 2-1: Infrastructure management system framework

An infrastructure management system mainly consists of the seven components. The actual structure may differ for each government, but the basic concepts are the same. First of all, an infrastructure management system begins with organization of the asset's inspection data. This is usually called "inventory of asset." In this step, the utility manager and officer establish a comprehensive record of asset including age, material, location and other general information. In the pavement area, national wide databases are available; but in sewer systems, only a few pipe line data are available. The second step in an infrastructure management system is condition assessment. After gathering data, the utility manager must analyze those data, and then evaluate and rank the condition of the asset using a predetermined coding system. While a 0-100 grading system and a 1-9 grading system are applied to pavement and bridges, respectively, a 1-5 grading system is used for sewer systems. Under the modified approach, the government agency should evaluate the condition of the asset at least every three years and, as required supplementary information, the government must present a schedule of condition assessment for the three most recent years. The third step is modeling infrastructure performance. Since infrastructure systems are critical for daily business, predicting their future performance is essential in order to avoid and unexpected collapse of the infrastructure asset. The forth step in an infrastructure management system is the decision-making process. Once the condition assessment and the prediction model are executed, then agencies have a comprehensive understanding of their infrastructure asset, which will lead to well-organized long-term R&R strategies and optimized resource allocation. Decisions should also reflect several aspects such as available funds, regulations, public health, etc. Some method of analysis such as life cycle cost analysis, fuzzy logic, risk analysis and real option theory, could support the decision making processes. The next step in the system is maintenance and rehabilitation, based on decisions made previously. Finally governments must prioritize assets for future investment.

In the current practice of asset management, all of the information discussed earlier is linked with a Geographic Information Systems (GIS) system. The system is a powerful and flexible tool for management of data. By using the GIS system, agencies can manage many layers of information and easily access and update the data.

2.1.2 Implementation of Asset Management

For the last 30 years, the need for expanding and upgrading sewer systems has extensively increased to meet the dramatic growth of communities. Because of this dramatic growth and the lack of timely information, most sewer systems operate in a reactive mode and allocate most resources to the rehabilitation or complete replacement of already failed systems. In addition, according to ASCE report (2005), most sewer systems are approaching a state of near collapse and undetected defects are getting more severe. In response, government agencies are paying more attention to the implementation of asset management systems, which will allow governmental agencies to manage and improve their sewer system efficiently and cost-effectively during the entire life of the asset by:

- Implementing long-term investment plans to minimize annual and overall costs throughout the useful life of the asset.
- Preventing premature failure through well-designed R&R investment plans and policies.
- Establishing well organized prioritization policies for the maintenance and rehabilitation of the asset.

- Optimizing resource allocation through life-cycle cost analysis and other economic analyses.

2.2 GASB 34

2.2.1 Background

The Governmental Accounting Standard Board (GASB) had revised the governmental reporting model and established new accounting requirements for local and state governing entities in 1999. This action was in response to a belief that governmental financial statements were not providing effective information to evaluate economic conditions and make financial decisions. The essence of GASB 34 is that governments show the value of their infrastructure assets with full accrual accounting while presenting statements for governmental funds in the traditional way. GASB 34 also gives two options for financial based reporting. One is the traditional approach called the depreciation method, and the other is a modified approach, called the preservation method. (FHWA 2000) The main differences in the application of these two approaches appear in Table 2-1 .

Table 2-1: Depreciation method vs. modified approach

	Depreciation method	Modified approach
Maintenance costs	Expense	Expense
Preservation costs	Capitalize	Expense
Improvement costs	Capitalize	Capitalize

2.2.2 Depreciation Method

Depreciation is an allocation of cost to expense an asset in a rational manner due to its use or obsolescence during service life. It is not a measure of actual deterioration but a cost allocation. Therefore, the asset may not deteriorate in a certain year, and further actual value of the asset may be increased.

Depreciation expense is defined as the share of the initial cost of an asset consumed for the current period. This also includes additions and improvements that give benefit to the asset for more than one accounting period. Specifically, when an asset is expected to increase its quantity, quality or its service life beyond the initial estimate, the net acquisition cost would be adjusted. Various ways to estimate depreciation exist, and the different depreciation methods can be used for the same capital assets. However, once a method is selected for a certain asset, the same method should be used for the life of the asset. According to GASB 34, any generally accepted method of depreciation is applicable.

2.2.3 Modified Approach (Preservation Method)

Another reporting option for local agencies is a modified approach. As long as certain requirements are met, agencies may report their asset at full historical cost without depreciation (FHWA 2000). First, the agency should keep maintain the system above the condition level determined by the government. Second, the agency must manage the system through the asset management system that follows certain requirements. These requirements include establishing the inventory of eligible assets, performing the condition assessments at least every three years, estimating the annual amount needed to maintain, and preserving the system specified by the government and compared with actual amounts expensed for past five years. Agencies also must submit a schedule of the three most recent condition assessments of the asset.

2.3 Asset Valuation

In recent years, due to a move toward privatization within infrastructure systems, asset valuation approaches are becoming a significant issue in comprehensive asset management systems. However, a review of the literatures indicates that no generally accepted basis for determining the value of infrastructure assets exist. (Lemer 1998). Since asset valuation outcomes would be different for the same asset under various valuation approaches, close consideration of the purpose of the valuation method is necessary to determine the right method under given circumstance (Amekudzi et al. 2002). Therefore, whatever valuation approaches are used for the estimation of value, the value should follow some degree of consistency and accuracy.

Earlier, Lemer (1998) presented equivalent present worth in place and added to existing methods including historical cost, current replacement cost, market value and productivity realized value. Amekudzi et al (2002) divided valuation methods into three classifications: past-based valuation, current-based valuation, and future-based valuation, as in Table 2-2.

Table 2-2: Classification of valuation methods (Amekudzi et al. 2002)

Past-based Valuation	Current-based Valuation	Future-based Valuation
Book value Historical cost GASB 34	Replacement cost Written down replacement cost	Net salvage value Replacement cost Written down replacement cost

More recently, Baik (2003) developed a deteriorated value method that reflects conditions of an infrastructure asset. Comparisons of the aforementioned valuation methods by features and applications appear in Table 2-3.

Most methods currently used in infrastructure asset valuation do not properly capture the time value of money and actual performance of the asset. Without consideration of these factors, valuation methods do not provide timely and helpful information to maintain the infrastructure system properly. Thus, this study presents a valuation method, that incorporates Markov chain-based prediction model and a construction cost index. The information from the proposed valuation method helps to establish long term investment plans and cost effective and efficient system management.

Table 2-3: Various valuation methods (Cowe Falls et al. 2004)

Valuation Method	Features
Historical Cost: Estimate cost for procurement from historical record	Data is generally available and relatively simple to use Does not consider the inflation and deterioration
Book Value : Value based on historical cost adjusted for depreciation	Most widely used and simple to use Potentially provide unrealistic value for older asset
Replacement Cost: Current cost to rebuild the asset	Potentially provides inflated value Does not consider current condition
Written Down Replacement Cost: Current market prices to replace the asset in current condition	Considers the current price and condition Hard to predict future cost
Equivalent Present Value: Historical cost adjusted for inflation, depreciation, and wear	Accounts for changes in prices and usages Requires many assumptions for inflation, depreciation and wear
Net Salvage Value: Difference between the cost to replace the asset and the cost to rehabilitate it	Difficult to predict future construction cost prices Subject to market forces
Market Value: The cost that is willingly accepted by buyer and owner for the transfer of the asset	Limited applicability for infrastructure assets Conjectural until offer is actually received
Productivity Realized Value: Net present value of benefit/cost stream for the remaining life of the asset	Realistic reflection of importance of asset Basis for budgeting
Deteriorated Value Method (Purdue): Value obtained by combining the condition factor and base value	Accounts for R&R history Does not consider time value of money and potentially provides deflated value Basis for budgeting

2.4 Life Cycle Cost Analysis

2.4.1 Background

Life Cycle Cost Analysis (LCCA) is an evaluation technique used to compare possible alternatives based on total costs including initial construction, operation, maintenance, rehabilitation and other cost anticipated throughout the entire service life of asset and determine the most cost effective way to complete the project (FHWA 2002).

Theoretically, LCCA can be divided into two categories based on the techniques and methods applied: deterministic method and stochastic method. The traditional deterministic approach typically consists of five steps, beginning with the development of alternatives to accomplish the objectives for the project. The analyst then defines the schedule of initial and future activities involved in implementing each project design alternative. In the next step, the costs associated with these activities are estimated. Best-practice LCCA calls for including not only direct agency expenditures but also costs to facility users that result from these agencies' activities. And then, using a discounting technique, these costs are converted into constant dollars and summed for each alternative. Finally, the analyst determines which alternative is the most cost-effective (FHWA 2002).

The process of life cycle cost analysis involves many issues can be involved and the traditional deterministic approach does not explicitly account for the uncertainty regarding useful life, future behavior of the infrastructure, effect of maintenance and rehabilitation, etc. These limitations of the conventional deterministic method can be complemented by the probabilistic method, called the Markov decision process.

For the last 20 years, Markov Decision Process (MDP) has been widely used for rehabilitation and replacement (R&R) decision making processes for infrastructure systems. Similar to the Markov chain, the MDP is a system that allows change from one specific state to another state, and in each step, the decision maker chooses one of the possible alternatives. The condition of a system and the decision made at the current stage affects the probability distribution of the next move and incurs an immediate gain and a subsequent gain. Uncertainties regarding the future condition of the pipe are represented by transition probability, and this probability distribution will be computed based on the Markov chain model.

Optimization techniques, such as Dynamic programming, have great potential for deciding optimal R&R policies for sewer systems at certain stages. However, although the main objective of dynamic programming is to minimize total R&R cost throughout the life cycle of sewer system, what should be kept in mind is that a lowest cost alternative may not mean the best way when taking risk, available funds and environmental concerns into consideration. LCCA could provide useful information for decision makers, but it does not guarantee the best answer.

2.4.2 Life Cycle Cost Analysis Method

Life Cycle Cost Analysis (LCCA) can be considered in two possible categories, based on techniques and methods applied: the Deterministic Model and Probabilistic Model as shown in Table 2-4 .

Table 2-4: Stochastic and deterministic Methods

Categories	Method	Description
Stochastic method	Dynamic programming (Markov Decision Process)	Accounts for probabilistic behavior of input parameter such as uncertainty and variation Minimizes total expected discounted cost
Deterministic method (Economic analysis)	Net present value method	Computes present worth of life cycle costs and find alternative with highest net present value
	Equivalent uniform annual costs	Computes uniformly distributed annual cost of alternatives throughout the analysis period and compare with other alternatives
	The internal rate of return (IRR)	Evaluates applicability of alternative by comparing the internal rate of return (IRR) for the project with minimum attractive rate of return (MARR). IRR should be equal or greater than MARR.
	Benefit-cost ratio	The alternative would be acceptable, when benefit/cost ratio is equal to or greater than 1
	Break-even analysis	Evaluates acceptability of alternatives by finding the factor and its break-even point that equates the costs for two competing projects

2.4.3 Application of LCCA in Infrastructure System

For the last decade, due to limited available funding resources and the change in the delivery of infrastructure systems, the demand for analyses that assist in determining the best and least expensive alternative for accomplishing a project has increased and substantial work regarding optimal R&R policies has been completed. However, these efforts were mostly related to pavement and bridges infrastructures at the facility level.

Earlier, Carnahan et al (1987) and Feighan et al. (1988) applied Markov Dynamic Programming linked with performance model to analyze various maintenance alternatives and determine optimal maintenance standard, using pavement condition index, for highway pavement, including timing and intensity of maintenance. Later, Ravirala and Grivas (1995) employed a state increment method of life cycle cost analysis (SILCCA) to evaluate highway management options at the project-level. According to Ravirala and Grivas(1995), SILCCA has some important advantages over traditional Markov and semi-Markov methods in applying engineering judgments to improve the accuracy of the models and analytical and computational efficiencies.

In the bridge system, Tam and Stiemer (1996) applied LCCA to minimize the cost of coating maintenance for steel bridges in two ways: equivalent annual cost analysis and dynamic programming. Frangopol et al. (1997) employed dynamic programming to develop a life time optimized inspection and maintenance strategies for highway bridges, and Robelin and Madanat (2006) optimized the cost for the maintenance and replacement for the bridge decks based on realistic, history-dependent prediction models.

In the underground infrastructure systems, Abraham et al. (1998) first introduced the use of dynamic programming for the selection of sewer R&R alternatives through the case study of large combined sewers from city of Indianapolis. Kleiner et al. (2001) combined dynamic programming with hydraulic constraints to provide the network-level renewal planning for water pipe systems. This comprehensive approach from dynamic programming produced strategies that cover optimal alternatives for rehabilitation and the optimal time of implementation. Recently, Baik (2004) applied dynamic programming for the selection of optimal R&R policies for sewer pipe line based on an ordered-probit prediction model and present the most cost effective alternatives for sewer pipeline maintenance at different times and under different conditions.

Most studies discussed earlier, just provide alternatives with minimum cost as optimal R&R policies, and do not properly take constraints such as available fund and prioritization policies into consideration. Thus, this study introduces the idea of two-step optimization process reflecting those concerns.

Chapter 3

DEVELOPMENT OF THE PREDICTION MODEL

The previous chapter discussed the importance of a prediction model as a critical component of an asset management system. Chapter 3 begins with a review of three different types of prediction models and their applications, followed by the basic idea of the Markov chain model and detailed procedures for estimation of transition probabilities. Then, using a nonlinear optimization approach, transition probabilities are estimated and a corresponding deterioration curve developed. Finally, the computed transition probabilities become input for the development of the two-step optimization for R&R policies presented in Chapter 4.

3.1 Prediction Model

For more than 20 years, development of an accurate prediction model has been considered an essential component for an effective asset management system. Even though, as indicated by Serpente (1993), pipe deterioration is more influenced by unexpected impact than certain defects, and anticipating when a system will fail seems impossible. Prediction models could play a pivotal role in comprehensive asset management in that they provide a forecast for long-term deterioration patterns as well as possibilities for system failure.

According to Morcous et al. (2002), such prediction models can be classified into three groups based on techniques and methods applied: deterministic models, stochastic models, and artificial intelligence models, as shown in Table 3-1 .

Table 3-1: Prediction models for bridge infrastructure assets (Morcous et al. 2002)

Category	Techniques	Method
Deterministic models	Straight-line extrapolation	-
	Regression models	Stepwise regression
		Linear regression
		Nonlinear regression
	Curve-fitting models	B-spline approximation
		Constraint least square
Stochastic models	Simulation model	-
	Markovian models	Percentage prediction
		Expected-value method
		Poisson distribution
		Negative-binomial model
		Ordered-probit model
		Random-effect model
		Latent Markov-decision
Artificial intelligence	Artificial neural network	-
	Case-based reasoning	-

Deterministic models include straight extrapolation, regression techniques and curve fitting models. Straight line extrapolation may provide unrealistic results because the mode of deterioration is not based on real data. The regression modeling technique relies mainly on historical data, which is not readily available for underground infrastructure such as water and sewer pipelines. In addition, these models do not reflect the inherent probabilistic feature of infrastructure deterioration and the influence of unobserved explanatory variables. (Jiang and Sinha 1989, Madanat and Wan Ibrahim 1995)

In stochastic models, probability-based techniques combine available historical data with prior knowledge and expert opinion to predict future outcomes. Thus, when a comprehensive database is not readily available, the probability-based Markov modeling technique can prove beneficial.

Artificial intelligence models including artificial neural networks (ANN) and the case-based reasoning approach (CBR) have been applied for predicting longevity of bridge systems since the late 1990s. An artificial neural network is a learning system that can be trained by external or internal information that flows through a network. This model can be used to identify complex relationships between inputs and outputs from historical information to model a pattern in data. The CBR method is a simulation technique that requires huge amounts of data of similar, previous cases, including structural features, operational history and environmental conditions to predict future performance. Thus, the task is extremely time consuming, and the results could be subjective due to the involvement of engineering judgment in measuring attribute weights and degrees of similarity (Morcous et al. 2002).

3.2 Markov Chains

The Markov chain is a discrete-time stochastic process developed by Andrei Markov in 1906. In probability theory, a stochastic process has the Markov property if the conditional probability distribution of future states of the process, given the present state and all past states, depends only upon the current state and not on any past states.

This property can be expressed for a discrete parameter stochastic process (X_t) with a discrete state space, as in Eq. 3.1:

$$P(X_{t+1} = i_{t+1} \mid X_t = i_t, X_{t-1} = i_{t-1}, \ldots, X_1 = i_1, X_0 = i_0) = P(X_{t+1} = i_{t+1} \mid X_t = i_t) \qquad 3.1$$

where i_t = state of the process at time t and P = conditional probability of any future event given the present and past events.

When the Markov chain is used to model deterioration of a system in state i, a fixed probability exists that the system will change from state i to state j during the next period. This probability is called transition probability and represented by p_{ij}, as shown in Eq. 3.2:

$$P(X_{t+1} = j \mid X_t = i) = p_{ij} \qquad 3.2$$

The transition probabilities are commonly represented by a matrix of order (m * m) called the transition probability matrix (P), where m is the number of possible condition states. Each element (P_{ij}) in the matrix represents the probability that the condition of a system will move from state i to state j during a certain period. The general form of transition matrix P is given in Eq. 3.3

$$P = \begin{bmatrix} P_{11} & P_{12} & \bullet\bullet\bullet & P_{1m} \\ P_{21} & P_{22} & \bullet\bullet\bullet & P_{2m} \\ \bullet & \bullet & & \bullet \\ \bullet & \bullet & & \bullet \\ P_{m1} & P_{m2} & \bullet\bullet\bullet & P_{mm} \end{bmatrix} \qquad 3.3$$

$$\sum_{j=1}^{m} P_{ij} = 1, \ for \ \ i = 1, 2, 3, \ldots, m$$

The probability that a process in state i will be in state j after n transition is defined as n-step transition probability, $P_{ij}^{(n)}$ and, using Chapman-Kolmogorov equation, the n-step transition probability matrix $P^{(n)}$ is obtained by taking n-th power of the one-step transition probability P as in Eq. 3.4 :

$$P^{(n)} = \underbrace{\mathrm{P} * \mathrm{P} * \ldots * \mathrm{P}}_{n-times} \tag{3.4}$$

3.3 Computation of Transition Probabilities

This section discusses the basic concept and detailed procedure of the expected value method for the computation of transition probabilities. Later, transition probabilities generated from this method will be used as input for dynamic programming and real option analysis for life cycle cost analysis and financial decisions, respectively.

3.3.1 Regression-Based Expected Value Method

The expected value method is one of the most common approaches used in estimating transition probabilities. This approach is widely used for the estimation of the transition probabilities in the field of infrastructure systems due to its simplicity and ease of use for pavements (Butt et al. 1987, Carnahan et al. 1987), bridges (Jiang et al. 1988), and sewers (Wirahadikusumah et al. 2001, Baik 2003). However, the application of linear regression in the development of prediction models is limited and inappropriate, since the condition rating has a discrete ordinal nature rather than a continuous one (Madanat et al. 1995). The step-by-step process for the nonlinear optimization is:

Step 1. Pipes are grouped into categories where each category consists of factors such as pipe material, size, length, depth of installation, soil condition, water level etc.

Step 2. For each subgroup, regression analysis is performed between condition rating data and ages.

Step 3. A nonlinear optimization technique is used to estimate transition probabilities, as shown in Eq. 3.5 :

$$Minimize \sum_{t=1}^{N} |Y(t) - E(t.P)| \qquad 3.5$$

where,

- t = age of asset;
- N = total number of transition periods;
- Y(t) = estimated condition from regression function;
- E(t,P) = expected value of condition at time t based on Markov chain model;
- $E(t=n,P) = [1\ 0\ 0\ 0\ 0]P^{(n)}C^{T;}$
- [1 0 0 0 0] = initial condition state matrix;
- $P^{(n)}$ = transition probabilities matrix after n transitions, and
- C^T = transpose of condition rating matrix; $[1\ 2\ 3\ 4\ 5]^T$.

This method only produces one transition matrix, as shown below:

$$P = \begin{bmatrix} P_{11} & 1-P_{11} & 0 & 0 & 0 \\ 0 & P_{22} & 1-P_{22} & 0 & 0 \\ 0 & 0 & P_{33} & 1-P_{33} & 0 \\ 0 & 0 & 0 & P_{44} & 1-P_{44} \\ 0 & 0 & 0 & 0 & P_{55} \end{bmatrix} \qquad 3.6$$

3.4 Data Description

3.4.1 Clean Water Atlanta (CWA)

The City of Atlanta's Bureau of Wastewater Services has managed over 2,000 miles of sanitary and combined sewers, six combined sewer overflow treatment plants, four water reclamation centers and 16 pump stations. In 2002, the City of Atlanta initiated Clean Water Atlanta (CWA), a comprehensive long-term project to secure clean water and waste water flow. As a part of CWA, the city also proposed the Five Point Plan. The plan included specific innovation strategies to reduce flooding and pollution by storm water; to prevent sanitary sewer overflow by inspection, cleaning and relining of the sewer system; to ensure water quality by monitoring forty stream sites, and to provide the highest water quality by implementation of a combined sewer over flow remediation program.

To comply with the Sanitary Sewer Overflow consent decree of the Five Point Pan, the city also implemented Maintenance, Operation and Management (MOM) programs and the City's Capital improvement program. The project includes the following aspects:

- Clean 25% of the sewer system each year
- Using closed circuit television cameras, inspect 15% of the sewer system each year and evaluate their condition (Sewer System Evaluation Survey)
- Prioritize based on the severity of their condition
- Repair and rehabilitate 24 miles of sewer each year

3.4.2 Data Acquisition

As a part of Sewer System Evaluation Survey program (SSES), the city has evaluated the condition of its sewer system. However, due to data availability, only three basins' data sets (of seven basins), are used for the development of the sewer pipeline performance model. These basins are Nancy Creek, Peachtree Creek and South River, as shown in Figure 3-1. Depending on material, diameter, and location of pipe line, the entire group of data sets were divided, resulting in 11 subsets to be analyzed and compared.

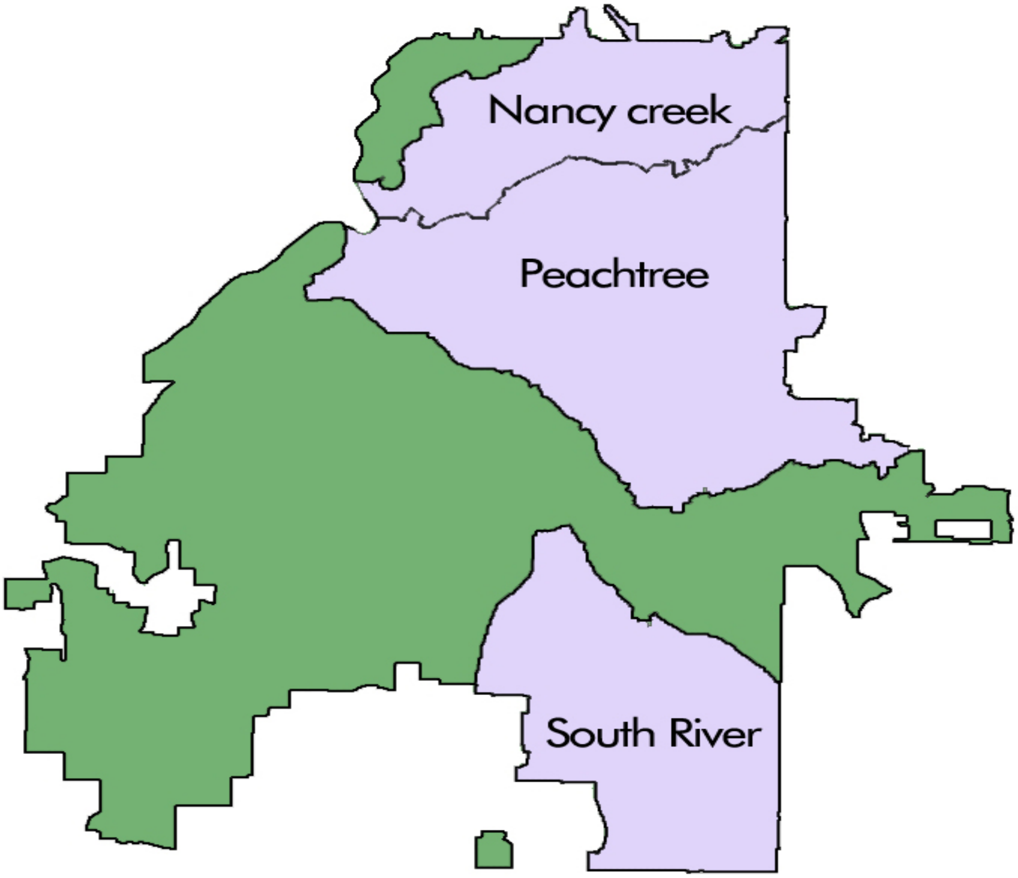


Figure 3-1: Location of three basins

3.5 Implementation of Deterioration Model

Originally, both expected value method and negative binomial model were supposed to be applied and compared to provide a better idea of the performance model of City of Atlanta’s sewer pipeline. However, due to the availability of panel data set, only the expected value method is used to compute transition probabilities and further produce a deterioration model in this research. First, all data sets are divided into locations: Peachtree Creek, Nancy Creek, and South River Creek. Then data from each basin is grouped into subgroups based on material and size of respective pipelines. Distribution of data is summarized in Table 3-2.

For each dataset, regression analysis investigates the relationship between the ages and conditions of pipelines. Then a nonlinear optimization approach is applied to estimate transition probabilities. Finally, comparison of the results from each subset examines the impact of size, material and location on the deterioration modes of the pipelines.

Table 3-2: Summary of data

Location	Sewer shed	Size (inch)	Material (No. of segments)					
			CO	VC	CI	DI	PVC	UD
Nancy Creek	NCR11a	8	59	1		1		
		12	4					
		24	4		1			
	NCR01_02c	8	16	1		1		
Peach Tree Creek	N/A	6	3					
		8	100			3		
		10	4	1				
		15	1					1
		18	2	2				
		42	12					
		60	6			1		
South River	SRV07_08a	8	32		1			
		10	1					
		12	8					
	SRV07_08b	8	33	11				2
		24	9					
	SRV07_08c	8	6	14	10			1
		10	5	8				
		12	2	1				
	SRV10	8	59	26	1	1	8	
		10	8					
		12		2				
		15	5					
		18	3					9
		30	30					
		36						4
	SRV13	8	36	58				
		10	7					
		24	10					

Notes: Shaded areas are used for analysis

Only the structural condition grade is used for analysis.

CO: Concrete, VC: Vitrified Clay, CI: Cast Iron, DI: Ductile Iron, PVC: Polyvinyl Chloride, UD: Undefined

3.5.1 Assumptions for Regression Analysis and Nonlinear Optimization

Since, distribution of raw data converges within certain range of age as shown in Figure 3-2, relationship between age and condition is very weak and even seems unreasonable. Therefore, the assumption that the condition of pipe stands the top condition just after the installation, is made to compensate with the narrow data interval of regression analysis. Depending on the size of the data set, the number of added data points is decided from 1 to 5.

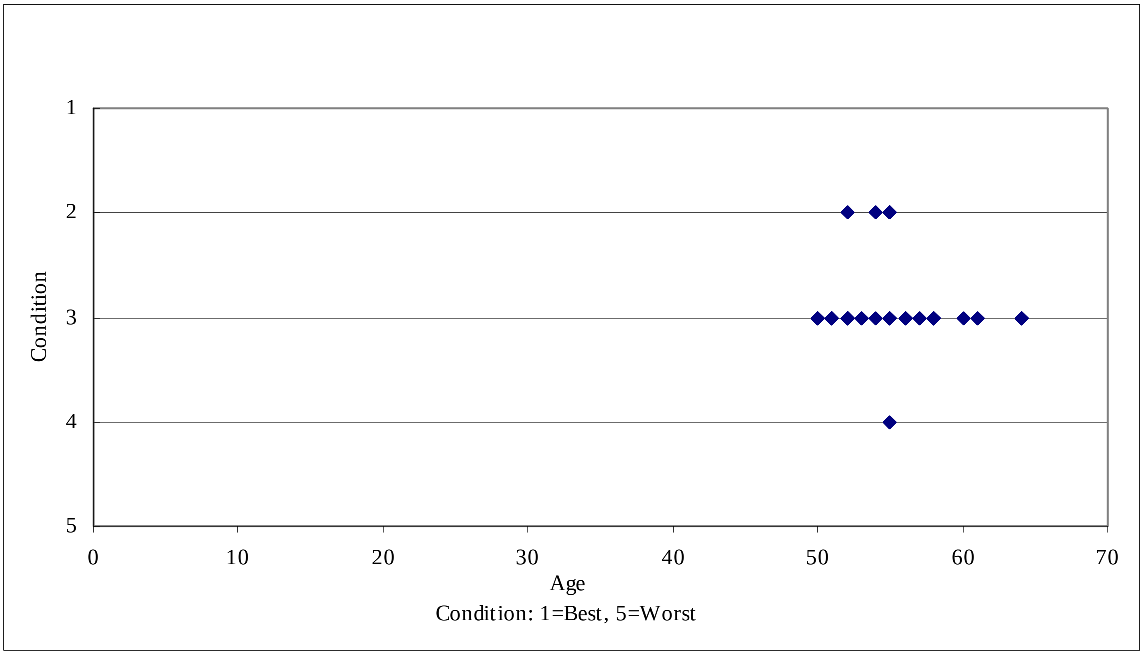


Figure 3-2: Scatter plot of raw data in Nancy Creek_11a

For the nonlinear optimization, a zoning concept is applied to make up the limited data availability and also to capture the tendency of a faster deterioration mode in later years. A zone is a certain period of time assumed to produce constant transition probabilities, and the period for a zone is based on engineering judgment or inspection intervals (Butt et al. 1987, Baik 2003). A five-year zone is applied, and the condition is assumed to drop by no more than one state in a single year to satisfy the one transition probability assumption of the regression based expected value method as shown in Eq. 3-6.

3.5.2 Illustrative Example for 8-inch Concrete Pipe in the Nancy Creek Basin

In this study, the regression based expected value method is used to develop a prediction model. First, from the available data, possible attributal factors are determined by engineering judgment or experience. Material, size and location are selected in this research. Then, pipes are grouped into factors to examine the impact of those attributes on the behavior of pipe performance as shown in Table 3-2. Using 59 concrete segments in the Nancy Creek, the estimated average condition at age t is obtained by regression analysis as shown in Eq. 3.7.

$$Y(t) = \exp(0.0236 + 0.0188t) \tag{3.7}$$

Since 5 year period zone is applied in this study, the nonlinear optimization approach for the first zone can be expressed as Eq. 3.8.

$$\begin{aligned} Minimize\,(&|e^{0.0236+0.0188\times 1} - 0.0238 - [1\,0\,0\,0\,0]\,P_1^{(1)}\,[1\,2\,3\,4\,5]^T\,| \\ &+ |e^{0.0236+0.0188\times 2} - 0.0238 - [1\,0\,0\,0\,0]\,P_1^{(2)}\,[1\,2\,3\,4\,5]^T\,| \\ &+ |e^{0.0236+0.0188\times 3} - 0.0238 - [1\,0\,0\,0\,0]\,P_1^{(3)}\,[1\,2\,3\,4\,5]^T\,| \\ &+ |e^{0.0236+0.0188\times 4} - 0.0238 - [1\,0\,0\,0\,0]\,P_1^{(4)}\,[1\,2\,3\,4\,5]^T\,| \\ &+ |e^{0.0236+0.0188\times 5} - 0.0238 - [1\,0\,0\,0\,0]\,P_1^{(5)}\,[1\,2\,3\,4\,5]^T\,|) \end{aligned} \tag{3.8}$$

While matrix [1 0 0 0 0] is used as the initial condition state matrix for Zone 1, the initial matrix with fifth transition of first transition probabilities matrix is used as the beginning matrix for the second zone:

$$\begin{aligned} \mathit{Minimize}\,(&|e^{0.0236+0.0188\times 6}-0.0238-[1\,0\,0\,0\,0]P_1^{(5)}P_2^{(1)}[1\,2\,3\,4\,5]^T\,| \\ &+|e^{0.0236+0.0188\times 7}-0.0238-[1\,0\,0\,0\,0]P_1^{(5)}P_2^{(2)}[1\,2\,3\,4\,5]^T\,| \\ &+|e^{0.0236+0.0188\times 8}-0.0238-[1\,0\,0\,0\,0]P_1^{(5)}P_2^{(3)}[1\,2\,3\,4\,5]^T\,| \\ &+|e^{0.0236+0.0188\times 9}-0.0238-[1\,0\,0\,0\,0]P_1^{(5)}P_2^{(4)}[1\,2\,3\,4\,5]^T\,| \\ &+|e^{0.0236+0.0188\times 10}-0.0238-[1\,0\,0\,0\,0]P_1^{(5)}P_2^{(5)}[1\,2\,3\,4\,5]^T\,|) \end{aligned} \quad 3.9$$

By iteration of the same method, transition probabilities for each zone are estimated and appear in Table 3-3.

Table 3-3: Transition probabilities for 8-inch concrete ipe in Nancy Creek

Description	8-inch concrete pipe in NCR_11a					
Regression	Condition = exp(0.0236 + 0.0188Age) R-Sq = 81.4% R-Sq(adj) = 81.1%					
Period	Zone	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
0-5	1	0.9805	0.9638	0.9125	0.9660	1
6-10	2	0.9817	0.9517	0.9486	0.9986	1
11-15	3	0.9792	0.9723	0.9096	0.9357	1
16-20	4	0.9874	0.9405	0.9108	0.9455	1
21-25	5	0.9860	0.9471	0.9140	0.9219	1
26-30	6	0.9813	0.9439	0.9274	0.9464	1
31-35	7	0.9775	0.9411	0.9330	0.9555	1
36-40	8	0.9728	0.9379	0.9346	0.9575	1
41-45	9	0.9679	0.9336	0.9338	0.9579	1
46-50	10	0.9633	0.9341	0.9289	0.9432	1
51-55	11	0.9539	0.9205	0.9222	0.9500	1
56-60	12	0.9429	0.9094	0.9136	0.9439	1
61-65	13	0.9272	0.8935	0.9001	0.9349	1
66-70	14	0.9018	0.8684	0.8800	0.9191	1
71-75	15	0.8596	0.8245	0.8395	0.8929	1
76-80	16	0.7490	0.7204	0.7602	0.8313	1
81-85	17	0.4047	0.3902	0.4792	0.6246	1
86-90	18	0	0	0	0	1

Under the supposition that no rehabilitation is applied to this sewer pipeline, the expected condition of 8-inch Concrete sewer in the Nancy Creek Basin after a certain number of years can be obtained by multiplying the transition probabilities with condition rating matrix:

Expected condition after 20 years:

$$\begin{aligned}
&[1\,0\,0\,0\,0]\,P_1^5 P_2^5 P_3^5 P_4^5\,[1\,2\,3\,4\,5]^T \\
&=[0.6982 \quad 0.1876 \quad 0.0719 \quad 0.0334 \quad 0.0089][1\,2\,3\,4\,5]^T \qquad 3.10 \\
&=0.6982\times 1+0.1876\times 2+0.0719\times 3+0.0334\times 4+0.0089\times 5 \\
&=1.4672
\end{aligned}$$

The probability that sewer pipeline initially in State 1 will be in States 1, 2, 3, 4, and 5 after 20 years, is 0.6982, 0.1876, 0.0719, 0.0334, and 0.0089, respectively, and the expected condition remains at 1.4672 as seen in Eq. 3.10 . Consequently, by repeating the same procedure, a deterioration curve for the 8-inch concrete sewer pipe in Nancy Creek Basin is obtained, and the expected service life is also estimated, as shown in Figure 3-3 .

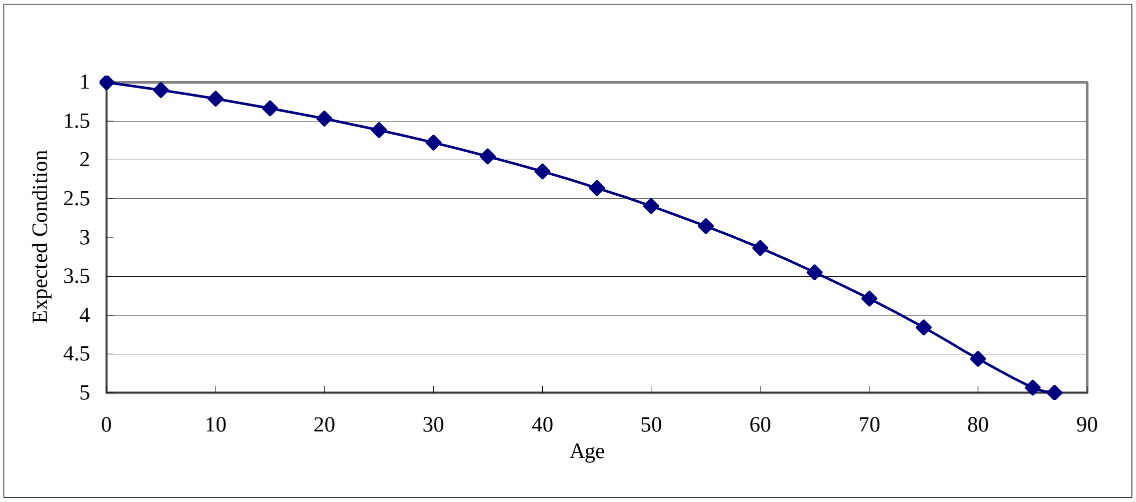


Figure 3-3: Deterioration curve for 8-inch concrete in Nancy Creek_11a

Appendix A contains the transition probabilities and deterioration curve for other sewer pipelines with different locations, materials, and sizes.

3.6 Results and Summary

By using the nonlinear optimization approach, expected service life from each data set is estimated and summarized in Table 3-4 .

Table 3-4: Estimated service life

Location (sewershed)	Diameter/Material			
	8-inch CO	8-inch VC	8-inch CI	30-inch CO
Nancy Creek (2c)	80			
Nancy Creek (11a)	87			
Peach Tree Creek	91			
South River (08a)	58			
South River (08b)	57			
South River (08c)			71	
South River (10)	62	52		58
South River (13)	63	66		

Table 3-4 shows the impact of various contributing factors. As seen in South River (10), the diameter of the pipeline does not seem to affect its expected service life. On the other hand, performance of the pipeline is apparently influenced somewhat by different materials and seriously controlled by location.

When the expected life of 8-inch concrete pipeline and geological position of three locations are carefully examined, a possible link between geological position and service life is found. As seen in Figure 3-1 , both the Nancy Creek Basin and Peach Tree

Creek Basin are located in northern area of Atlanta and they are contiguous to each other. Those basins show closely similar results. On the other hand, South River is somewhat apart from those basins and is located in the southern part of Atlanta. The estimated service life of this area is much shorter than the other two. Thus, the inference is that the surrounding soil condition of this area is much more aggressive than the soil in the more northern basins. However, due to limited availability of property data such as soil condition, ground water table, depth of installation, etc., exact attributes for deterioration of the pipeline are not clearly established.

Chapter 4

TWO-STEP OPTIMIZATION FOR R&R POLICIES

Due to a lack of well-structured integrated asset management systems, including long-term based condition data and prediction models, in most cases, governmental maintenance and rehabilitation polices for state and local agencies are quite reactive and simply respond customers' complaints. Consequently, these policies result in more frequent emergency repair and unexpected system failures. Another issue in the development of optimal R&R policies is reasonable and effective budget allocation. Because budgets are limited, establishing criteria for prioritization policies is important as well as considering every aspect of the system to secure maximum performance.

Recently, dynamic programming has been widely applied to the development of optimal maintenance and rehabilitation policies for life cycle cost analysis. However, most research focuses on the minimum cost of an R&R alternative in a given state and these studies do not properly account for concerns such as limited funding resources, prioritization policies and minimum acceptable conditions established by government agencies for the management of infrastructure systems. This perspective focuses on the facility level of optimal R&R policies rather than on a network level. Thus, this study considers the idea of a two-step optimization process reflecting those concerns.

In this chapter, first section describes the fundamental idea of, and background information for, dynamic programming. The next section covers input variables for dynamic programming and the composition of transition probabilities. Finally, the application of fuzzy logic at the network level of optimal R&R policies is discussed.

4.1 Dynamic Programming

4.1.1 Background

Dynamic programming, originally introduced by Bellman in 1940s, is an optimization technique, which attempts to describe the process of solving multistage decision problems. Later, Bellman refined this concept to the modern meaning which can be used for optimal control, Markovian decision problems and sequential interrelated decision making under uncertainty. Dynamic programming divides the original problem into small subsets of problems, called stages, and finds optimal solutions for each subset individually. Each stage has a number of states and decisions made in the preceding stage which affect the next stage. This process continues until optimal solutions for the entire problem are found, as shown in Figure 4-1 (Wirahadikusumah 1999).

The detailed procedure and basic structure for probabilistic dynamic programming are discussed later.

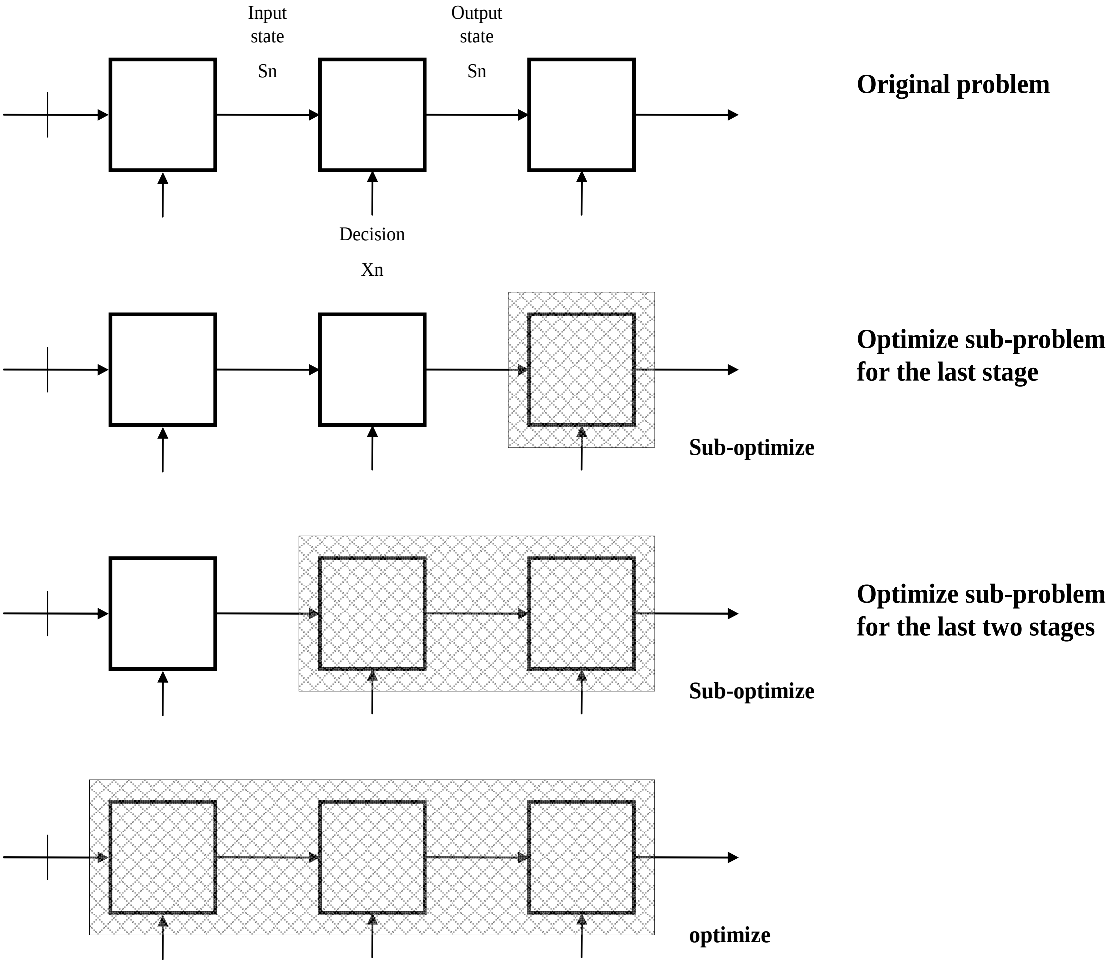


Figure 4-1: Process of dynamic programming: Optimization of serial systems (adapted from Wirahadikusumah 1999)

4.2 Inputs for Dynamic Programming

4.2.1 Observed States

One of the most significant problems in the prediction of future performance of a sewer pipeline is the absence of a generally accepted condition rating system. While a 0-100 scale is usually used in pavement systems, as shown in Table 4-1, and a 0 to 9 scale is dominant in bridge systems, as expressed in Table 4-, no widely accepted condition rating system exists for underground infrastructure system.

In this study, a 1 to 5 condition rating system as adapted from the City of Atlanta will be used, as shown in Table 4-3. This rating system will be used as states for dynamic programming.

Table 4-1: Pavement condition state classification (Carnahan et al. 1987)

PCI rating	State Representation (condition state)	State Classification
91-100	8	Excellent
81-90	7	-
71-80	6	-
61-70	5	-
51-60	4	-
41-50	3	-
21-40	2	-
0-20	1	Failed

Table 4-2: Bridge condition rating categories (adapted from FHWA 2004)

Rating	Condition Category	Description
9	Excellent	
8	Very Good	
7	Good	No problems noted.
6	Satisfactory	Some minor problems.
5	Fair	All primary structural elements are sound but may have minor section loss, cracking, spalling, or scour.
4	Poor	Advanced section loss, deterioration, spalling, or scour.
3	Serious	Loss of section, deterioration, spalling, or scour have seriously affected the primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	Critical	Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may be removed substructure support. Unless closely monitored, it may be necessary to close the bridge until corrective action is taken.
1	Imminent Failure	Major deterioration or section loss present in critical structural components, or obvious loss present in critical structural components, or obvious vertical or horizontal movement affecting structural stability. Bridge is close to traffic, but corrective action may put back in light service.
0	Failed	Out of service; beyond corrective action.

Table 4-3: Internal condition grade of the City of Atlanta

ICG	Typical defect description
5	Pipe or brick sewer already collapsed; or, Deformation exceeds 10% and pipe is broken; or, Extensive areas of material missing; or, Deformation exceeds 10% with fracture; or Extreme loss of concrete/mortar
4	Pipe or brick sewer is broken; or, Deformation < 10% with fracture; or, Multiple fractures; or, Serious loss of gradient; or Severe concrete corrosion; or bricks displaced
3	Pipe or brick sewer is fractured with deformation between 5% and 10%; or, Longitudinal cracking or multiple cracking; or, Severe joints defects; or, Badly made connections; or Moderate concrete corrosion; or, Bricks displaced
2	Light corrosion; or circumferential cracks; or moderate joint defects
1	No corrosion or structural defects

4.2.2 Transition Probabilities

As described previously, transition probabilities, estimated from a deterioration model, are used as input in dynamic programming. These transition probabilities represent the possibility that the system will change from a previous stage to the next stage with no performed R&R activities. Consequently, when any rehabilitation or replacement methods have been applied to a system, adjusted transition probability matrices reflecting the effect of the performed activities are required. Demonstration of how to manipulate transition probabilities for given treatments begins with the transition probability matrix obtained from a deterioration model, as the example of a 5-by-5 matrix, P, as given in Eq. 4.1 .

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ 0 & P_{22} & P_{23} & P_{24} & P_{25} \\ 0 & 0 & P_{33} & P_{34} & P_{35} \\ 0 & 0 & 0 & P_{44} & 1-P_{44} \\ 0 & 0 & 0 & 0 & P_{55} \end{bmatrix} \qquad 4.1$$

where, $\sum_{j=1}^{5} Pij = 1$ for i = 1,2,…5

This transition matrix P assumes that no R&R action is taken for the system. A set of 0, located at the left-bottom of the matrix represents that the system cannot be restored to its original state without R&R activities. The transition probability matrix for maintenance and rehabilitation activities, as illustrated by Madanat and Ben-Akiva (1994), and Baik (2003), can be acquired by manipulating this transition matrix. In accordance with the effectiveness of R&R activities, five different types of transition probability matrices arise from shifting or repeating the first row of transition probabilities. The number of shifts depends on the effectiveness of the action taken, as determined by engineering judgment.

4.2.2.1 Case 1

If the performed activity can upgrade the condition of the system by 1, and the deterioration rates of the system in condition states 2, 3, 4 and 5 are also improved to conform at the rate of 1, 2, 3 and 4 respectively, then the transition probabilities for the activity would be:

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ 0 & P_{22} & P_{23} & P_{24} & P_{25} \\ 0 & 0 & P_{33} & P_{34} & P_{35} \\ 0 & 0 & 0 & P_{44} & 1-P_{44} \end{bmatrix} \tag{4.2}$$

Renewal technology such as cathodic protection, chemical grouting, reinforced shotcrete, joint rehabilitation and high-build epoxy, falls in this category

4.2.2.2 Case 2

If the performed activity can upgrade the condition of system by more than one state (2 levels higher, here), then the transition probabilities for the activity would be:

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ 0 & P_{22} & P_{23} & P_{24} & P_{25} \\ 0 & 0 & P_{33} & P_{34} & P_{35} \end{bmatrix} \tag{4.3}$$

Rehabilitation technologies such as pipe lining, close-fit pipe lining, cured in-place pipe, and conventional slip lining, fall in this category.

4.2.2.3 Case 3

If the performed activity can upgrade the condition of the system by 1, and the deterioration rates of the system in condition levels 3, 4, and 5 conform to the deterioration rate of condition level 1, then the transition probabilities for the activity would be:

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ 0 & P_{11} & P_{12} & P_{13} & P_{14} \\ 0 & 0 & P_{11} & P_{12} & P_{13} \\ 0 & 0 & 0 & P_{11} & P_{12} \end{bmatrix} \qquad 4.4$$

4.2.2.4 Case 4

If a performed activity can upgrade the condition of the system by more than one state (2 levels higher, in this case) and also improve deterioration rate of the system to follow the deterioration of condition state 1, then transition probabilities for the activity would be:

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ 0 & P_{11} & P_{12} & P_{13} & P_{14} \\ 0 & 0 & P_{22} & P_{23} & P_{24} \end{bmatrix} \qquad 4.5$$

4.2.2.5 Case 5

If the performed activity can restore the system to its original condition, then the transition probabilities for the activity (pipe bursting, trenched replacement, micro tunnelling) would be:

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad 4.6$$

When uncertainties including quality of installation, geological difficulty or unexpected conditions are involved with these activities, the confidence level is a consideration as shown in equation Eq. 4.7 (Cesare et al. 1992, Madanat and Ben-Akiva 1994)

$$P = \begin{bmatrix} C\times 1 & 1-C\times 1 & 0 & 0 & 0 \\ C\times 1 & 1-C\times 1 & 0 & 0 & 0 \\ C\times 1 & 1-C\times 1 & 0 & 0 & 0 \\ C\times 1 & 1-C\times 1 & 0 & 0 & 0 \\ C\times 1 & 1-C\times 1 & 0 & 0 & 0 \end{bmatrix} \qquad 4.7$$

where, C = Confidence level

4.2.3 Other Inputs

4.2.3.1 Rehabilitation and Replacement Alternatives

Possible decision sets may vary with each governmental agency and different decision sets result in different outcomes of life cycle cost analysis. The following table represents general R&R alternatives for sewer pipe lines.

Table 4-4: Available decision sets

K	Action	Type
1	No action	-
2	Chemical cleaning	Maintenance
3	Chemical grouting	Preservation
4	Cathodic protection	Preservation
5	Joint rehabilitation	Preservation
6	Pipe lining	Improvement
7	CIPP	Improvement
8	Slip lining	Improvement
9	Trenched replacement	Improvement
10	Pipe bursting	Improvement
11	Micro tunneling	Improvement

4.2.3.2 R&R Policies

The possible decision sets discussed earlier should link with R&R policies, such as minimum acceptable condition level of pipe, effectiveness and applicability of each alternative.

Table 4-5: Effectiveness and applicability of R&R actions

K	Action	Effectiveness/ Applicability
1	No action	- / 1.2
2	Chemical cleaning	- / 1.2
3	Chemical grouting	Upgrade 1 level higher/ 2,3
4	Cathodic protection	Upgrade 1 level higher/ 2,3
5	Joint rehabilitation	Upgrade 1 level higher/ 2,3
6	Pipe lining	Upgrade 2 level higher/ 3,4
7	CIPP	Upgrade 2 level higher/ 3,4
8	Slip lining	Upgrade 2 level higher/ 3,4
9	Trenched replacement	Return to original / 4,5
10	Pipe bursting	Return to original / 4,5
11	Micro tunneling	Return to original / 4,5

4.2.3.3 Expected Costs

Expected costs are the required investments for selected R&R alternatives. In addition, the costs are the most influencing attributes to the outcome of dynamic programming. The costs for various R&R techniques, obtained from Environmental Protection Agency (EPA), are presented in Table 4-6.

Table 4-6: Expected cost

Category	**Technology**	**Unit Cost ($/LF)**
	No action	
Maintenance	Chemical cleaning	10
Preservation	Chemical grouting	18.8
	Cathodic protection	25.8
	Joint rehabilitation	35.2
Rehabilitation	Pipe lining	26.3
	CIPP	32.6
	Slip lining	49.9
Replacement	Trenched replacement	78.1
	Pipe bursting	64.9
	Micro tunneling	128.7

4.3 Project-Level Optimization

As discussed previously, the main objective of the life cycle cost analysis is to minimize not only initial construction cost, but also total expected cost (operating cost, maintenance and rehabilitation cost and other associated future costs) incurred throughout the service life of the system. Uncertainties regarding the future condition of the system and future incurred costs need to be resolved by adopting probabilistic life cycle cost analysis such as dynamic programming for selection of R&R alternatives as well as timing of application of the alternatives.

The basic idea for selecting an optimal R&R policy is: The decision made at the current stage affects the future condition through transition probabilities. If the state i, having the value of an optimal policy $V^t(i)$, is defined as the total expected gain obtained with k decision, then the algorithm for the optimal R&R alternatives can be expressed as shown in Eq. 4.8 :

$$V^T(i) = g(i) \qquad \forall i$$

$$V^t(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{m} p_{ij}^{(k)} V^{t+1}(j)\} \quad \forall i, t = 0,.....,T-1 \qquad 4.8$$

Where,

$V^T(i)$ = Terminal cost, given that the state of the facility is in state i at year T;

$V^t(i)$ = Minimum expected cost from year t to end of the problem, given that the state of the facility is in state i at year t;

$g(i,k)$ = Expected cost when a facility is in state i in year t and alternative k is chosen;

k = R&R alternatives;

m = Possible condition state;

$p_{ij}^{(k)}$ = Probabilities that the system goes from current state i to j with k decision,

$\alpha =$ Discount factor, assumed as 1 for the simplicity of computation.

The optimization process starts from the last stage T and at this stage, optimal alternatives are determined based on the minimum cost of application. Once having analyzed the last stage, the process moves onward to Stage T-1, T-2, etc., and at every state, optimal alternatives are obtained by minimizing the total cost, including cost of selected alternatives at the current stage and expected future discounted cost from the current stage onward. Finally, this process stops at Stage 0. After comparing the total expected cost at every stage, an optimal alternative will be obtained.

4.3.1 Illustrative Example for Project-Level Optimization

The following example is the application of dynamic programming for the selection of optimal R&R alternatives for an 8-inch cast iron pipeline. All the numbers come from a deterioration model of an 8-inch cast iron pipe in South River Basin and for simplicity of the computation, the discount factor is assumed to be 1. A 70-year life span is used for life-cycle cost analysis, and the 70-year life span is divided into 14 stages that represent 5-year periods.

Assumptions for the life cycle cost analysis:

- Observed states

  As previously indicated, a 1 to 5 condition rating system is used as states.

  Possible state i = 1, 2, 3, 4, 5;

  where, states 1, 2, 3, 4, and 5, correspond to structural condition of sewer pipeline (1= best condition, 5 = worst condition)

- Possible decisions sets with associated costs are as shown in Table 4-7.

Table 4-7: Cost and applicability of R&R alternatives

Condition (i)	k(R&R alternatives)										
	1	2	3	4	5	6	7	8	9	10	11
1	0	10									
2	0	10	18.8	25.8	35.2						
3			18.8	25.8	35.2	26.3	32.6	49.9			
4						26.3	32.6	49.9	78.1*	64.9	128.7
5									78.1*	64.9	128.7

Where, in the table, k = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or 11 correspond to “no action,” “chemical cleaning,” “chemical grouting,” “cathodic protection,” “joint rehabilitation,” “pipe lining,” “cured-in-place pipe,” “slip lining,” “trenched replacement,” “pipe bursting,” “micro tunneling” respectively. (*For the cost of trenched replacement, $30 of indirect cost is assumed.)

- Transition probabilities for no action and chemical cleaning are given in Table 4- .

The transition probabilities for no action and chemical cleaning are obtained from the deterioration model for an 8-inch cast iron pipeline. As seen in Table 4-8, the transition probabilities for no action and maintenance techniques are varying in each stage.

Table 4-8: Transition probabilities for no action and chemical cleaning

Description	Transition probabilities for each Stage					
Period	Stage	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
0-5	0	0.9731	0.9528	0.9425	0.9985	1
6-10	1	0.9731	0.9537	0.9142	0.9756	1
11-15	2	0.9781	0.9328	0.9291	0.9383	1
16-20	3	0.9817	0.9311	0.9190	0.8689	1
21-25	4	0.9781	0.9344	0.9129	0.9024	1
26-30	5	0.9705	0.9272	0.9196	0.9331	1
31-35	6	0.9634	0.9198	0.9215	0.9393	1
36-40	7	0.9535	0.9104	0.9208	0.9438	1
41-45	8	0.9442	0.9023	0.9094	0.9354	1
46-50	9	0.9265	0.8866	0.8958	0.9284	1
51-55	10	0.9015	0.8612	0.8730	0.9141	1
56-60	11	0.8532	0.8171	0.8311	0.8862	1
61-65	12	0.7474	0.7082	0.7360	0.8209	1
66-70	13	0.2839	0.3192	0.4036	0.5744	1

- Transition probabilities for preservation technology: Preservation technologies such as chemical grouting, cathodic protection, and joint rehabilitation can upgrade the pipe condition by 1, and as illustrated in Section **4.2.2** , transition probabilities for these technologies can be obtained by shifting the transition probabilities for no action and routine cleaning, as shown in Eq. 4.9 and the transition probabilities are constant for all stages.

$$P = \begin{bmatrix} 0.9731 & 0.0269 & 0 & 0 & 0 \\ 0.9731 & 0.0269 & 0 & 0 & 0 \\ 0 & 0.9528 & 0.0472 & 0 & 0 \\ 0 & 0 & 0.9425 & 0.0575 & 0 \\ 0 & 0 & 0 & 0.9985 & 0.0015 \end{bmatrix} \qquad 4.9$$

- Transition probabilities for rehabilitation technology: Rehabilitation technology such as pipe lining, cured-in-place pipe, and slip lining can upgrade the pipe condition by 2 and transition probabilities for those activities can be expressed as shown in Eq. 4.10 and the transition probabilities are constant for all stages.

$$P = \begin{bmatrix} 0.9731 & 0.0269 & 0 & 0 & 0 \\ 0.9731 & 0.0269 & 0 & 0 & 0 \\ 0.9731 & 0.0269 & 0 & 0 & 0 \\ 0 & 0.9528 & 0.0472 & 0 & 0 \\ 0 & 0 & 0.9425 & 0.0575 & 0 \end{bmatrix} \qquad 4.10$$

- Transition probabilities for replacement technology: As previously discussed, replacement technology such as trenched replacement, pipe bursting and micro tunneling can change the current condition to best condition and the effect of those technologies can be expressed as shown in Eq. 4.11 :

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad 4.11$$

- Detailed process

As discussed earlier, the optimization process begins with the last stage, where the optimal alternative would be the lowest cost one among all possible alternatives at a given state as shown in Table 4-9.

Table 4-9: Dynamic programming for last stage

i	$V^{t}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{t+1}(j)\}$											$V^{14}(j)$	k*
	1	2	3	4	5	6	7	8	9	10	11		
1	0	10										0	1
2	0	10	18.8	25.8	35.2							0	1
3			18.8	25.8	35.2	26.3	32.6	49.9				18.8	3
4						26.3	32.6	49.9	78.1	64.9	128.7	26.3	6
5									78.1	64.9	128.7	64.9	10

The optimal decision for the last stage is “no action” for pipeline in State 1 and 2, “chemical grouting” for State 3, “pipe lining” for State 4, and “pipe bursting” for State 5. When the optimal decision for the last stage is determined, then optimization process moves to the next Stage, 13. At Stage 13, the value of the optimal alternative, “k*,” of the last stage is used as an input. Accordingly, the expected cost can be estimated as:

$$V^{13}(1) = \{g(1,1) + 1 * \sum_{j=1}^{5} p_{ij}^{(1)} V^{14}(j)\}, \text{ where i = 1, k = 1}$$

$$= 0 + 1.0 \times (0.2839 \times 0 + 0.7161 \times 0) = 0;$$

$$V^{13}(1) = \{g(1,2) + 1 * \sum_{j=1}^{5} p_{ij}^{(2)} V^{14}(j)\}, \text{ where i = 1, k = 2}$$

$$= 10 + 1.0 \times (0.2839 \times 0 + 0.7161 \times 0) = 10;$$

$$V^{13}(2) = \{g(2,1) + 1 * \sum_{j=1}^{5} p_{ij}^{(1)} V^{14}(j)\}, \text{ where i = 2 , k = 1}$$

$$= 0 + 0.3192 \times 0 + 0.6808 \times 18.8 = 12.80;$$

$$V^{13}(2) = \{g(2,2) + 1 * \sum_{j=1}^{5} p_{ij}^{(2)} V^{14}(j)\}, \text{ where i = 2, k = 2}$$

$$= 10 + 0.3129 \times 0 + 0.6808 \times 18.8 = 22.80;$$

$V^{13}(2) = \{g(2,3) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =2, k = 3

= 18.8 + 1.0 × (0.9731×0 + 0.0269×0) = 18.8;

$V^{13}(2) = \{g(2,4) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =2, k = 4

= 25.8 + 0.9731 × 0 + 0.0269 × 0 = 25.8 ;

$V^{13}(2) = \{g(2,5) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =2, k = 5

= 35.2 + 0.9731 × 0 + 0.0269 × 0 = 35.2;

$V^{13}(3) = \{g(3,3) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =3, k = 3

$= 18.8 + 0.9528 \times 0 + 0.0472 \times 18.8 = 19.69$;

$V^{13}(3) = \{g(3,4) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =3, k = 4

$= 25.8 + 0.9528 \times 0 + 0.0472 \times 18.8 = 26.69$;

$V^{13}(3) = \{g(3,5) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =3, k = 5

$= 35.2 + 0.9528 \times 0 + 0.0472 \times 18.8 = 36.09$;

$V^{13}(3) = \{g(3,6) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =3, k = 6

$= 26.3 + 0.9731 \times 0 + 0.0269 \times 0 = 26.3$;

$V^{13}(3) = \{g(3,7) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =3, k = 7

$= 32.6 + 0.9731 \times 0 + 0.0269 \times 0 = 32.6$;

$V^{13}(3) = \{g(3,8) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$,   where i =3, k = 8

$= 49.9 + 0.9731 \times 0 + 0.0269 \times 0 = 49.9$;

$V^{13}(4) = \{g(4,6) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =4, k = 6

$= 26.3 + 0.9528 \times 0 + 0.0472 \times 18.8 = 27.19$;

$V^{13}(4) = \{g(4,7) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =4, k = 7

$= 32.6 + 0.9528 \times 0 + 0.0472 \times 18.8 = 33.49$;

$V^{13}(4) = \{g(4,8) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =4, k = 8

$= 49.9 + 0.9528 \times 0 + 0.0472 \times 18.8 = 50.79$;

$V^{13}(4) = \{g(4,9) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$,   where i =4, k = 9

$= 78.1 + 1 \times 0 = 78.1$;

$V^{13}(4) = \{g(4,10) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =4, k = 10

$= 64.9 + 1 \times 0 = 64.9$;

$V^{13}(4) = \{g(4,11) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =4, k = 11

$= 128.7 + 1 \times 0 = 128.7$;

$V^{13}(5) = \{g(5,9) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}$, where i =5, k = 9

$= 78.1 + 1 \times 0 = 78.1$;

$$V^{13}(5) = \{g(5,10) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}, \quad \text{where i =5, k = 10}$$

$$= 64.9 + 1 \times 0 = 64.9, \textit{ and}$$

$$V^{13}(5) = \{g(5,11) + 1 * \sum_{j=1}^{5} p_{ij}{}^{(3)} V^{14}(j)\}, \quad \text{where i =5, k = 11}$$

$$= 128.7 + 1 \times 0 = 128.7.$$

Table 4-10: Dynamic programming for stage 13

i	$V^{t}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}{}^{(k)} V^{t+1}(j)\}$											$V^{13}(j)$	k*
	1	2	3	4	5	6	7	8	9	10	11		
1	0	10										0	1
2	12.8	22.8	18.8	25.8	35.2							12.8	1
3			19.69	26.69	36.09	26.3	32.6	49.9				19.69	3
4						27.19	33.49	50.79	78.1	64.9	128.7	27.19	6
5									78.1	64.9	128.7	64.9	10

All computation results for dynamic programming for an 8-inch cast iron and other pipelines of different diameters and materials are presented in Appendix D.

4.4 Network-Level Optimization

Although significant efforts have focused on applying dynamic programming in the development of optimal R&R policies, most studies show a limitation in that they are based just on the idea of minimum total expected cost during the life cycle without considering some constraints such as budgets and levels of service. These studies are aimed at project-level optimization, which focuses on assigning one deterministic alternative for the pipeline in a certain state. The objective of network-level optimization is the allocation of available resources based on a prioritization policy and associated constraints to establish an investment plan that guides the highest benefit and lowest cost to maintaining the system above required condition levels.

In this study, the fuzzy logic algorithm is applied for optimization at the network-level.

4.4.1 Fuzzy Logic

Fuzzy set theory was first introduced by Zadeh in 1965 to assist the concept of classical set theory. In classical set theory, membership of the set's elements can be expressed in a binary condition – fully included or excluded in a set. By contrast, a fuzzy set is a set without clearly defined boundaries and it permits partial membership of its elements.

Fuzzy logic basically starts from the concept of fuzzy set theory. Fuzzy logic is the application of a fuzzy set to map the subjective, qualitative, and vague linguistic concepts such as good, bad, nice, important etc. into precise numerical values between 0 and 1, by membership function as shown in Eq. 4.12 .

$$\begin{gathered} \mu_A : x \rightarrow [0,1] \mid x \in A \\ \mu \text{ :membership function} \end{gathered} \qquad 4.12$$

Membership function is a line or curve that represents the appropriate relationship between each element of input space and degree of membership. Membership function can be defined as any shape one wishes. Triangular, trapezoidal, or bell shapes are commonly used. The only condition membership function must meet is that it should range from 0 to 1.

Fuzzy logic for decision making is controlled by some logical operations over fuzzy decision rules, which uses IF/THEN rules: IF variable IS set THEN action (consequence). Also, AND, OR, NOT operators of Boolean logic exist in fuzzy logic. These operators are usually represented by minimum, maximum, and complement operations. Thus, the aforementioned decision rules can be extended to the general form: IF precondition 1 and precondition 2 …THEN consequence 1 and consequence 2…. The following example of a fuzzy set exhibits how fuzzy inference links with logical operations.

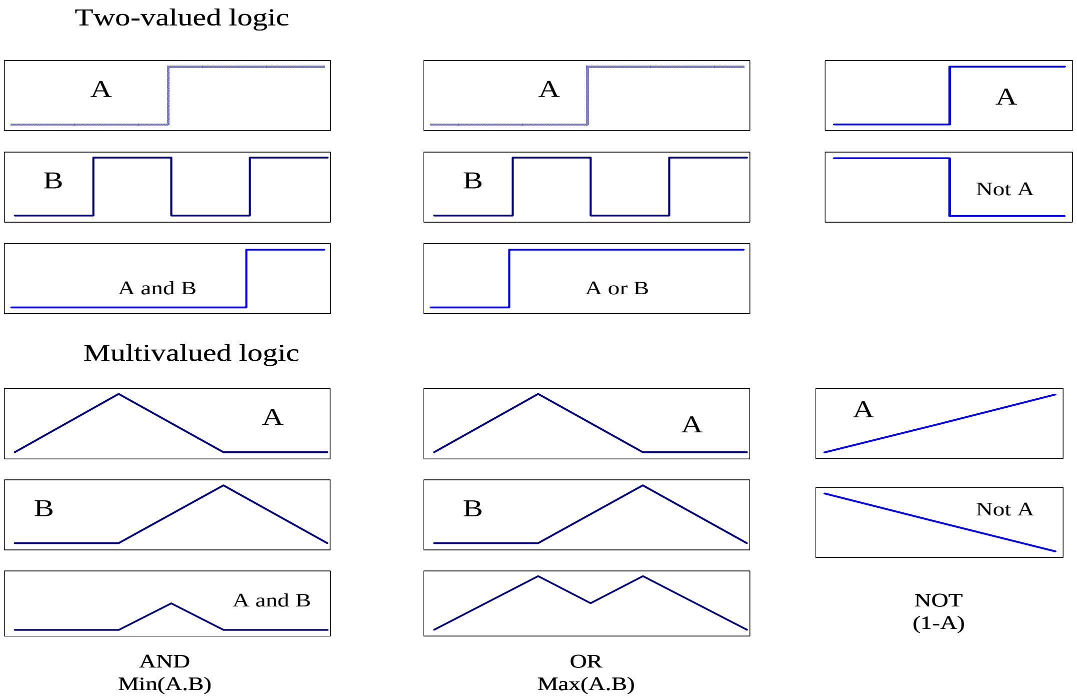


Figure 4-2: Logical operations (adapted from: Matlab Fuzzy Logic Toolbox User guide 2005)

When decision rules are decided, a proper weight for each rule must be assigned to arrange the attributes of every rule to a reasonable consequent. Based on the input numbers and weighted rules, implication process reshapes consequents. The reshaped consequents are combined in some manner to make a decision. This is an aggregation process by which the fuzzy inference integrates the output of each rule into one fuzzy set. Finally, by a defuzzification process such as centroid, bisector, and middle of maximum calculation, this fuzzy set provides a single number.

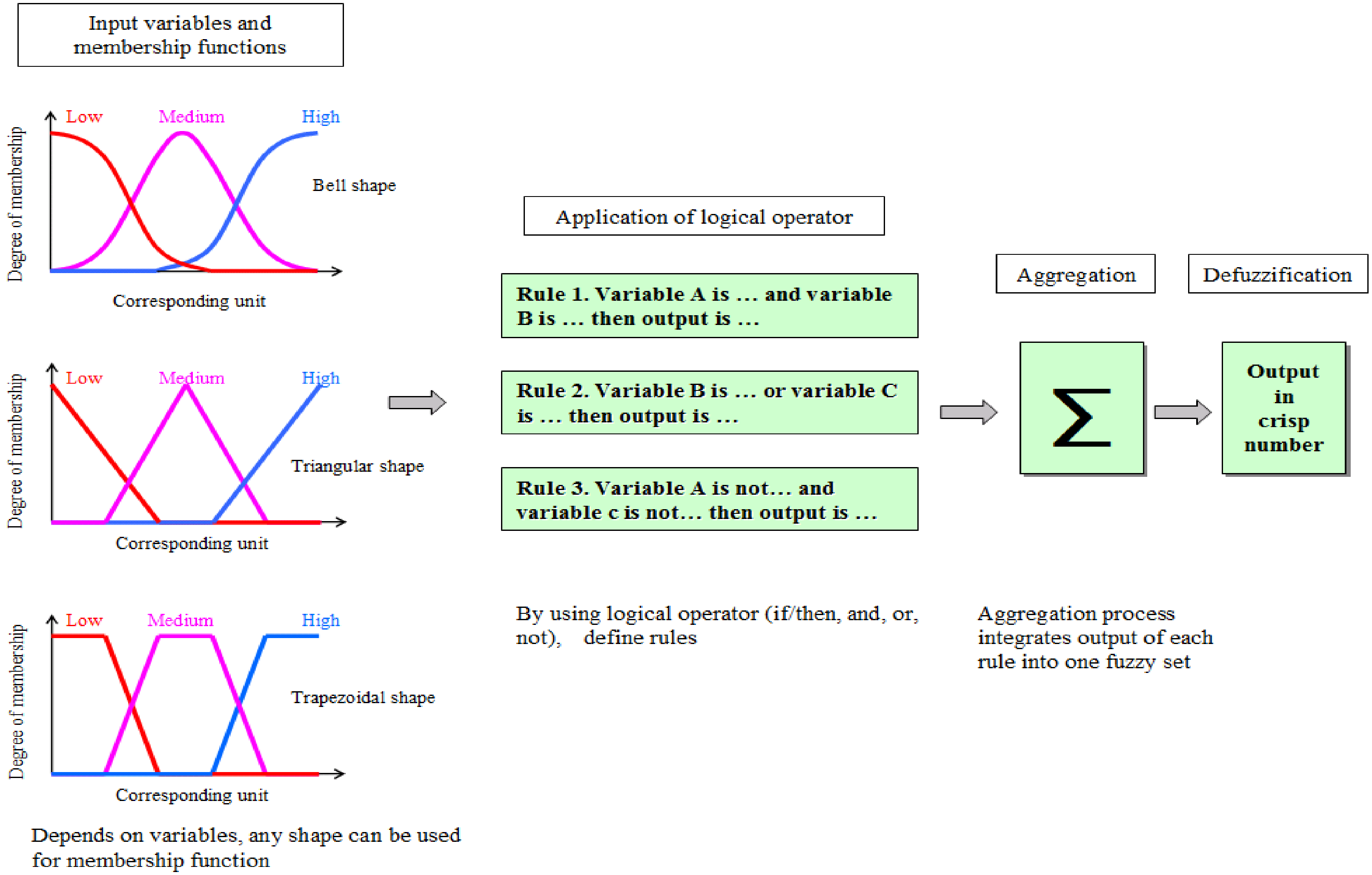


Figure 4-3: Overview of fuzzy inference process

4.4.2 Input Variables for Prioritization

In the fuzzy logic approach for network level optimization, factors that may affect priority policies will be included as input variables. The variables are:

- Pipe material: Replace sewer line made of a certain material to establish a trend or policy for the agency.
- Break history: Replace sewer line with an excessive number of breaks and user complaints.
- Diameter/capacity: Replace with larger diameter first to comply with necessary capacity.
- Age of pipe: Replace older pipe that is approaching the end of its service life first.
- Other work: Consider other major utility work and replace the sewer lines at the same time.
- Critical lines: Replace essential sewer lines to prevent unexpected failure and provide steady and reliable service.
- Soil and underground condition: Bad soil condition and improper installation increase the need for replacement.
- Benefit / Cost: From cost-wise perspective, prioritize sewer lines assuring maximized benefit and minimized cost to optimize budget allocation.
- Installation type: Usually installation Type 1 carries more loading than lower type so that the latter requires earlier replacement than other types.
- Condition of pipe: Replace pipe line in worse condition in advance.

4.4.3 Two-Step Optimization for R&R Policies

- Step 1. Using probabilistic dynamic programming, determine the optimum R&R alternative that ensures minimal life cycle cost at given condition state for each pipeline (Project level).
- Step 2. Establish a list of factors considered in prioritization policies.
- Step 3. Formulate associated membership function and decision rules that conform to R&R policies of the agency based on engineering experience and judgment.
- Step 4. Using fuzzy inference, prioritize the project.
- Step 5. Make the ideal investment plan ensuring maximum benefit from a number of feasible strategies.

4.4.4 Illustrative Example for Network-Level Optimization

As mentioned, in project-level optimization an agency can identify the best rehabilitation method for each pipeline by using dynamic programming. The next decision is how to prioritize those pipe lines and allocate budgets to ensure the maximum performance of the system. The following is an example of network level optimization using fuzzy logic analysis. All the figures are randomly assigned to assist in understanding the network level optimization process.

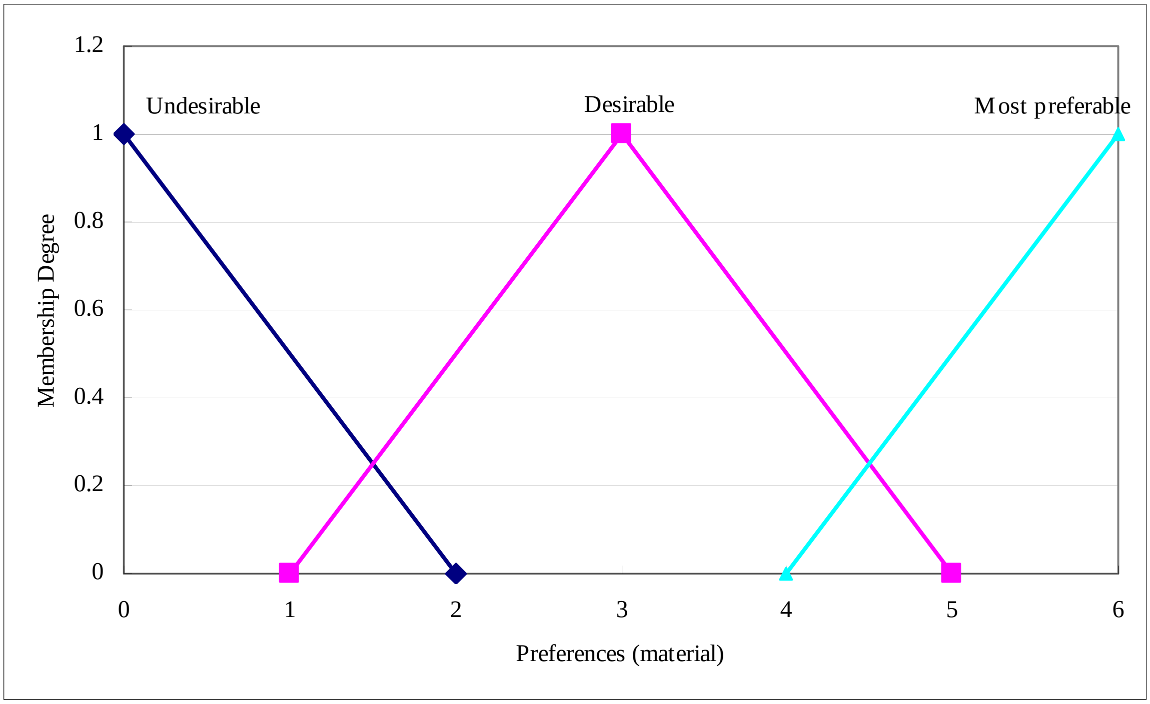
Let us suppose that there are 10 different pipe lines in the system with six associated factors, as shown in Table 4-11.

Table 4-11: Factors considered for prioritization policies

Project	Attributes					
	Material	# of Breaks	Diameter (inch)	Age (years)	Condition (1 to 5)	Benefit/ Cost
1	CON	6	8	50	4	0.8
2	VC	3	18	45	3	1.2
3	CON	1	8	50	4	0.6
4	CON	0	12	20	3	0.7
5	CI	5	18	40	2	0.8
6	CON	3	15	45	3	1.1
7	VC	4	30	65	4	0.6
8	CI	6	42	60	4	0.4
9	VC	2	18	35	3	0.9
10	PVC	5	8	55	4	1.3

First, the membership function is formulated using engineering intuition and judgment. Since membership function is somewhat subjective, establishing membership function on a reasonable and reliable guess is important. Membership functions used for each variable and output appear in Figure 4-4 and Figure 4-5, respectively.

Once membership functions are decided, the fuzzy rules reflecting R&R policies need to be framed. Examples of R&R policies and corresponding fuzzy rules are summarized in Table 4-12.



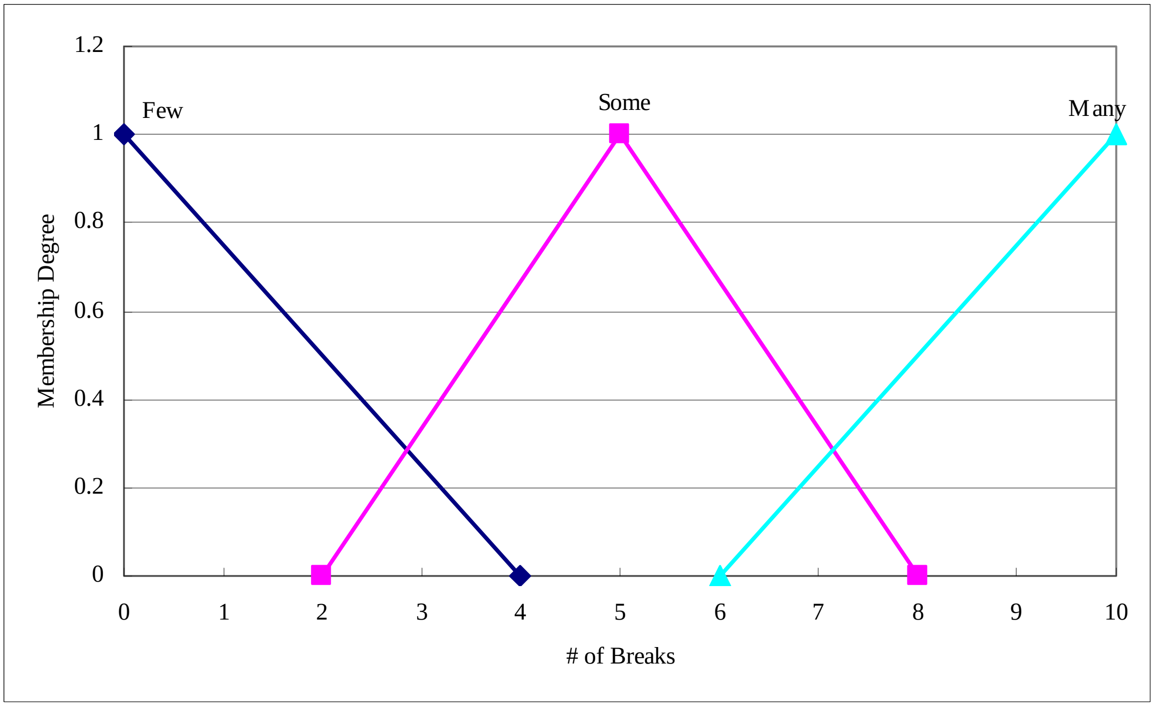
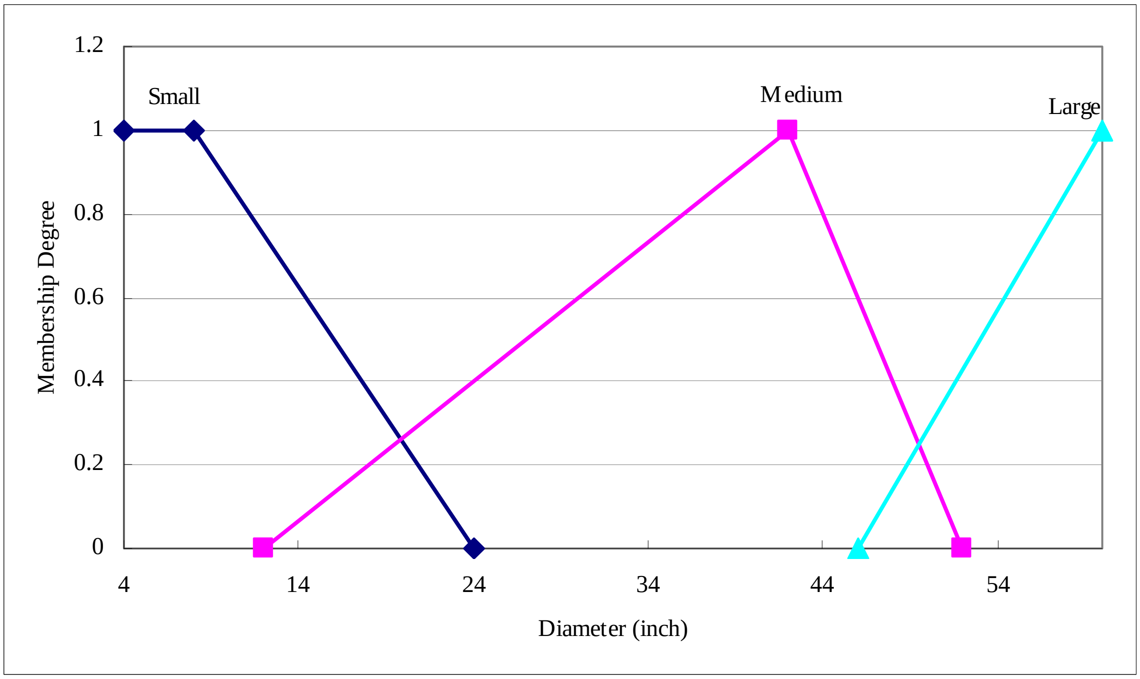


Figure 4-4: Membership function for illustrative example



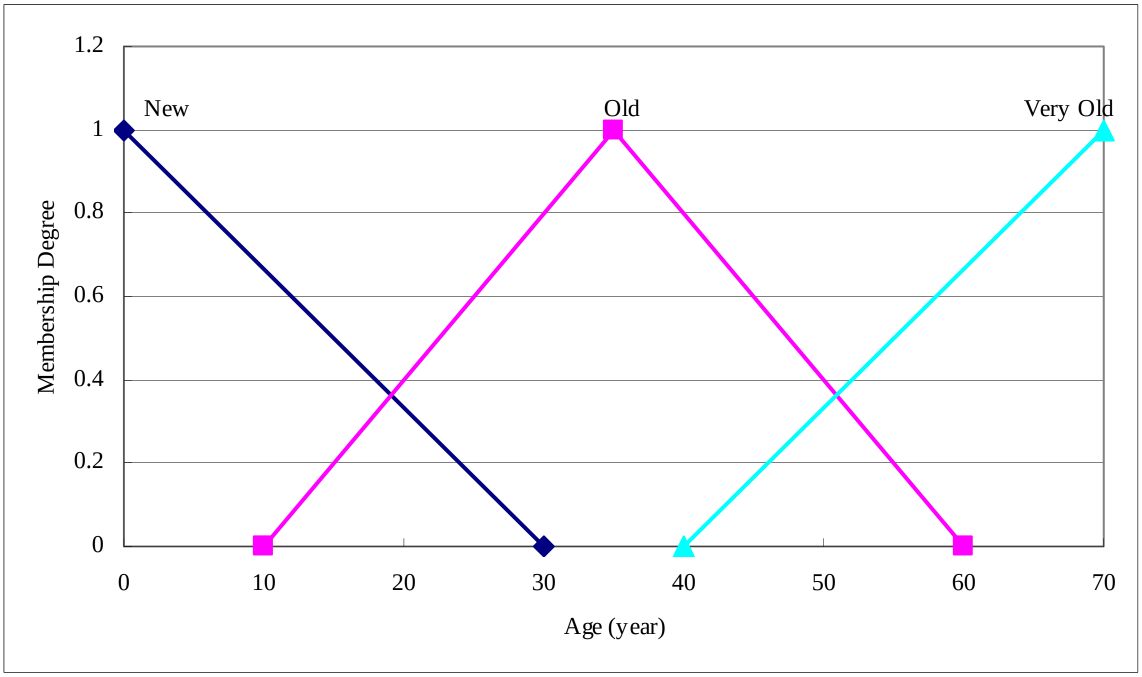
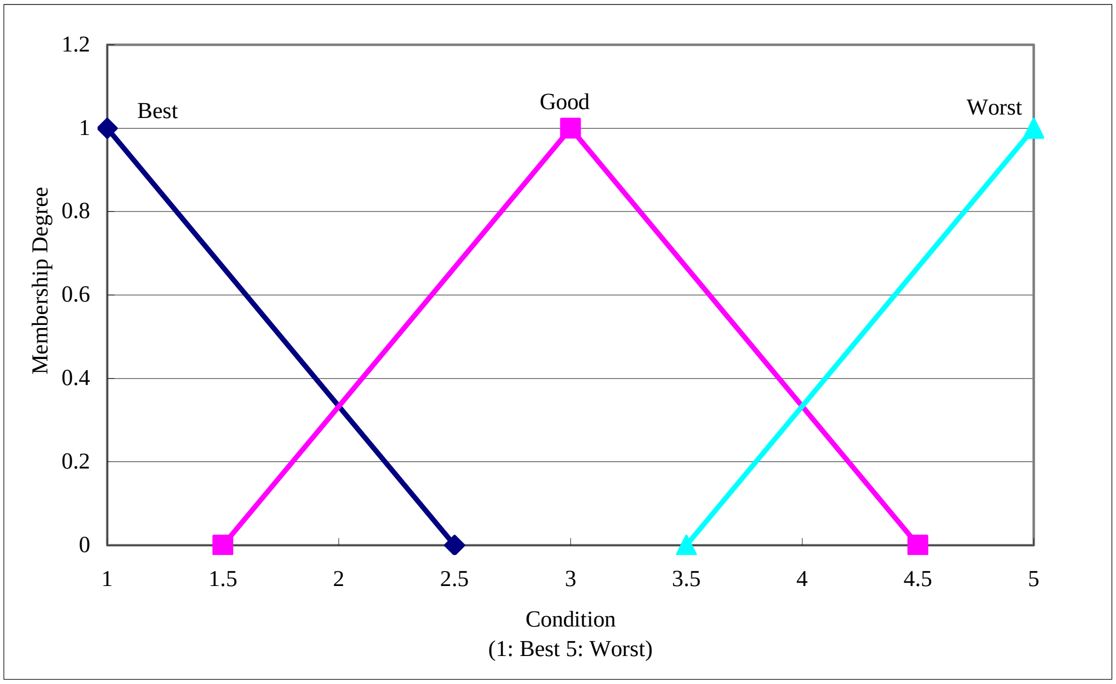


Figure 4-4: (Continued) Membership function for illustrative example



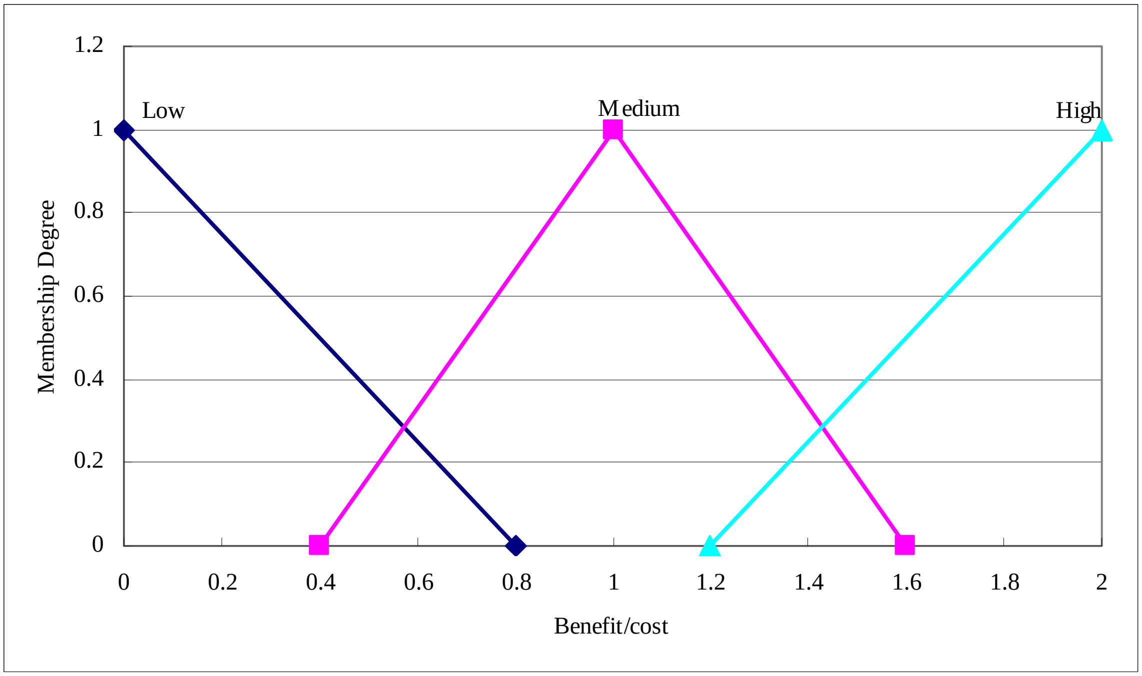


Figure 4-4: (Continued) Membership function for illustrative example

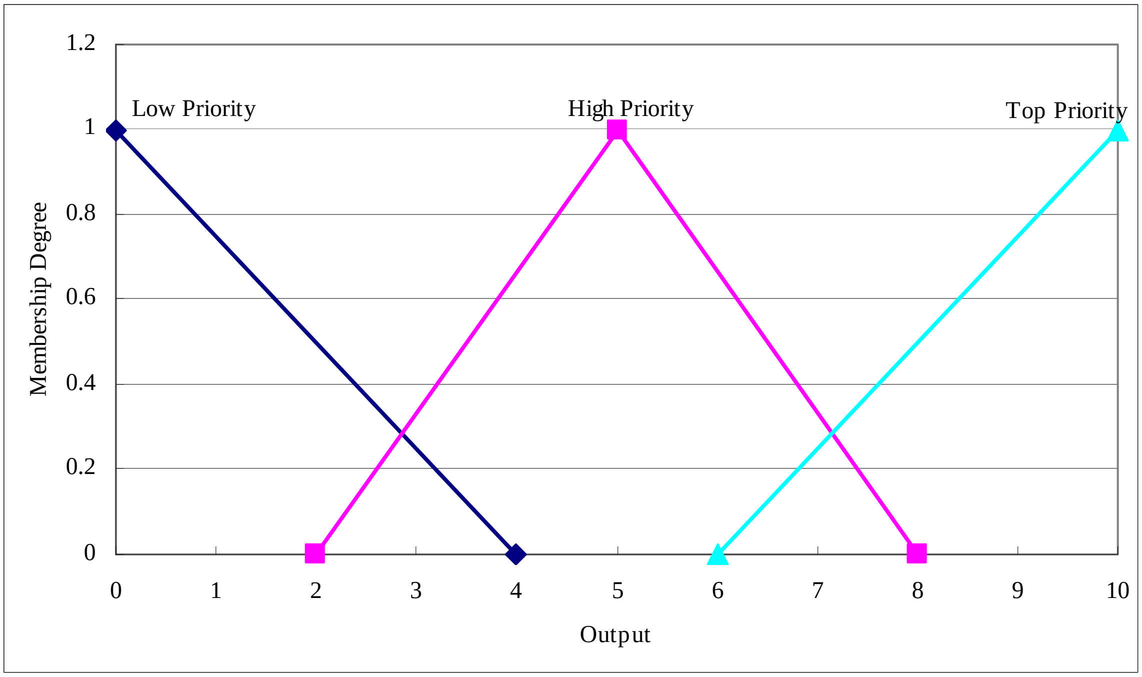


Figure 4-5: Membership function for output

Table 4-12: Fuzzy rule for illustrative example

R&R policies	Priority	Fuzzy rule	Weight
Replace worst condition of sewer line in advance	1	IF pipe condition is Best, then output is low priority IF pipe condition is Good, then output is High priority IF pipe condition is Worst, then output is Top priority	1
Change sewer line with excessive number of breaks and user complaints	2	IF #of breaks is Few, then output is low priority IF #of breaks is Some, then output is High priority IF #of breaks is Many, then output is Top priority	0.9
Replace larger diameter pipes first to meet required function	3	IF diameter is Small, then output is low priority IF diameter is Medium, then output is High priority IF diameter is Large, then output is Top priority	0.8
Replace older sewer line that is approaching the end of service life first	4	IF age is new, then output is low priority IF age is old, then output is High priority IF age is very old, then output is Top priority	0.7
Prioritize sewer lines assuring maximized benefit and minimized cost	5	IF Benefit/Cost is Low, then output is low priority IF Benefit/Cost is Medium, then output is High priority IF Benefit/Cost is High, then output is Top priority	0.6
Replace sewer line with certain material based on preference of agency	6	IF pipe material is most preferable, then output is low priority. IF pipe material is favorable, then output is High priority IF pipe material is undesirable, then output is Top priority	0.5

Notes: Weight is arbitrarily but reasonably assigned based on the priority of the R&R
In the example, preference of material is assumed CON>VC>PVC>CI

As presented in Table 4-12, fuzzy rules reflect the R&R policies of the municipal agency and the weight of a fuzzy rule is influenced by the importance of the R&R policies. Since a decision rule and its weight greatly affect the result of the fuzzy model, the rule should appropriately carry a prioritization algorithm and also comply with engineering authority requirements. When a fuzzy rule is reasonably designed, using aggregation and the defuzzification process, the fuzzy inference system analyzes the significance of the project and gives a single crisp number, as shown in Figure 4-6 .

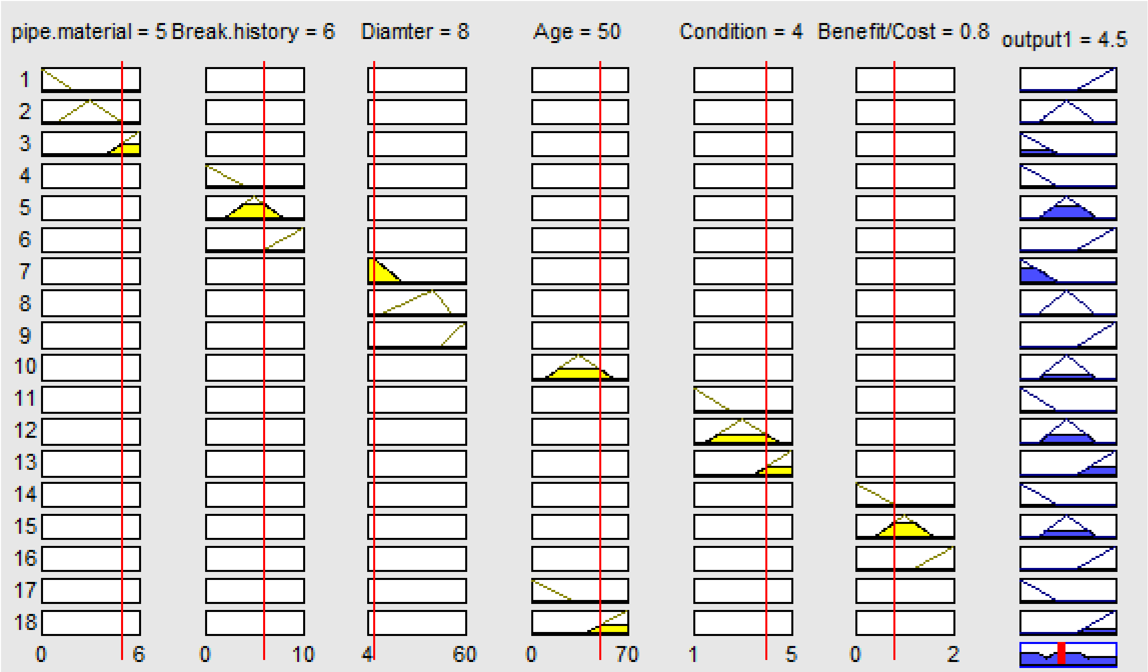


Figure 4-6: Aggregation and defuzzification for Project 1

The result of the illustrative example appears in Table 4-13. As defined by the output membership function, the larger output number represents higher priority.

Table 4-13: Result of illustrative example

Project	Output	Prioritization
1	4.5	5
2	4.64	3
3	4.42	6
4	3.59	10
5	4.15	8
6	4.38	7
7	5.85	1
8	5.34	2
9	4.05	9
10	4.55	4

Currently, most municipal agencies use a worst-first approach as their basic R&R strategy. Therefore, a question arises when the pipelines are in the same condition. As demonstrated in the above example, application of the fuzzy logic approach in the development of prioritization policies shows great potential.

The best feature of using the fuzzy logic approach is the capability of reflecting various types of data based on complicated R&R policies and a flexibility that allows additional consideration to easily update the policies. Also, capturing the linguistic expression is feasible by simple modification of membership function, as the pipe material membership function exemplifies.

Consequently, by using the simple fuzzy logic approach for prioritization policies, an agency can allocate budgets properly, reduce unexpected system failures, and further obtain more cost-effective and efficient operation of a system.

Chapter 5

DEVELOPMENT OF THE ASSET VALUATION MODEL

Chapter 5 presents an asset valuation method which reflects the time-value of money and the change of an asset’s condition. The first section addresses the underlying concept and basic structure of the proposed valuation method. Then, comparisons of estimated value, based on different valuation methods, and deterioration scenarios are discussed to clarify how rehabilitation and replacement techniques impact the value of an asset.

5.1 Implementation of a Valuation Model

The basis for implementation of a valuation method is to provide a means for relevant and timely information for the managers of infrastructure so that they can make decisions for serving the customers more efficiently and cost effectively.

The fundamental idea of the valuation method proposed in this study arises mainly from a realization of the limitations of existing methods. Including the Purdue Study, most existing methods do not adequately capture the actual performance of an asset and the time-value of money. Thus, a valuation method that reflects these factors will be proposed in this research. This method can estimate the value of asset by incorporating an inflation factor, the original cost, and the condition ratio as shown in Eq. 5.1

$$\text{Asset value} = O \times E(t.P) \times \left(\frac{E(t,C) - \mathit{Worst\ condition}}{\mathit{Best\ condition} - \mathit{Worst\ condition}} \right) \quad 5.1$$

where, O = Original cost or estimated historical cost;

E(t,C) = Expected condition at year t (come from deterioration model), and

E(t,P) = Expected price index factor at year t; computed as follows:

$$\text{E(t,P)} = \frac{\mathit{Construction\ cost\ index\ at\ year\ t}}{\mathit{Construction\ cost\ index\ at\ base\ year}}$$

For the estimation of the future construction-cost index, regression analysis is applied in this study. Appendix C contains the prediction of the construction-cost index.

5.2 Accounting Principles for R&R Policies

Depending on the type of R&R technology utilized, diverse accounting principles are applied and also different amounts of costs are capitalized. This section discusses the details of the accounting principles in each valuation approach.

5.2.1 For Preservation Techniques

In this study, preservation activities refer to renewal techniques, introduced in Chapter 4, such as Cathodic Protection and Joint Rehabilitation. According to GASB 34, preservation activities are defined as “treatments that extend the service life of an asset beyond its original designed service life but do not increase capacity or efficiency of the asset.” Preservation cost is not capitalized, but treated as an expense in the modified approach. However, in other valuation methods, preservation cost is capitalized, but in a different manner.

While book value method capitalizes the full amount of preservation cost only, the deteriorated value method and this study's proposed valuation method consider the effectiveness of applied technique and capitalize preservation cost accordingly, as shown in Eq. 5.2 .

Deteriorated value method:

$$ETAV = P_{21} \times C$$

Where, P_{21} = *the transition probabilities that applied technique upgrades condition from 2 to 1*

C = *preservation cost*

Proposed valuation method:

$$\text{Increased value} = P_{21} \times O \times IC / 4 \times E(t, p) \tag{5.2}$$

Where, P_{21}= *the transition probabilities that applied technique upgrades condition from 2 to 1*

O = *original cost*

IC = *increased condition*

$E(t, p)$= *expected price index factor at year t*

As seen in Eq. 5.2 , the increased value of the proposed valuation approach is determined by the impact of applied techniques on current asset value. Therefore, depending on the increased condition and current asset value, capitalized cost can be greater than the investment cost for the preservation technique.

5.2.2 For Improvement Techniques

Improvement techniques include most rehabilitation and replacement methods such as pipe lining, cured in-place pipe, open cut replacement, pipe bursting and micro tunneling. The book value method, deteriorated value method and even the modified approach capitalize the full improvement cost. On the other hand, the proposed valuation method capitalizes the increased value for the application of improvement techniques as shown in Eq. 5.3 .

$$\text{Increased value} = P_{ij} \times O \times IC / 4 \times E(t, p) \tag{5.3}$$

Where, P_{ij} = transition probability that represents the effectiveness of the applied technique

O = original cost

IC = increased condition

$E(t, p)$= expected price index factor at year t

5.3 Comparison of Existing Valuation Methods

This section compares currently existing valuation methods with each other. First, the influence of different deterioration modes on the value of various valuation methods is observed. Later, the impact of the different R&R technology applications on the value of an asset also will be examined.

5.3.1 Case 1: Without Rehabilitation Method

1) When a straight-line deterioration model is applied

Assumptions

- Best condition 1; Worst condition 5 and the condition rating system is continuous.
- Useful life: 58 years
- Year of construction: 1970

- Original cost: $50,000 with no salvage value after 58 years.
- Price index: use construction cost index obtained form ENR (Engineering News Record 2005)
- Prediction model: assumed to be a straight line as shown in Figure 5-1.

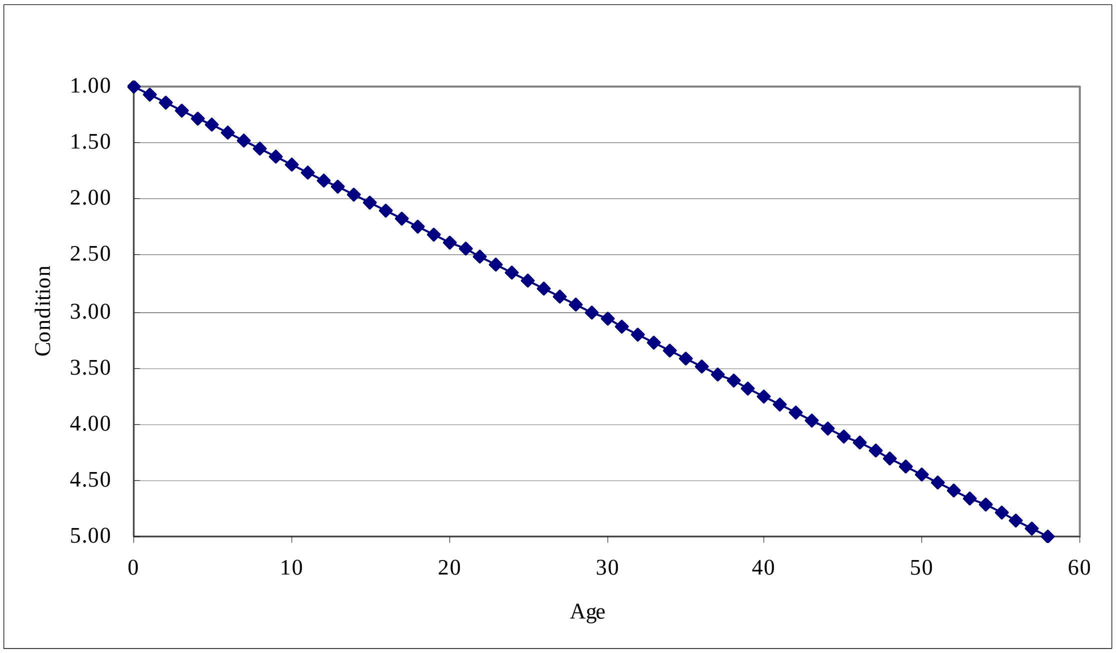


Figure 5-1: Straight line deterioration model

When deterioration mode is assumed as straight line, the estimated future values from various valuation approaches are presented in Figure 5-2.

As seen in Figure 5-2, straight line depreciation and sum-of-years-digits method show continuous decrease of asset value during the service life of the asset and deteriorated value method (Baik 2003) shows the same performance as straight line depreciation. On the other hand, the value obtained from modified approach does not change during the useful life of the asset.

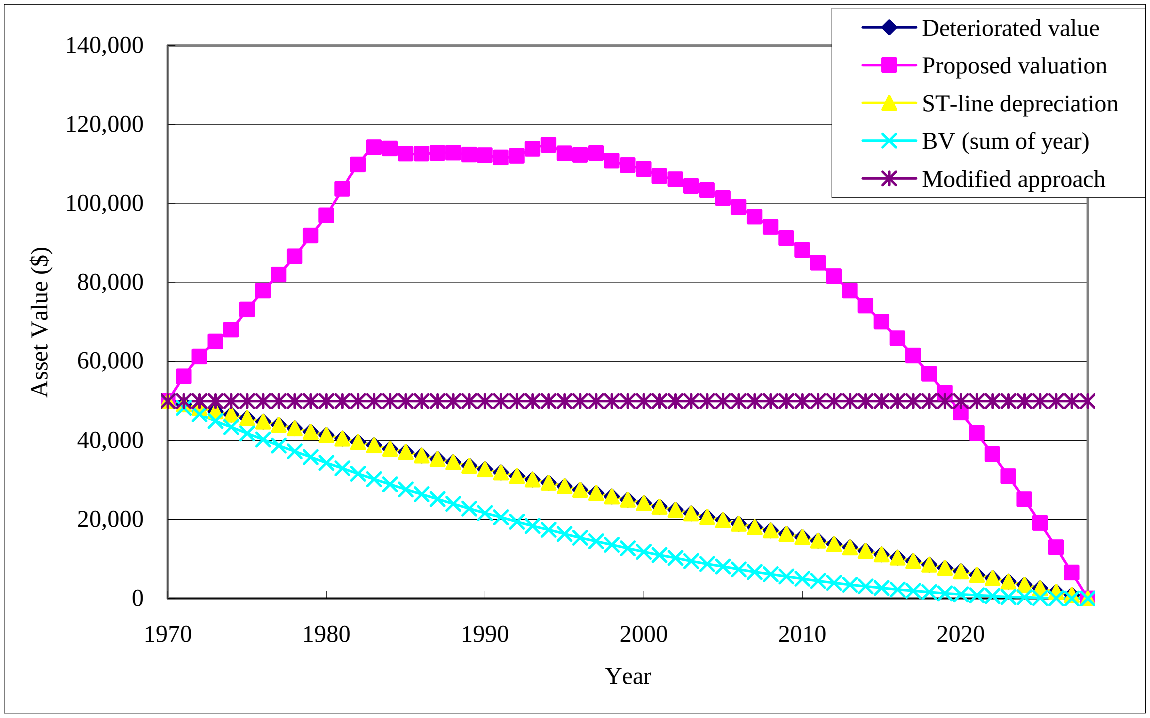


Figure 5-2: Comparison based on straight line deterioration

The value from the proposed valuation model increases in the beginning, then moves somewhat laterally and in the end sharply decreases until end of service life. This fluctuation of value arises from the difference between the inflation rate from the construction cost index, and the deterioration rate. Consequently, when the inflation rate is greater than the deterioration rate, asset value increases. To the contrary, when the deterioration rate is greater than the inflation rate, asset value decreases.

2) When Markov chain based deterioration model is applied

Assumptions

- As with the straight line case, the same assumptions will be used for consistency.
- 8-inch concrete pipeline deterioration model is used as the prediction model, as shown in Figure 5-3.

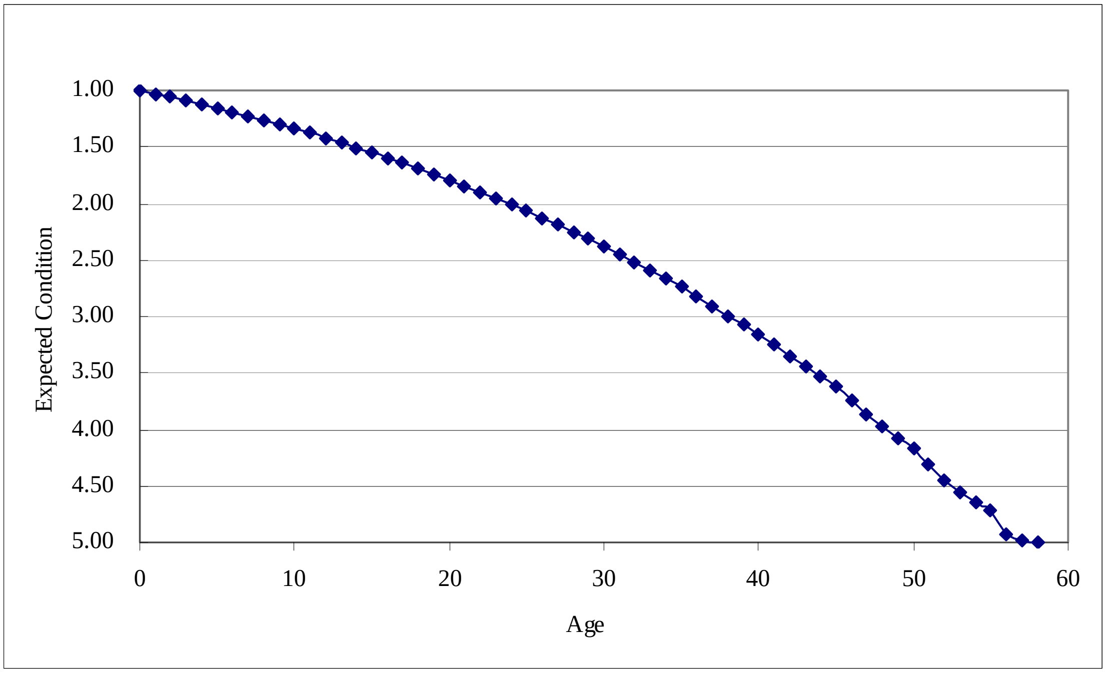


Figure 5-3: Curved deterioration model

When the Markov chain based deterioration model is used as prediction model, the estimated future values from various valuation approaches are, as presented in Figure 5-4.

Since the book value method and modified approach do not reflect the condition of the asset, the mode of these valuation methods show the same performance in both the straight-line deterioration case and the curved deterioration case, as shown in Figure 5-4**.**

On the other hand, the deteriorated value method and the proposed valuation approach depreciate the asset value differently, because they capture the actual performance of the asset. However, while the deteriorated value method closely follows the performance pattern of the curved deterioration model, the mode of the proposed valuation approach is more influenced by inflation.

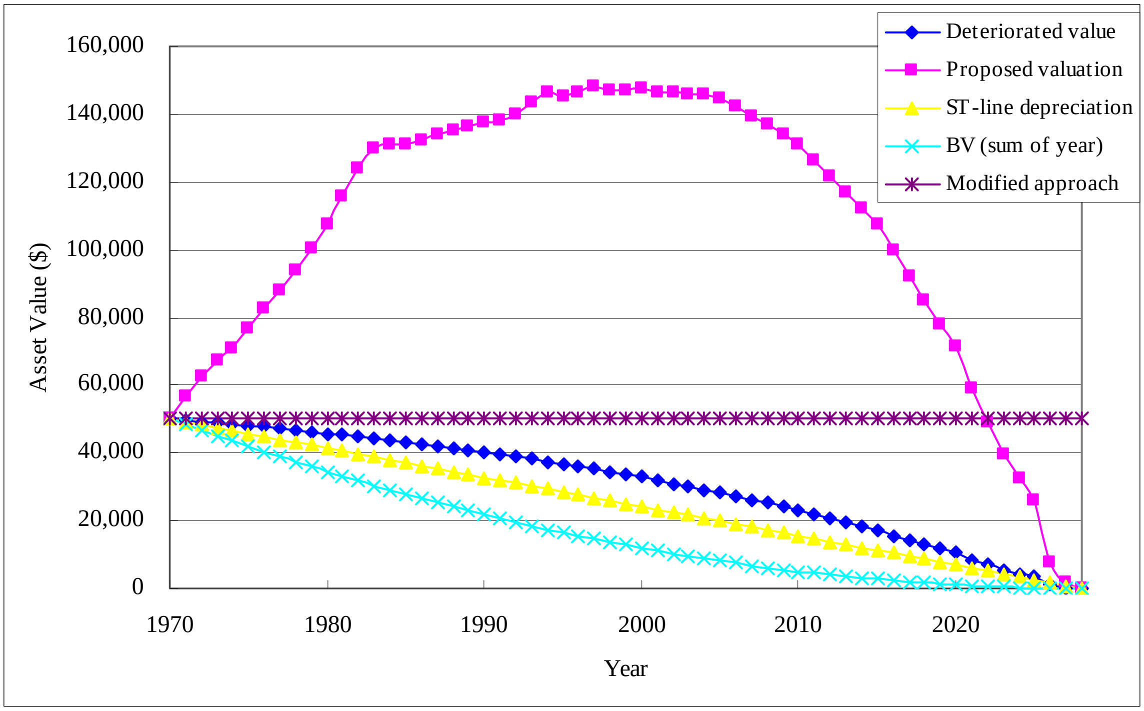


Figure 5-4: Comparison based on curved deterioration model

As seen in both cases, the best aspect of using the proposed valuation methods in the prediction of future values is that this approach enables the governmental agencies to have clearer idea of the timing for investment. Therefore, the agencies can control timing of renewal or rehabilitation flexibly, depending on funding availability, and still maintain the best value for the system.

5.3.2 Case 2: Application of the Preservation Technique

Assumptions

- Basic performance follows the deterioration model.
- The chemical grouting method will be applied after 30 years at a cost of $60,000, and this activity will upgrade the condition of asset by1.
- All other assumptions will be same with Case 1.

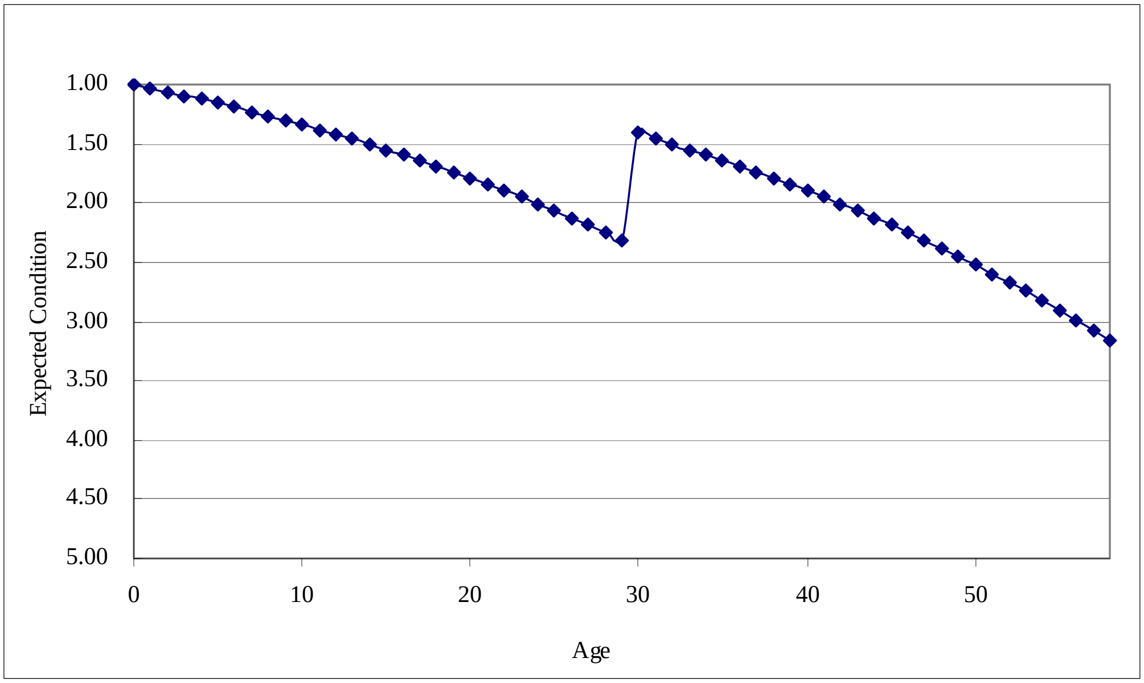


Figure 5-5: Performance curve with chemical grouting technology

When a preservation technique, such as chemical grouting is applied, the impact of the applied technique on the estimated future value of the deteriorated value method, the proposed valuation method, and the modified approach is, as presented in Figure 5-6.

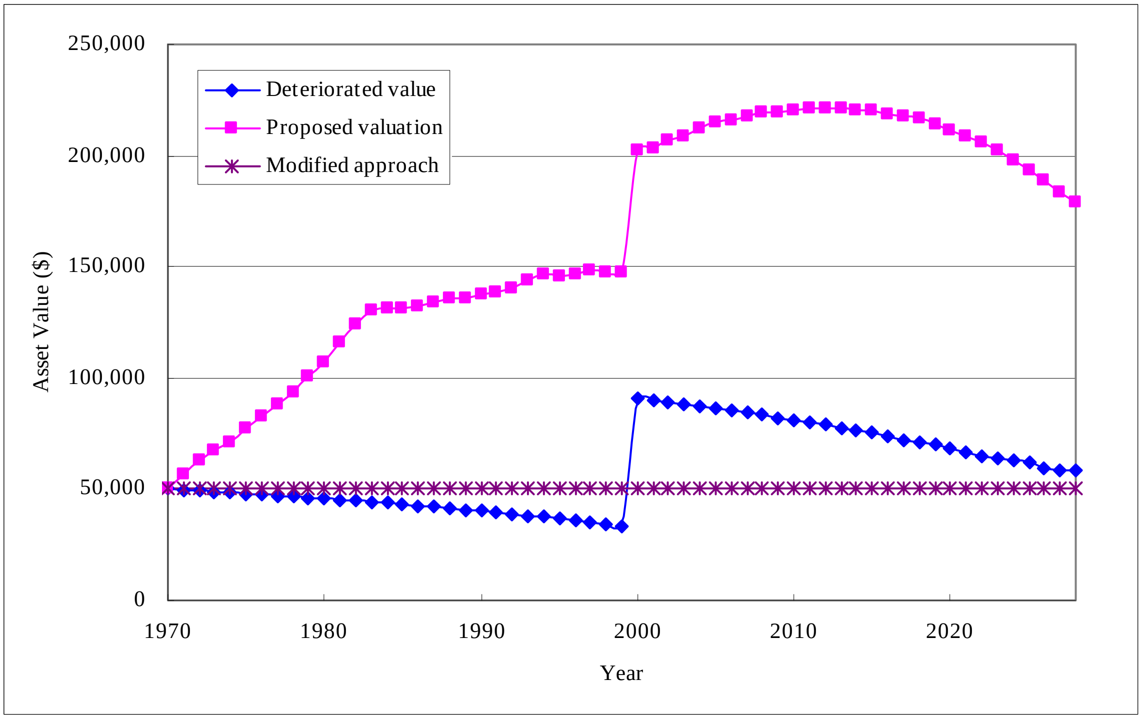


Figure 5-6: Results of comparison with preservation method

As shown in Figure 5-6, at the time of chemical grouting, a sudden increase of value occurs in all valuation approaches except the modified approach. This unusual result arises from the accounting principle for the modified approach. As previously indicated, preservation cost is not capitalized but treated as an expense in the modified approach. On the other hand, both the deteriorated value method and the proposed valuation method capitalize the preservation cost, but they estimate the capitalized amount differently. The corresponding capitalized amounts for the deteriorated value method and the proposed valuation method, can be estimated as:

- Deteriorated value method: $0.9697 \times \$60{,}000 = \$58{,}182$
- Proposed valuation method: $0.9697 \times \$50{,}000 \times 1/4 \times 4.5 = \$54{,}545$

Cathodic protection, joint rehabilitation, reinforced shotcrete, and high-build epoxy are considered as preservation technologies in this study.

5.3.3 Case 3: Application of the Improvement Technique

Assumptions

- Basic performance follows the 8-inch concrete deterioration curve.
- The pipe bursting method will be applied after 50 years at a cost of $250,000, and this activity will restore the pipe condition to initial condition.
- All other assumptions remain the same as Case 1.

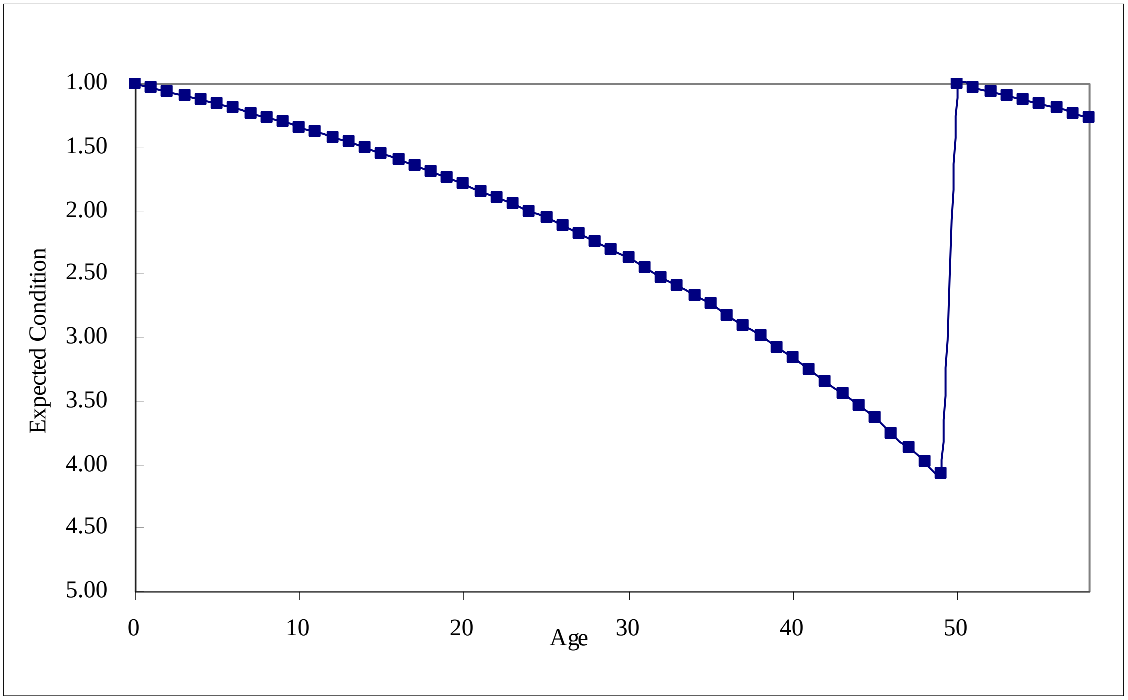


Figure 5-7: Assumed performance curve with pipe bursting technology

The estimated future value of the deteriorated value method, the proposed valuation method, and the modified approach with pipe bursting technique appears in Figure 5-8.

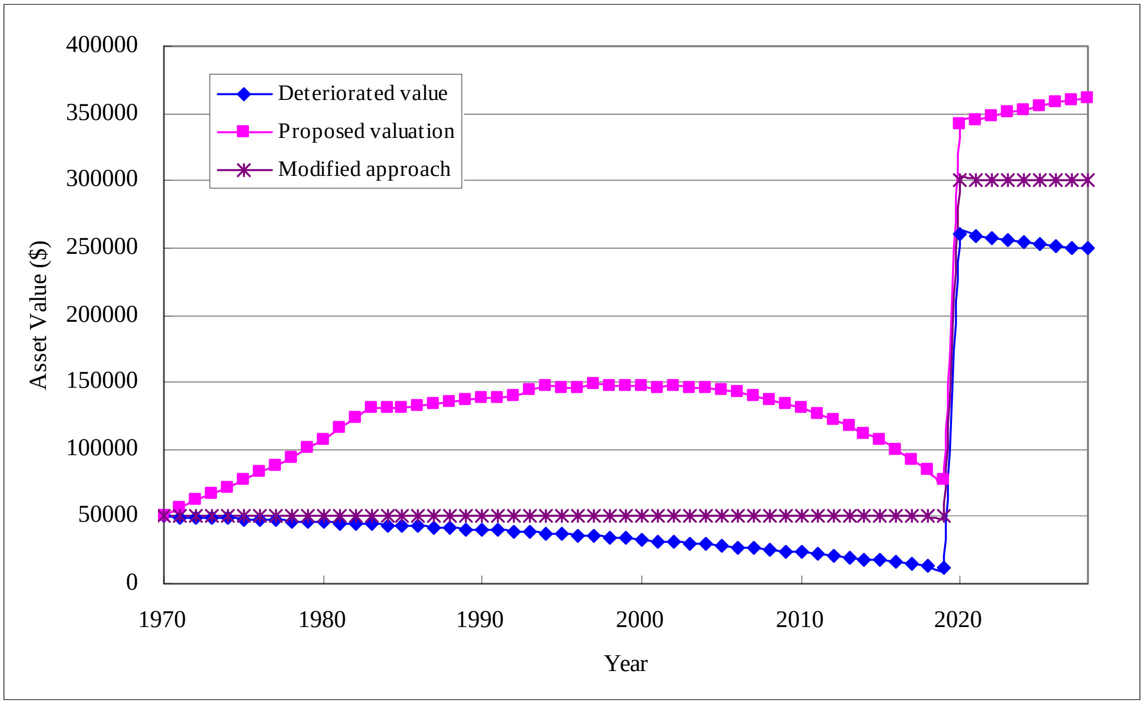


Figure 5-8: Results of comparison with improvement method

Since pipe bursting technology is an improvement technique, even the modified approach capitalizes the full amount of the investment cost. Thus, identical increases of asset value from both the deteriorated value method and the modified approach are observed, as shown in Figure 5-8. On the other hand, the proposed valuation method capitalizes differently, and the amount can be estimated as:

- $\$50,000 \times 1 \times (4.16-1)/4 \times 6.83 = \$269,785$

Most rehabilitation and replacement methods that increase capacity or efficiency of the asset fall into an improvement category and the expenditure for these activities should be capitalized.

5.3.4 Summary

Value is a subjective concept and can be estimated quite differently using various valuation approaches (Dewan and Smith 2005). The value is also defined differently, based on the different perspectives. Therefore, consideration of the objectives of a valuation approach is significantly important.

A sewer infrastructure is a particular capital asset in that it pursues public interests rather than its own profits, and the value of a sewer infrastructure system to the public is its consistent and reliable service. Therefore, the driving attribute for valuation of this infrastructure would be its inherent capacity to provide service. In addition, as indicated earlier, infrastructures have significantly longer service lives than other capital assets. Accordingly, consideration of the concept of time-value of money is also required.

The proposed valuation approach practically estimates the future value of an infrastructure asset from an engineering perspective by incorporating the Markov chain-based prediction model and the construction cost index. Consequently, this valuation approach helps to establish a long-term investment plan and further manage the infrastructure system more cost-effectively and soundly.

Chapter 6

ASSET VALUE AND INVESTMENT DECISON

Chapter 6 examines, by illustrative examples, the impact of asset value and other uncertainties regarding the change of an asset's condition and the interest rate on the investment decisions. The first section covers the fundamental concept for the traditional discounted cash flow method and emerging real option analysis, followed by the types of options. The second section illustrates the influence of variations from uncertainty on investment decisions according to cases.

6.1 Capital Investment Decisions for Infrastructure

Over the last two decades, private participation in infrastructure projects has dramatically increased (Garvin 2005). This circumstance demands increased evaluation techniques for private investment in public infrastructures. Since the tradition approach such as net present value method does not adequately take into account for managerial flexibilities and uncertainties underlying infrastructure investment decisions (Dixit and Pindyck 1994), the real option theory as an evaluation technique for infrastructure investment decisions is receiving significant attention in these days.

6.1.1 Discounted Cash Flow

In discounted cash flow methods, the net present value method (NPV) and internal rate of return (IRR) are prevalent methods used to evaluate investment decisions for those assets not occupying a position in an active market. While the net present value method measures the sum of the discounted cash flows at a discount rate that reflects time value of money and project risk, as shown in Eq. 6.1, IRR computes the discount rate that makes the company’s cash flow positive. Due to their simplicity, these methods have been widely used, but they do not properly account for the effect of managerial flexibilities for future uncertainties. Investments frequently hold uncertainty over future rewards, and the degree of risk can change with new information. In such cases, the net present value method underestimates the value of flexibilities that change operational strategies in response to a dynamic environment.

$$\text{NPV} = -\text{I} + \sum_{t=0}^{n} \frac{C_t}{(1+r)^t}, \tag{6.1}$$

where, I = Investment, and
C= Expected future cash flow.

6.1.2 Real Option Analysis

For the last 20 years, real option analysis has been widely applied for the valuation of opportunity cost by incorporating real investment into a financial option pricing model; and lately, many researchers have expanded the concept of real option into the field of infrastructure systems. Ho and Liu (2002) proposed the BOT (build-operate-transfer) option valuation model to evaluate financial viability, such as government guarantees and negotiation options for privatized infrastructure projects. Ford et al. (2002) discussed potential challenges of the real option analysis in evaluating and determining strategies for construction projects with dynamic uncertainties. Zhao and Tseng (2003) used a trinomial lattice model and stochastic dynamic programming to obtain the value of expansion option in public parking garages. Garvin and Cheah (2004) used a simple binomial model to assess the value of a deferment option of the Dulles Greenway project in northern Virginia. Later, Garvin (2005) provided illustration of the classic and the marketed asset disclaimer (MAD) approaches to assess the value of the deferment option within the Dulles Greenway project. In 2006, Cheah and Liu applied Monte Carlo simulation of a discounted cash flow model to evaluate the value of governmental support in infrastructure.

The real option approach, a new emerging concept, complements the conventional discounted cash flow (DCF) method by reflecting a dimension of managerial flexibility. Managerial flexibility has value, because it could alter future investment response to changing uncertainty to allow maximizing expected rewards or minimizing expected losses. Typical real options are: growth option, that expands scale as market grows; deferment option, that holds investment until new information is revealed; temporary suspension; or abandonment. All of these flexibilities represent operational strategies on real assets that increase the value of the project. Thus, valuation of such options would be quite important for government a agency to determine favorable financial decisions.

6.2 Uncertainties and Investment Decisions

As described earlier, investment decisions often hold uncertainties from future economic environments, and traditional discounted cash flow (DCF) methods do not properly capture managerial flexibilities under those conditions. This section examines the conflicting decisions between the traditional approach and real option analysis under various situations.

6.2.1 Case 1: Change of Asset Value

I. Assumptions:

- Investment I = \$1,000,000
- Current asset value = \$1,200,000
- Risk free rate 10% and average inflation 3%
- Current condition of system is 1 (Best condition 1, Worst condition 5)
- Uncertainty is represented by transition matrix
- $P = \begin{bmatrix} 0.95 & 0.05 & 0 & 0 & 0 \\ 0 & 0.8 & 0.2 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$
- Options are to invest now or wait one year

➢ **By traditional approach**

$NPV = -\$1,000,000 + \$1,200,000 = \$200,000$

The positive net pay off from the NPV approach supports that the project is worthy of investment. However, this decision is not favorable, because it results from neglecting the opportunity cost.

- **By real option approach**

$$NPV = 0.95 \times [\frac{-\$1,000,000}{1.1} + \frac{\$1,200,000 \times (1.03)}{1.1}] = \$203,818$$

When applying real option theory, the result would be different. This example carries the option to invest now or wait one year. If the investment decision is postponed until next year and the opportunity cost for the wait is considered, then NPV of the project is $203,818 as shown above. Because greater NPV is obtained in the case of the real option approach, it is better to wait and decide later.

Depending on the value of opportunity, the amount of required investment is changed, as shown below:

$$NPV = 0.95 \times [\frac{-I*}{1.1} + \frac{\$1,200,000 \times (1.03)}{1.1}] = \$200,000 \qquad I* = \$1,004,421$$

The above equation shows that the value of the opportunity with the now-or-never option at a cost of $1,000,000 has the same value as the opportunity with the now-or-next-year option at a cost of $1,004,421. Consequently, the inference is that a flexible project with options has a higher value than an inflexible one.

- **Critical investment cost for decision rule**

When investment cost is changed, the decision would also change. Thus, a critical point exists that affects investment decisions directly. The critical decision point for the investment cost can be estimated as shown below:

$$-I^{*}+\$1,200,000 \geq \frac{0.95}{1.1}[-I^{*}+\$1,200,000*1.03\} \qquad I^{*} \leq \$972,000$$

As seen above, the critical investment cost is $972,000. Thus, if investment cost is less than $972,000, then the better choice is to invest now rather than wait one year.

II. Assumptions:

- Current asset value = $1,500,000
- All other assumptions are same

➢ **By traditional approach**

NPV = - $1,000,000 + $1,500,000 = $500,000

The conventional NPV method shows considerable positive net pay off at the time of execution, but still needs to be compared with the result of the real option. As previously indicated, the conventional NPV method does not properly capture the value of opportunity cost.

➢ **By real option approach**

$$NPV = 0.95 \times [\frac{-\$1,000,000}{1.1} + \frac{\$1,500,000 \times (1.03)}{1.1}] = \$470,682$$

Compared with the result of the traditional approach, the real option approach yields a smaller output. Thus, in this case, the better choice is to invest now rather than wait.

➢ **Critical asset value for decision rule**

Like the calculation of critical investment cost, a similar procedure is applied to estimate the critical decision point for asset value as shown below:

$$-\$1000,000 + AV^* \geq \frac{0.95}{1.1}[-\$1,000,000 + AV^* * 1.03\} \qquad AV^* \geq \$1,234,568$$

The critical asset value is $1,234,568. Consequently, the project needs to invest now in case the project value is greater than $1,234,568. On the other hand, the project should be postponed, if the value of the project is less than $1,234,568.

6.2.2 Case 2: Change of Uncertainty

I. Assumptions:

- All other assumptions are same as Case 1.
- Uncertainty is changed as follows:
- From $P = \begin{bmatrix} 0.95 & 0.05 & 0 & 0 & 0 \\ 0 & 0.8 & 0.2 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$ to $P = \begin{bmatrix} 0.80 & 0.20 & 0 & 0 & 0 \\ 0 & 0.7 & 0.3 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$

➢ **By traditional approach**

NPV = - $1,000,000 + $1,200,000 = $200,000

Since the conventional NPV method does not take into account the flexibility of the project, the change of uncertainty does not affect the result of the analysis. Thus, the result is the same as Case 1.

➢ **By real option approach**

$$NPV = 0.80 \times [\frac{-\$1,000,000}{1.1} + \frac{\$1,200,000 \times (1.03)}{1.1}] = \$171,636$$

As previously discussed, a change in the transition probabilities greatly affects the result. In this example, compared with Case 1, a decrease of NPV is observed in the real option approach. This means that higher uncertainty reduces the value of the project and potential benefit from execution of the project is also reduced. Based on these results, the recommended decision is immediate investment.

- **Critical investment cost for decision rule**

$$-I*+\$1,200,000 \geq \frac{0.80}{1.1}[-I*+\$1,200,000*1.03\} \quad I* \leq \$1,104,000$$

The critical investment cost is now \$1,104,000. The critical point is increased compared with Case 1. Thus, the inference is that a higher uncertainty reduces the influence of investment cost on the decision. According to the above result, the wait option is recommended, until investment cost is greater than \$1,104,000.

- **Critical probability for decision rule**

$$-\$1000,000+\$1,200,000 \geq \frac{p*}{1.1}[-\$1,000,000+\$1,200,000*1.03\} \quad p* \leq 0.932$$

As seen above example, if probability is smaller than 0.932, the better choice is to invest now rather than wait.

6.2.3 Case 3: Change of Interest Rate

I. Assumptions:

- Risk free rate = 15 %
- All other assumptions are same with Case 1.

➢ **By traditional approach**

NPV = - $1,000,000 + $1,200,000 = $200,000

The conventional NPV method is not influenced by the change of surrounding circumstances, except asset value and investment cost. Thus, the above equation shows the same result as Case 1.

➢ **By real option approach**

$$NPV = 0.95 \times [\frac{-\$1,000,000}{1.15} + \frac{\$1,200,000 \times (1.03)}{1.15}] = \$194,957$$

As seen in the change of uncertainty case, an increase of interest rate also reduces the value of the project with the wait option. Consequently, investing now is favorable.

➢ **Critical investment cost for decision rule**

$$-I* + \$1,200,000 \geq \frac{0.95}{1.15}[-I* + \$1,200,000 * 1.03\} \qquad I* \leq \$1,029,000$$

As expected, the critical investment cost is increased. If investment cost is less than $1,029,000, the invest now option is preferred.

➢ **Critical interest rate for decision rule**

$$-\$1000,000 + \$1,200,000 \geq \frac{0.95}{r*}[-\$1,000,000 + \$1,200,000 * 1.03\} \qquad r* \geq 12.1\%$$

Similarly, when the interest rate is greater than 12.1%, investing now is better that waiting.

II. Assumptions:

- Average inflation rate = 5%
- All other assumptions are the same as Case 1.

➢ **By traditional approach**

NPV = - $1,000,000 + $1,200,000 = $200,000

No change in the traditional approach is found.

➢ **By real option approach**

$$NPV = 0.95\times[\frac{-1,000,000}{1.10}+\frac{1,200,000\times(1.05)}{1.10}] = \$224,545$$

Unlike uncertainty and interest rate, the growth of inflation rate increases the value of a project with the wait option. Thus, selecting the project with a wait option is better in this case.

➢ **Critical investment cost for decision rule**

$$-I^{*}+\$1,200,000 \geq \frac{0.95}{1.15}[-I^{*}+\$1,200,000*1.05\} \qquad I^{*} \leq \$820,000$$

The critical investment cost is now $820,000. The critical point is decreased as compared to Case 1. Consequently, the inference is that an increase of expected future value of the project greatly influences the investment decision and also lowers the critical investment cost, ensuring the implementation of the project with invest-now or wait options.

Chapter 7

CONCLUSIONS AND FUTURE STUDIES

7.1 Summary of the Study

This study develops a comprehensive asset management system by introducing the idea of a two-step optimization approach for optimal R&R policies and valuation method from engineering perspectives. The study also presents the Markov chain-based prediction model by using the expected value method. Finally, the information from the performance model and the valuation approach is applied in real option analysis to attain favorable infrastructure management, which accounts for managerial flexibilities and underlying uncertainties in infrastructure investment decisions.

The aforementioned two-step optimization process combines project-level probabilistic life-cycle cost analysis from dynamic programming and network-level prioritization policies from fuzzy logic theory. This approach may assist municipal agencies in establishing optimal R&R policies and corresponding investment plans. This thesis also proposes a new valuation approach that incorporates the Markov chain-based deterioration model and the construction cost index. The proposed valuation method practically provides timely information about the intrinsic productivity based value, adjusted for the construction cost index and timing of R&R activities.

For the development of deterioration curves for the sewer pipelines in the City of Atlanta, the expected value method is used to estimate transition probabilities. Based on materials, diameters and locations of sewer pipelines, 11 deterioration curves and corresponding transition matrices are presented, and possible attributes for the deterioration of sewer pipelines are discussed. Generally, this work assists governmental agencies to implement a comprehensive sewer infrastructure management system.

7.2 Limitations of the Study

This thesis attempts to complement conventional infrastructure systems by presenting pipeline-performance model, valuation approach, as well as project and network-level optimal R&R policies. However, some issues exist in the application of these approaches.

- Application of expected value method

Due to a lack of panel data of the sewer pipelines in the City of Atlanta, the expected value method is used to estimate transition probabilities in this study. While poisson regression model and ordered probit model can create a full-transition probability matrix, this approach can only provide one-transition probability matrix. In addition, as indicated by Madanat and Wan Ibrahim (1995), the regression-based expected value method does not properly account for the structure of deterioration processes and the latent nature of involved variables affecting the infrastructure deterioration. Lastly, the application of linear regression in this approach to deterioration modeling is also inadequate, because the condition rating is not continuous, but discrete and ordinal (McKelvey and Zavoina 1975).

- Insufficient knowledge for deterioration mechanisms

The most critical part of the proposed valuation method is the estimation of an accurate prediction model. However, well-structured databases and careful examinations of deterioration mechanisms are not readily available for underground infrastructures. Accordingly, performance parameters that affect deterioration modes are not adequately identified, and selection of attributes for the deterioration model may be improper. Consequently, a prediction model could be inaccurate and likewise the value from the valuation model.

- Transition probabilities for R&R techniques

In this study, transition probabilities used for preservation and improvement techniques arise not from real field data, but the manipulation of transition probabilities for maintenance. As indicated by Baik (2003), these implementations may lead to inaccurate outcomes of probabilistic dynamic programming of life cycle cost analysis and the proposed valuation approach.

7.3 Recommendations for Future Study

Some deficiencies and issues for existing infrastructure management system that could possibly be studied in the future are listed below.

- Establishment of nationwide standardized database

A fundamental requirement for the development of the comprehensive asset management system is a well-structured and standardized database. However, no nationwide inventory of sewer pipelines is currently available (EPA 2004), and the format of existing database varies by agencies. Thus, in most cases, governmental fund allocation is reactive and just responds to the requests of the local and state agencies to avoid the imminent failure. By constructing a nationwide standardized database, the entire sewer infrastructure systems could be effectively managed and the national scope of fund allocation becomes possible.

- Development of a detailed condition rating system

One of the most significant challenges in the preparation of an accurate prediction model is development of a detailed condition rating system. Current 1 to 5 condition rating systems are not minute enough to provide reasonable projections of condition states of underground systems. In addition, serviceability of pipelines relates to not only structural condition but also to hydraulic capacity of the pipe. (Coombes et al. 2002) Therefore, a more minutely classified condition rating systems, that combines structural and functional aspects of sewer pipelines will greatly advance the development of a more accurate performance models for underground infrastructures.

- Identification of performance parameters

As discussed earlier, another critical issue in the development of an accurate deterioration model is the close examination of performance parameters. However, not much works regarding the deterioration mechanism for the sewer pipeline have been conducted, and the performance parameters that affect the mode of pipe deterioration are not adequately defined. Accordingly, these circumstances result in unreliable deterioration model, and further cause difficulty to prepare a long-term investment plan. When reasonable and careful identification of performance parameters that affect pipe deterioration process can be achieved, more accurate modeling will result.

- Application of fuzzy logic theory in the evaluation of condition rating

Development of the condition rating system that reflects structural and functional aspects of sewer pipelines requires a reasonable and consistent evaluation technique. In the City of Atlanta, three types of defects are available for evaluation, but irrespective of the number of defects and types of defects, only the worst defect determines the overall condition of a sewer segment. Therefore, the evaluated condition does not explicitly represent the overall condition of the segment. As seen in network level of optimization, fuzzy logic theory shows significant strengths for the aggregation of data from different layers and types of sewer segments. Accordingly, by using fuzzy logic theory, agencies will reasonably combine different types of defects and appropriately evaluate the overall condition of the system

- Application of real option analysis in sewer system expansion

In this study, simple real option analysis is adopted for examining the impact of various uncertainties on the investment decisions with the wait option. However, in most cases, the more frequent investment decision, arising in sewer management, is the whether or not system expansion copes with public necessity. Therefore, application of real option analysis in the investment decision regarding operation and expansion of a system will promise the municipal agency’s ability to provide service to public in a more practical manner at an appropriate level.

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Appendix A

Transition Probabilities and Deterioration Curve

Table A-1: Transition probabilities for 8-inch concrete pipe in South River_08a

Description	8-inch concrete in SRV07_08a					
Regression	Condition = exp (0.069 + 0.0276 Age) R-Sq = 69.8% R-Sq(adj) = 68.9%					
Period	Zone	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
0-5	1	0.9697	0.9489	0.8553	0.8969	1
6-10	2	0.9713	0.9323	0.9206	0.9396	1
11-15	3	0.9728	0.9420	0.8723	0.8819	1
16-20	4	0.9783	0.9238	0.8637	0.8844	1
21-25	5	0.9656	0.9155	0.8880	0.9277	1
26-30	6	0.9552	0.9041	0.8932	0.9332	1
31-35	7	0.9406	0.8904	0.8886	0.9298	1
36-40	8	0.9185	0.8726	0.8761	0.9144	1
41-45	9	0.8852	0.8356	0.8431	0.8955	1
46-50	10	0.8121	0.7667	0.7744	0.8527	1
51-55	11	0.6169	0.5782	0.6158	0.7366	1
56-60	12	0	0	0	0	1

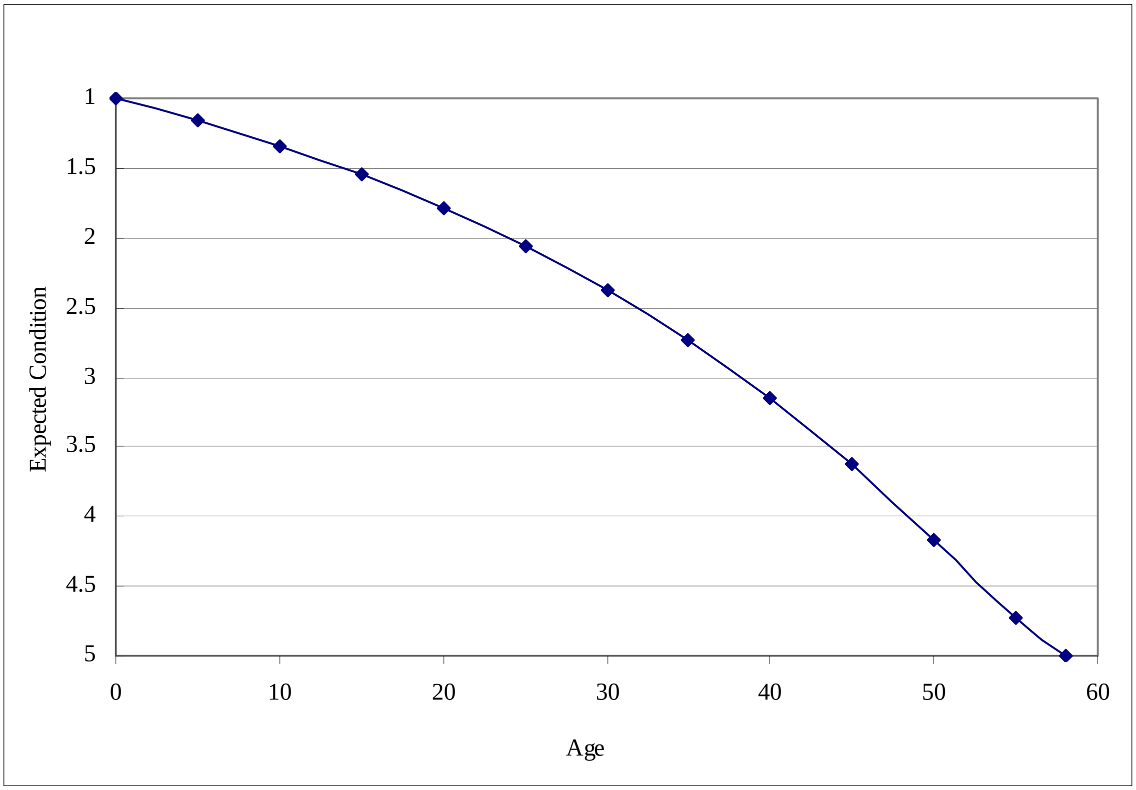

Figure A-1: Deterioration curve for 8-inch concrete pipe in South River_08a

Table A-2: Transition probabilities for 8-inch concrete pipe in South River_08b

Description	8-inch concrete in SRV07_08b					
Regression	Condition = exp (- 0.005 + 0.0293 Age) R-Sq = 69.3% R-Sq(adj) = 68.4%					
Period	Zone	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
0-5	1	0.9704	0.9402	0.9100	0.9939	1
6-10	2	0.9708	0.9384	0.8970	0.9419	1
11-15	3	0.9822	0.9105	0.8595	0.8680	1
16-20	4	0.9732	0.9129	0.8898	0.9109	1
21-25	5	0.9609	0.9080	0.9081	0.9276	1
26-30	6	0.9532	0.8994	0.8982	0.9280	1
31-35	7	0.9376	0.8692	0.8915	0.9432	1
36-40	8	0.9117	0.8579	0.8755	0.9159	1
41-45	9	0.8707	0.8399	0.8351	0.8761	1
46-50	10	0.7842	0.7342	0.7470	0.8295	1
51-55	11	0.4800	0.4536	0.5088	0.6518	1
56-60	12	0	0	0	0	1

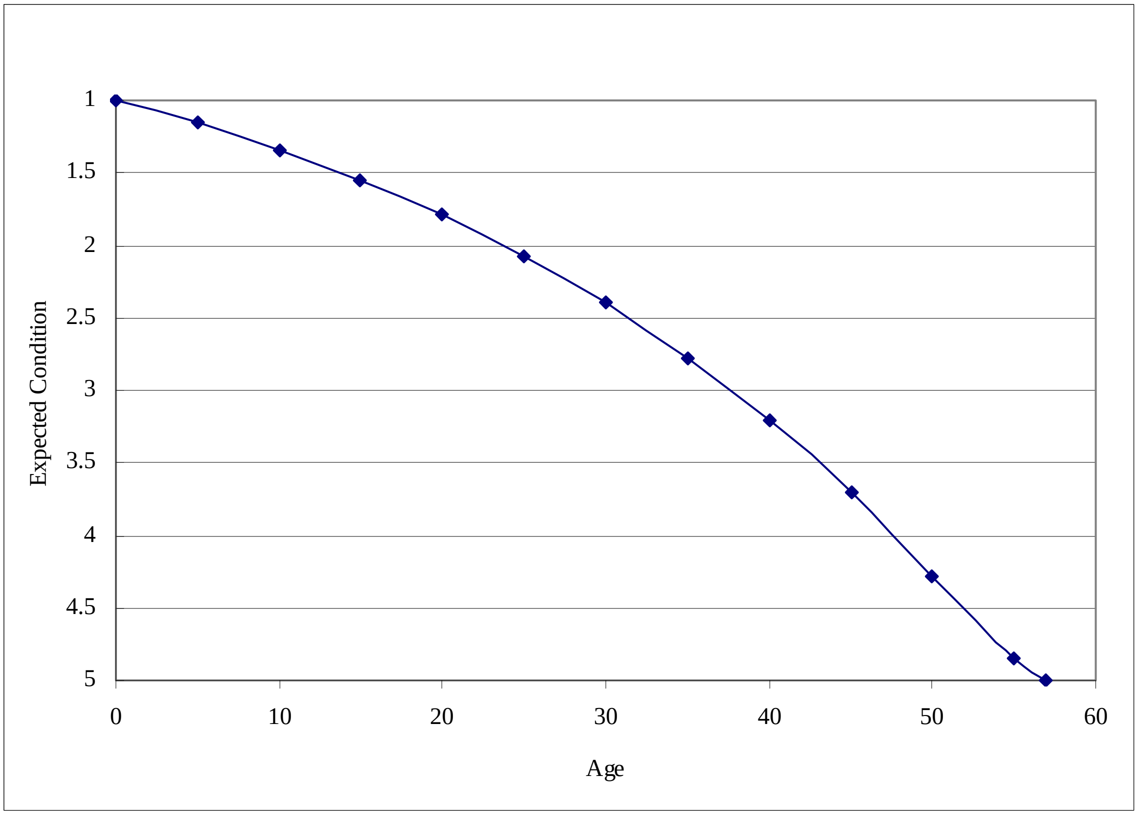

Figure A-2: Deterioration curve for 8-inch concrete pipe in South River_08b

Table A-3: Transition probabilities for 8-inch cast iron pipe in South River_08c

Description	8-inch cast iron in SRV07_08c					
Regression	Condition = exp (0.281 + 0.0201 Age) R-Sq = 65.1% R-Sq(adj) = 62.2%					
Period	Zone	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
0-5	1	0.9731	0.9528	0.9425	0.9985	1
6-10	2	0.9731	0.9537	0.9142	0.9756	1
11-15	3	0.9781	0.9328	0.9291	0.9383	1
16-20	4	0.9817	0.9311	0.9190	0.8689	1
21-25	5	0.9781	0.9344	0.9129	0.9024	1
26-30	6	0.9705	0.9272	0.9196	0.9331	1
31-35	7	0.9634	0.9198	0.9215	0.9393	1
36-40	8	0.9535	0.9104	0.9208	0.9438	1
41-45	9	0.9442	0.9023	0.9094	0.9354	1
46-50	10	0.9265	0.8866	0.8958	0.9284	1
51-55	11	0.9015	0.8612	0.8730	0.9141	1
56-60	12	0.8532	0.8171	0.8311	0.8862	1
61-65	13	0.7474	0.7082	0.7360	0.8209	1
66-70	14	0.2839	0.3192	0.4036	0.5744	1
71-75	15	0	0	0	0	1

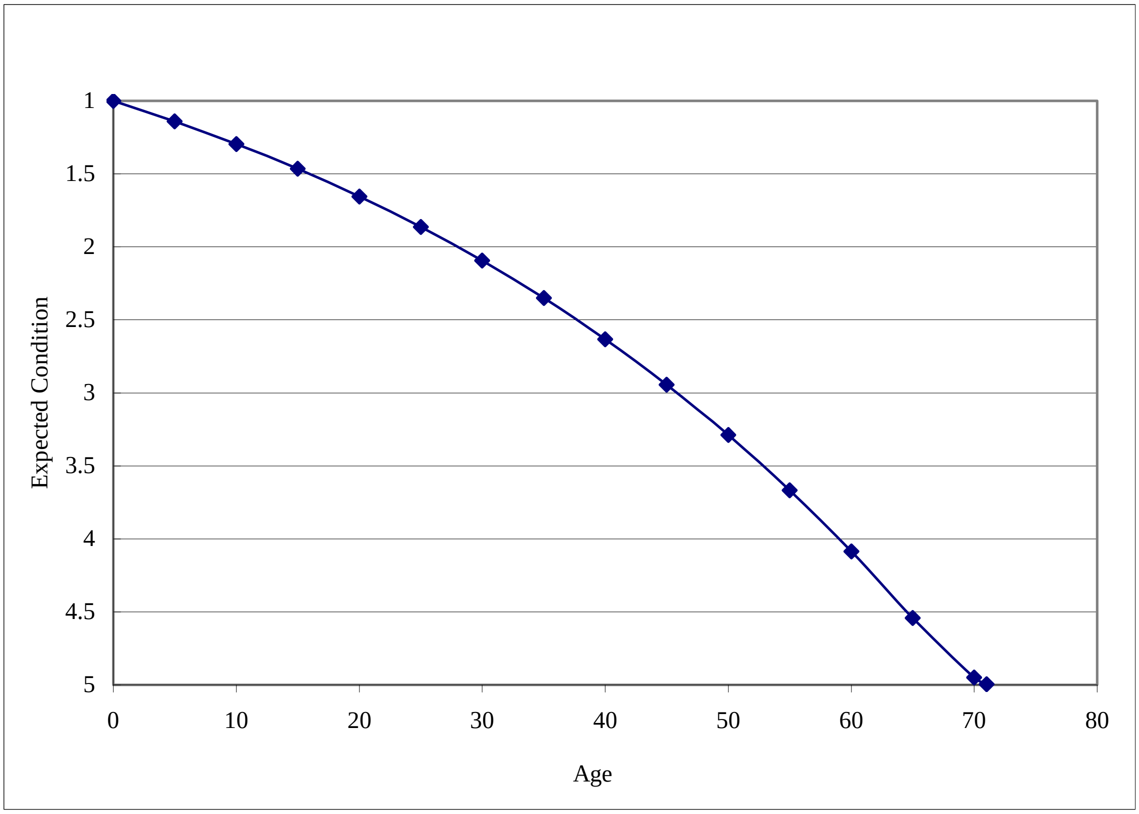

Figure A-3: Deterioration curve for 8-inch cast iron pipe in South River_08c

Table A-4: Transition probabilities for 8-inch concrete pipe in South River_10

Description	8-inch concrete in SRV10					
Regression	Concrete = exp (0.022 + 0.0267 Age) R-Sq = 53.2% R-Sq(adj) = 52.4%					
Period	Zone	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
0-5	1	0.9723	0.9446	0.9329	0.9974	1
6-10	2	0.9814	0.8804	0.9140	0.9665	1
11-15	3	0.9792	0.9162	0.9007	0.8595	1
16-20	4	0.9750	0.9141	0.9030	0.9102	1
21-25	5	0.9680	0.9106	0.9118	0.9336	1
26-30	6	0.9578	0.9077	0.9128	0.9412	1
31-35	7	0.9492	0.8982	0.9048	0.9334	1
36-40	8	0.9470	0.8685	0.8835	0.9254	1
41-45	9	0.9054	0.8461	0.8745	0.9178	1
46-50	10	0.8803	0.8081	0.8289	0.8796	1
51-55	11	0.7627	0.6993	0.7403	0.8264	1
56-60	12	0.4124	0.3664	0.4544	0.6127	1
61-65	13	0	0	0	0	1

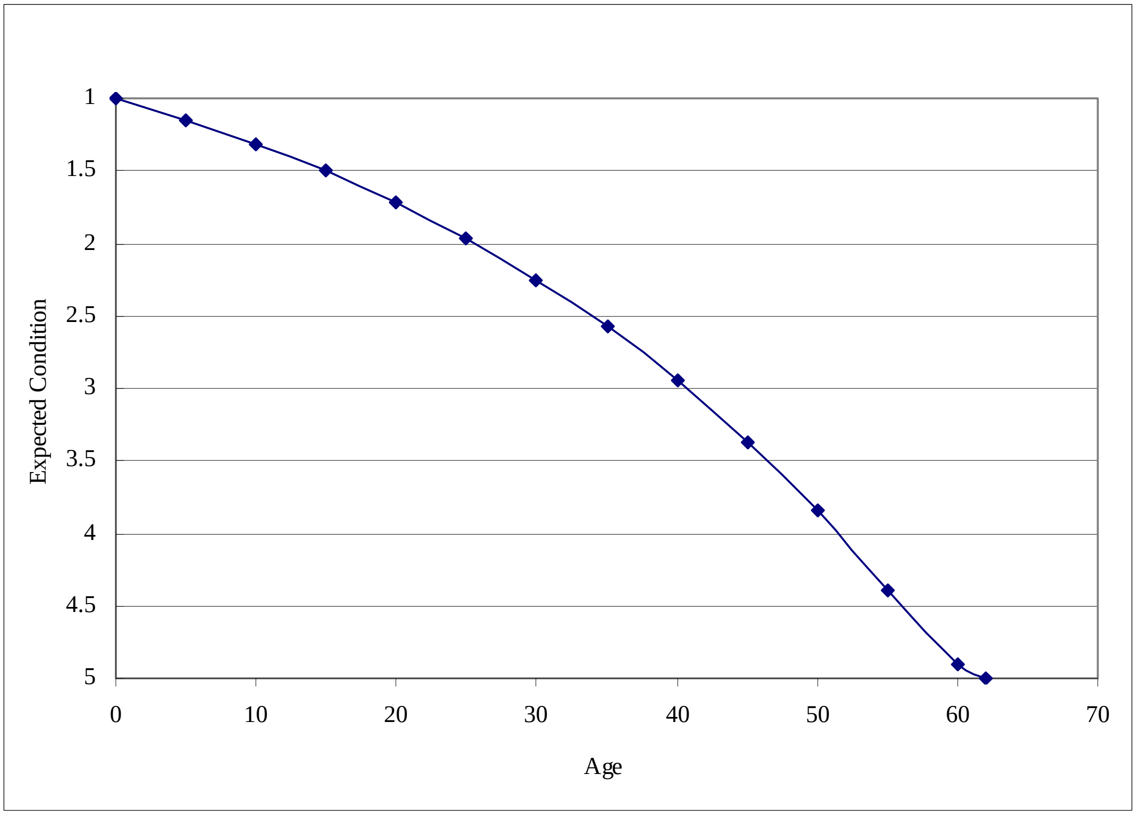

Figure A-4: Deterioration curve for 8-inch concrete pipe in South River_10

Table A-5: Transition probabilities for 8-inch vitrified clay pipe in South River_10

Description	8-inch vitrified clay in SRV10					
Regression	Condition = exp (0.069 + 0.0316 Age) R-Sq = 68.9% R-Sq(adj) = 67.8%					
Period	Zone	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
0-5	1	0.9653	0.9407	0.8337	0.9829	1
6-10	2	0.9831	0.8360	0.8440	0.9477	1
11-15	3	0.9684	0.8834	0.9018	0.9238	1
16-20	4	0.9610	0.8895	0.9052	0.9321	1
21-25	5	0.9514	0.8798	0.9005	0.9329	1
26-30	6	0.9337	0.8701	0.8922	0.9231	1
31-35	7	0.9097	0.8502	0.8667	0.9067	1
36-40	8	0.8663	0.8061	0.8198	0.8793	1
41-45	9	0.7525	0.6931	0.7252	0.8129	1
46-50	10	0.2987	0.2976	0.3829	0.5500	1
51-55	11	0	0	0	0	1

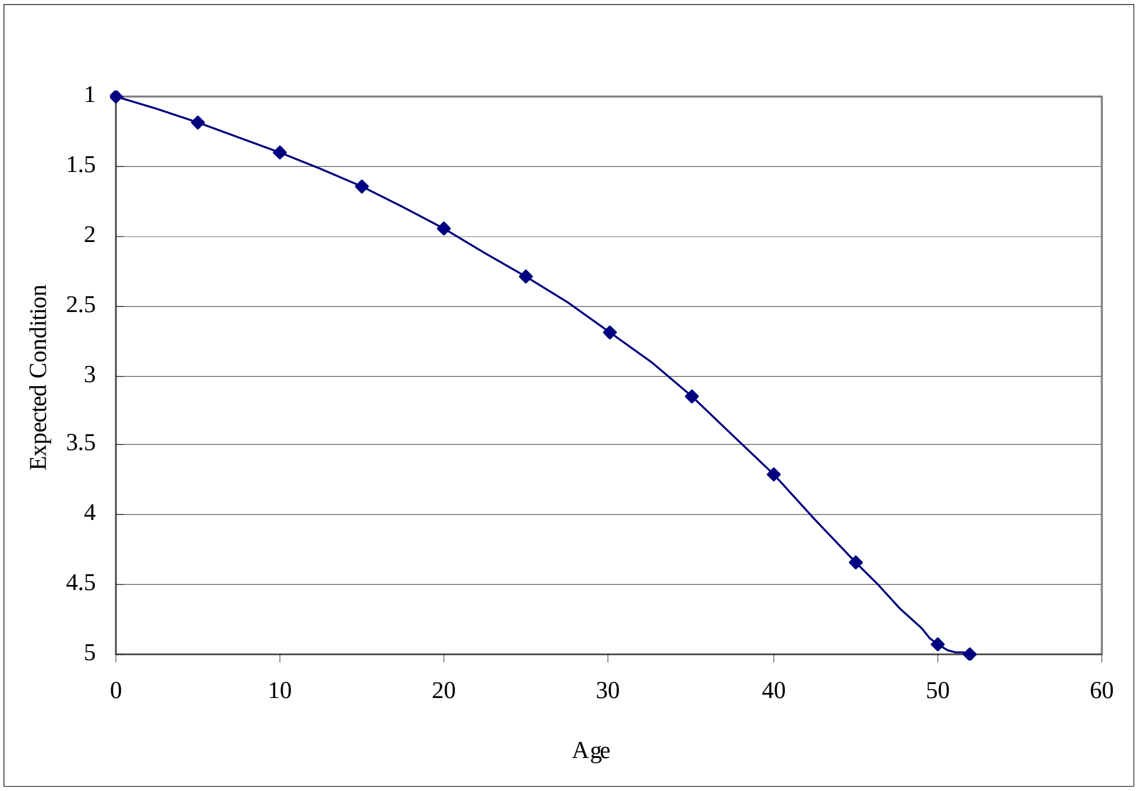

Figure A-5: Deterioration curve for 8-inch vitrified clay pipe in South River_10

Table A-6: Transition probabilities for 30-inch concrete pipe in South River_10

Description	30-inch concrete in SRV10					
Regression	Condition = exp (0.0472 + 0.0278 Age) R-Sq = 77.6% R-Sq(adj) = 76.9%					
Period	Zone	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
0-5	1	0.9703	0.9398	0.9681	0.9993	1
6-10	2	0.9723	0.9318	0.8988	0.9911	1
11-15	3	0.9799	0.9140	0.8974	0.8248	1
16-20	4	0.9754	0.9177	0.8930	0.8750	1
21-25	5	0.9659	0.9097	0.9013	0.9164	1
26-30	6	0.9555	0.9001	0.9019	0.9259	1
31-35	7	0.9397	0.8851	0.8980	0.9289	1
36-40	8	0.9210	0.8657	0.8833	0.9141	1
41-45	9	0.8870	0.8356	0.8486	0.8951	1
46-50	10	0.8163	0.7657	0.8760	0.8531	1
51-55	11	0.6221	0.5774	0.6219	0.7352	1
56-60	12	0	0	0	0	1

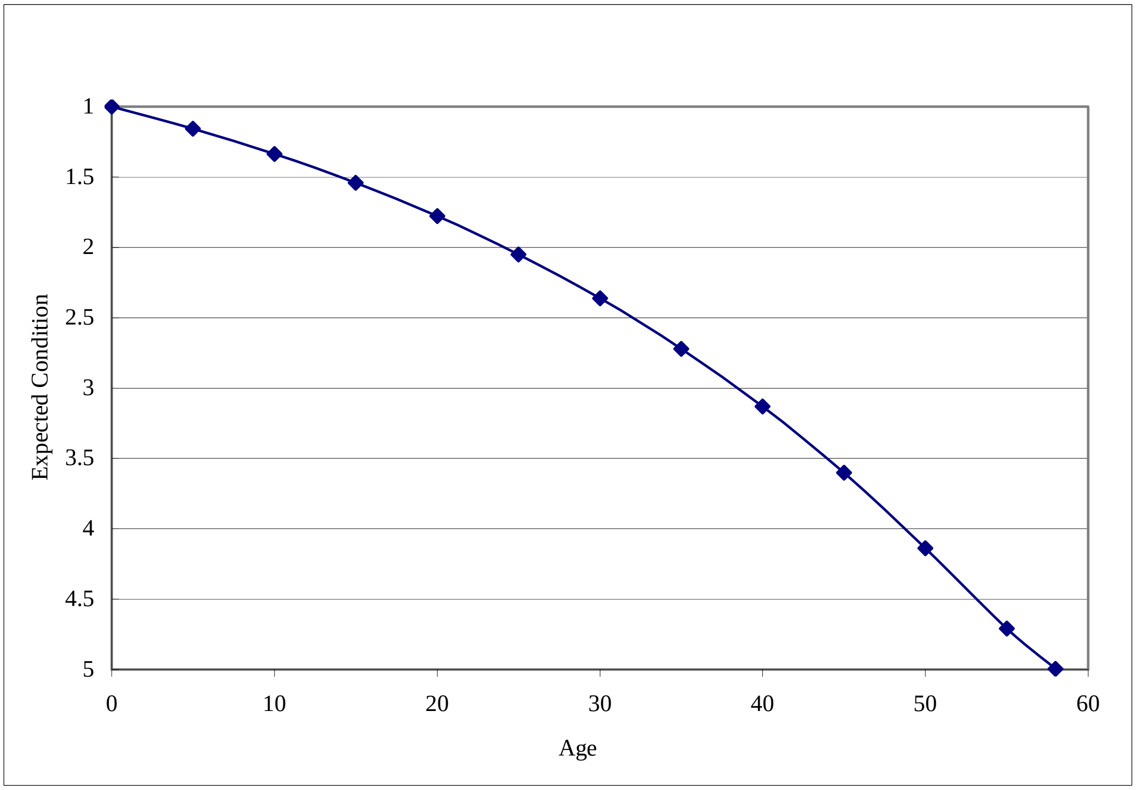

Figure A-6: Deterioration curve for 30-inch concrete pipe in South River_10

Table A-7: Transition probabilities for 8-inch concrete pipe in South River_13

Description	8-inch concrete in SRV13					
Regression	Concrete = exp (0.272 + 0.0232 Age) R-Sq = 53.1% R-Sq(adj) = 51.9%					
Period	Zone	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
0-5	1	0.9689	0.9474	0.9354	0.9991	1
6-10	2	0.9724	0.9255	0.9352	0.9595	1
11-15	3	0.9795	0.9043	0.9247	0.8530	1
16-20	4	0.9781	0.9235	0.9005	0.8484	1
21-25	5	0.9679	0.9134	0.9110	0.9168	1
26-30	6	0.9587	0.9074	0.9114	0.9309	1
31-35	7	0.9481	0.8994	0.9055	0.9316	1
36-40	8	0.9330	0.8853	0.8936	0.9262	1
41-45	9	0.9102	0.8638	0.8736	0.9139	1
46-50	10	0.8764	0.8041	0.8435	0.8941	1
51-55	11	0.7809	0.7264	0.7669	0.8373	1
56-60	12	0.5047	0.4680	0.5451	0.6754	1
61-65	13	0	0	0	0	1

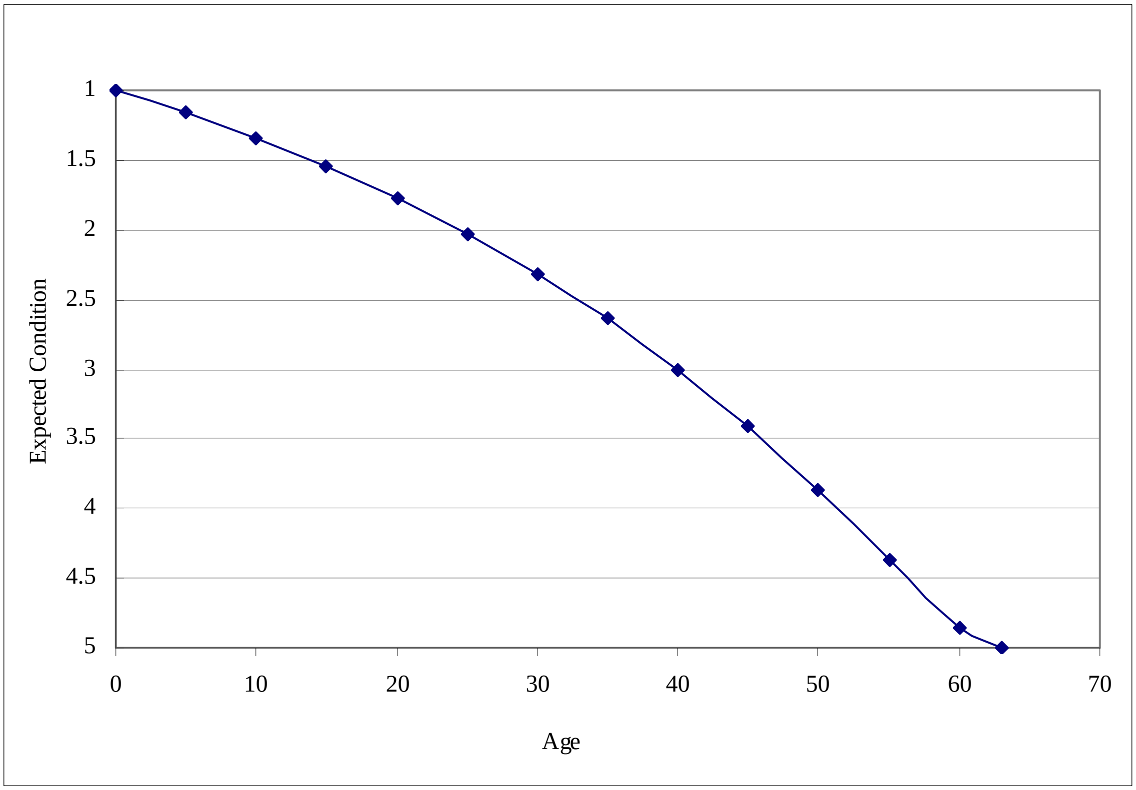

Figure A-7: Deterioration curve for 8-inch concrete pipe in South River_13

Table A-8: Transition probabilities for 8-inch vitrified clay pipe in South River_13

Description	8-inch vitrified clay in SRV13					
Regression	Condition = exp (0.482 + 0.0196 Age) R-Sq = 39.6% R-Sq(adj) = 38.7%					
Period	Zone	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
0-5	1	0.9680	0.9473	0.9423	0.9971	1
6-10	2	0.9679	0.9513	0.8884	0.9877	1
11-15	3	0.9805	0.9124	0.9070	0.9089	1
16-20	4	0.9768	0.9290	0.9007	0.8891	1
21-25	5	0.9698	0.9222	0.9100	0.9262	1
26-30	6	0.9619	0.9164	0.9135	0.9379	1
31-35	7	0.9526	0.9069	0.9139	0.9390	1
36-40	8	0.9403	0.8982	0.9045	0.9341	1
41-45	9	0.9237	0.8818	0.8891	0.9260	1
46-50	10	0.8933	0.8534	0.8673	0.9108	1
51-55	11	0.8415	0.8098	0.8191	0.8791	1
56-60	12	0.7240	0.6807	0.7135	0.7977	1
61-65	13	0.0602	0.0929	0.2415	0.4338	1
66-70	14	0	0	0	0	1

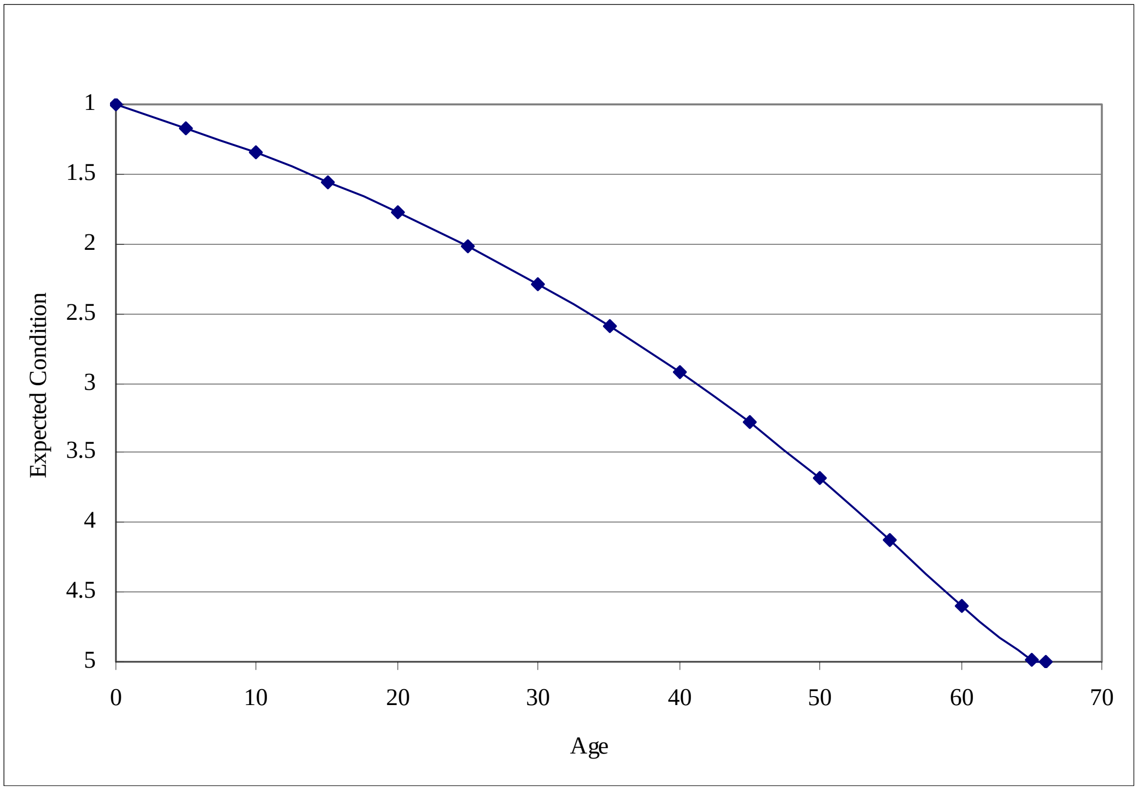

Figure A-8: Deterioration curve for 8-inch vitrified clay pipe in South River_13

Table A-9: Transition probabilities for 8-inch concrete in Nancy Creek_2c

Description	8-inch concrete in Nancy_2C					
Regression	Condition = exp (0.123 + 0.0195 Age) R-Sq = 59.0% R-Sq(adj) = 56.9%					
Period	Zone	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
0-5	1	0.9771	0.9735	0.6584	0.9486	1
6-10	2	0.9770	0.9658	0.9141	0.7979	1
11-15	3	0.9883	0.9188	0.8848	0.9767	1
16-20	4	0.9797	0.9458	0.9295	0.9299	1
21-25	5	0.9820	0.9399	0.9170	0.9283	1
26-30	6	0.9769	0.9365	0.9259	0.9465	1
31-35	7	0.9717	0.9324	0.9297	0.9534	1
36-40	8	0.9661	0.9283	0.9291	0.9539	1
41-45	9	0.9591	0.9222	0.9257	0.9519	1
46-50	10	0.9499	0.9138	0.9193	0.9470	1
51-55	11	0.9373	0.9017	0.9085	0.9400	1
56-60	12	0.9189	0.8832	0.8920	0.9289	1
61-65	13	0.8885	0.8527	0.8633	0.9103	1
66-70	14	0.8300	0.7925	0.8115	0.8749	1
71-75	15	0.6746	0.6339	0.6720	0.7757	1
76-80	16	0	0	0	0	1

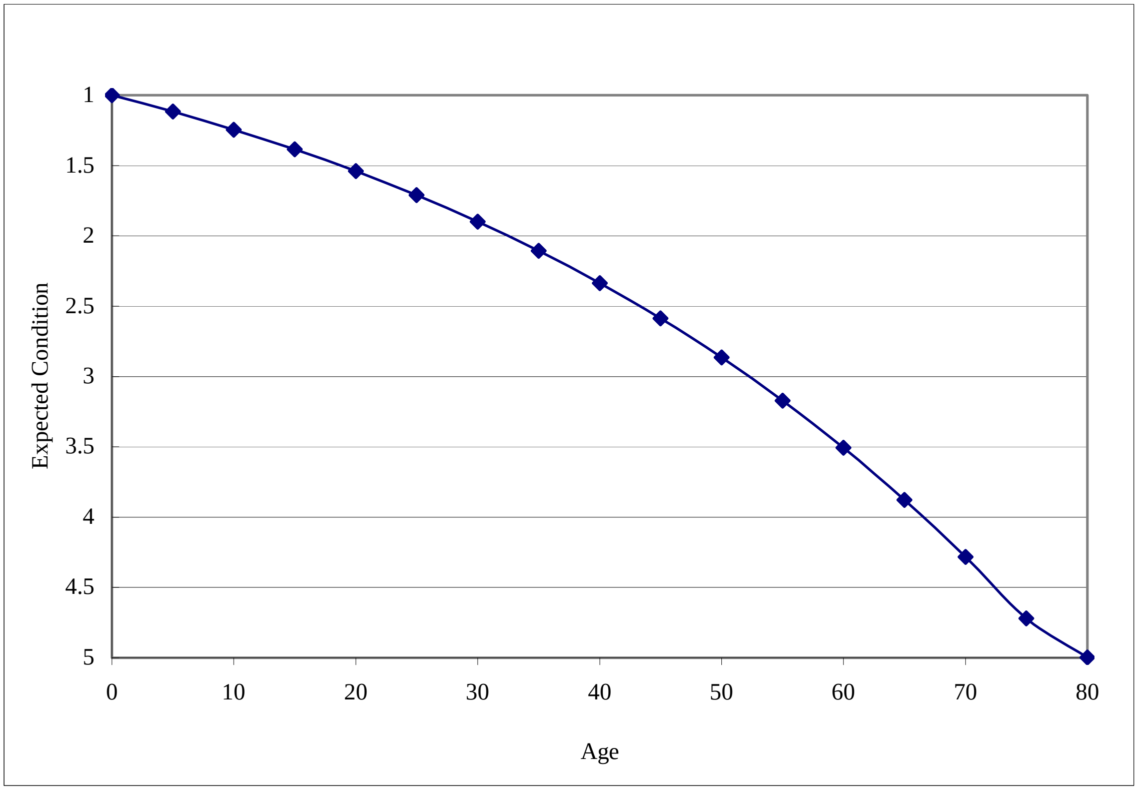

Figure A-9: Deterioration curve for 8-inch concrete in Nancy Creek_2c

Table A-10: Transition probabilities for 8-inch concrete pipe in Peach Tree Creek

Description	8-inch concrete in Peach Tree Creek					
Regression	Condition = exp (0.104 + 0.0173 Age) R-Sq = 51.1% R-Sq(adj) = 50.6%					
Period	Zone	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
0-5	1	0.9803	0.9721	0.8942	0.9991	1
6-10	2	0.9801	0.9654	0.9467	0.9960	1
11-15	3	0.9846	0.9434	0.9351	0.9956	1
16-20	4	0.9854	0.9521	0.9152	0.9362	1
21-25	5	0.9865	0.9478	0.9163	0.9271	1
26-30	6	0.9822	0.9453	0.9305	0.9521	1
31-35	7	0.9785	0.9426	0.9366	0.9579	1
36-40	8	0.9748	0.9396	0.9394	0.9615	1
41-45	9	0.9703	0.9363	0.9393	0.9593	1
46-50	10	0.9655	0.9325	0.9358	0.9568	1
51-55	11	0.9572	0.9246	0.9319	0.9597	1
56-60	12	0.9495	0.9181	0.9245	0.9508	1
61-65	13	0.9381	0.9064	0.9141	0.9441	1
66-70	14	0.9201	0.8877	0.8973	0.9338	1
71-75	15	0.8997	0.8596	0.8743	0.9130	1
76-80	16	0.8386	0.8032	0.8255	0.8837	1
81-85	17	0.6928	0.6649	0.7116	0.8053	1
86-90	18	0.0489	0.1180	0.2639	0.4604	1

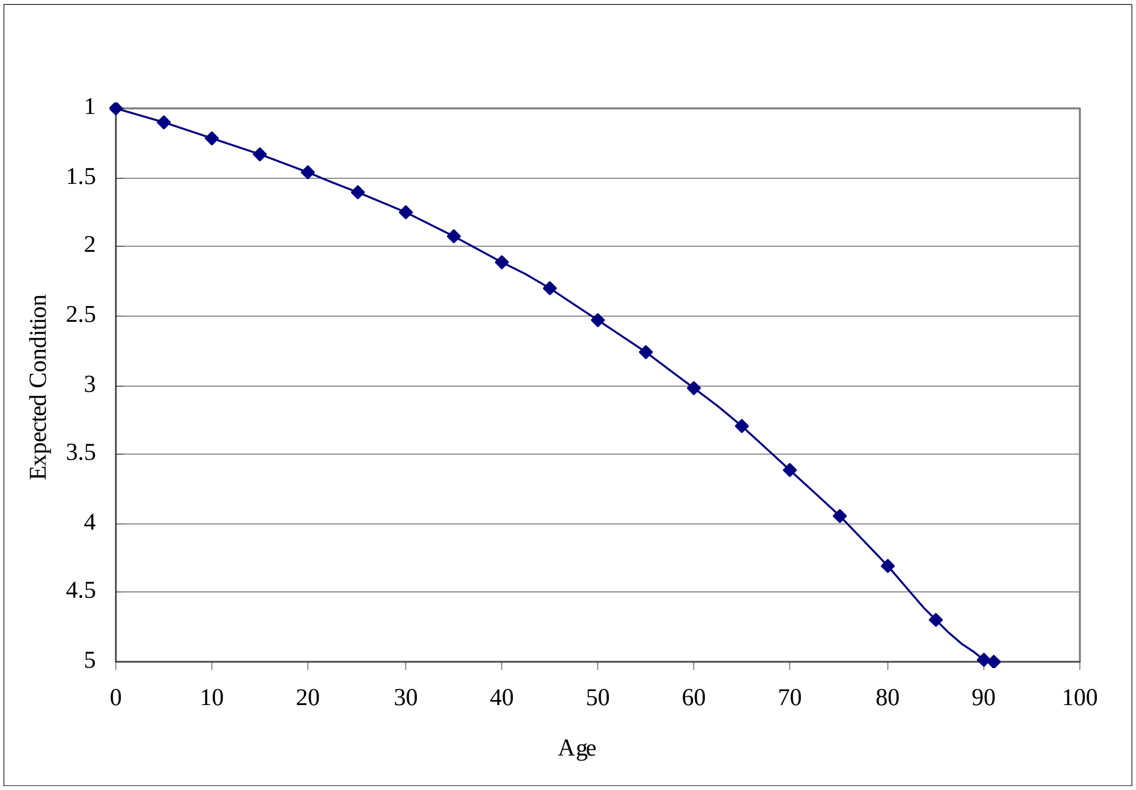

Figure A-10: Deterioration curve for 8-inch concrete pipe in Peach Tree Creek

Appendix B
Internal Sewer Condition Assessment (City of Atlanta)

Table B-1: Internal sewer condition assessment

CODE	DEFINITION	CONDITION	APPLICATION
ABS	Abandon Service	1	Service
AD	Area Drain	4	Structural
B	Pipe Broken	4	Structural
BCO	Broken Cleanout	3	Structural
CBX	Catch Basin	5	Structural
CC	Crack Circumferential	2	Structural
CL	Crack Longitudinal	2	Structural
CM	Cracks Multiple	3	Structural
CNI	Connection Intruding	4	Structural
DB	Brick Displaced	3	Structural
DEP	Defective Plumbing in Bldg	1	Service
DES	Deposit Silt	2	Service
DE	Deposit	2	Service
DH	Deformation Horizontal	4	Structural
DI	Dropped Invert	4	Structural
DEG	Deposit Grease	2	Service
EH	Encrustation Heavy	4	Service
EL	Encrustation Light	2	Service
EM	Encrustation Medium	3	Service
DV	Deformation Vertical	4	Structural
DWD	Driveway Drain	4	Structural

Table B-1: Internal sewer condition assessment (continued)

CODE	DEFINITION	CONDITION	APPLICATION
CX	Connection Defective	4	Structural
EXP	Exposed Pipe	3	Structural
FC	Fracture Circumferential	3	Structural
FCL	Frame/Cover Leaks	3	Structural
FDD	Foundation Drain	3	Structural
FL	Fracture Longitudinal	3	Structural
FM	Fractures Multiple	4	Structural
BJ	Sewer Broken at Joint	4	Structural
H	Hole	4	Structural
HOL	Soil Fissures	3	Structural
HSD	Hole in Storm Ditch	4	Structural
JDL	Joint Displaced Large	2	Structural
JDM	Joint Displaced Medium	1	Structural
OJL	Open Joint Large	2	Structural
OJM	Open Joint Medium	1	Structural
ESH	Scale Heavy	4	Service
ESL	Scale Light	1	Service
ESM	Scale Medium	3	Service
MM	Missing Mortar Medium	2	Structural
MS	Missing Mortar Surface	1	Structural
MB	Brick Missing	4	Structural
MCC	Missing Cleanout Cover	2	Service
MFC	Manhole Frame/Cover	3	Structural
MHS	Manhole Structure	3	Structural
MLK	Multiple Soil Fissures	3	Structural
OB	Obstruction	2	Service

Table B-1: Internal sewer condition assessment (continued)

CODE	DEFINITION	CONDITION	APPLICATION
MT	Missing Mortar Total	3	Structural
RF	Fine Roots	1	Service
RM	Mass Roots	3	Service
RT	Tap Root	3	Service
RLD	Roof Leader Connected	4	Structural
SC	Sewer Shape Change	1	Miscellaneous
SGL	Surface Damage Corrosion Large	4	Structural
SGM	Surface Damage Corrosion Medium	3	Structural
SW	Surface Damage Wear	4	Structural
CXI	Connection Defective Intruding	4	Structural
SMH	Storm Manhole	4	Structural
SS	Surface Spalling	3	Service
SWD	Stairwell Drain	2	Structural
V	Vermin – Rats	1	Service
WWD	Window well Drain	2	Structural
D	Deformed	4	Structural
X	Collapsed	5	Structural
BC	MH Cover Cracked or Broken	5	Structural
BF	MH Frame Cracked or Broken	5	Structural
HI	MH Below Grade	1	Service
LO	MH Above Grade	1	Service
Z	Multiple	3	Structural
CCJ	Crack Circumferential at Joint	2	Structural
CLJ	Crack Longitudinal at Joint	2	Structural
CMJ	Crack Multiple at Joint	3	Structural
CN	Connection	1	Miscellaneous

Table B-1: Internal sewer condition assessment (continued)

CODE	DEFINITION	CONDITION	APPLICATION
CNA	Connection Abandoned	1	Miscellaneous
CU	Camera Underwater	1	Miscellaneous
DC	Dimension Change	1	Miscellaneous
DEJ	Debris at Joint	2	Service
EHJ	Encrustation Heavy at Joint	4	Service
ELJ	Encrustation Light at Joint	2	Service
EMJ	Encrustation Medium at Joint	3	Service
FCJ	Fracture Circumferential at Joint	3	Structural
FH	Finish Survey	1	Miscellaneous
FLJ	Fracture Longitudinal at Joint	3	Structural
FMJ	Fracture Multiple at Joint	4	Structural
GO	General Observation	1	Miscellaneous
GOA	General Observation Abandon	1	Miscellaneous
ID	Infiltration Dripper	2	Service
IDJ	Infiltration Dripper at Joint	2	Service
IG	Infiltration Gusher	4	Service
IR	Infiltration Runner	3	Service
IRJ	Infiltration Runner at Joint	3	Service
IS	Infiltration Seeper	2	Service
ISJ	Infiltration Seeper at Joint	3	Service
JDS	Joint Displaced Slight	2	Structural
JN	Junction	1	Miscellaneous
JNA	Junction Abandoned	1	Miscellaneous
JX	Junction Defective	4	Structural
LC	Liner Changes	1	Miscellaneous
LD	Line Deviates Down	1	Miscellaneous

Table B-1: Internal sewer condition assessment (continued)

CODE	DEFINITION	CONDITION	APPLICATION
LL	Line Deviates Left	1	Miscellaneous
LN	Liner Defect	1	Structural
LR	Line Deviates Right	1	Miscellaneous
LU	Line Deviates Up	1	Miscellaneous
MC	Material Change	1	Miscellaneous
MH	Manhole	1	Miscellaneous
OJS	Open Joint Slight	1	Structural
RFJ	Roots Fine at Joint	1	Service
RMJ	Roots Medium at Joint	3	Service
RTJ	Roots Tap at Joint	3	Service
SA	Survey Abandoned	1	Miscellaneous
SSL	Surface Damage Spalling Large	4	Structural
SSM	Surface Damage Spalling Medium	3	Structural
SSS	Surface Damage Spalling Slight	2	Service
ST	Start Survey	1	Miscellaneous
SWL	Surface Wear Large	4	Structural
SWM	Surface Wear Medium	3	Structural
SWS	Surface Wear Slight	2	Structural
WL	Water Level	1	Miscellaneous
XM	Collapsed Manhole	5	Structural

Appendix C

Prediction of Construction Cost Index by Regression Method

In this study, construction cost index from ENR (Table C-1) is used for the estimation of future price index. As shown in the Figure C-1, and the result of Minitab analysis, the simple linear regression method shows a great fit for the given data set.

```
     Regression Analysis: PI versus Year

The regression equation is

Cost index = - 310133 + 158 Age


Predictor     Coef  SE Coef       T      P

Constant   -310133     5824  -53.25  0.000

Age        158.227    2.932   53.97  0.000


S = 167.709   R-Sq = 98.9%   R-Sq(adj) = 98.9%


Analysis of Variance


Source          DF        SS        MS        F      P

Regression       1  81929805  81929805  2912.92  0.000

Residual Error  32    900044     28126

Total           33  82829849
```

```
Unusual Observations


Obs   Age  Cost index     Fit  SE Fit  Residual  St Resid

 13  1982      3825.0  3473.2    31.6     351.8     2.14R

 14  1983      4066.0  3631.5    30.5     434.5     2.64R

 15  1984      4146.0  3789.7    29.7     356.3     2.16R


R denotes an observation with a large standardized residual.
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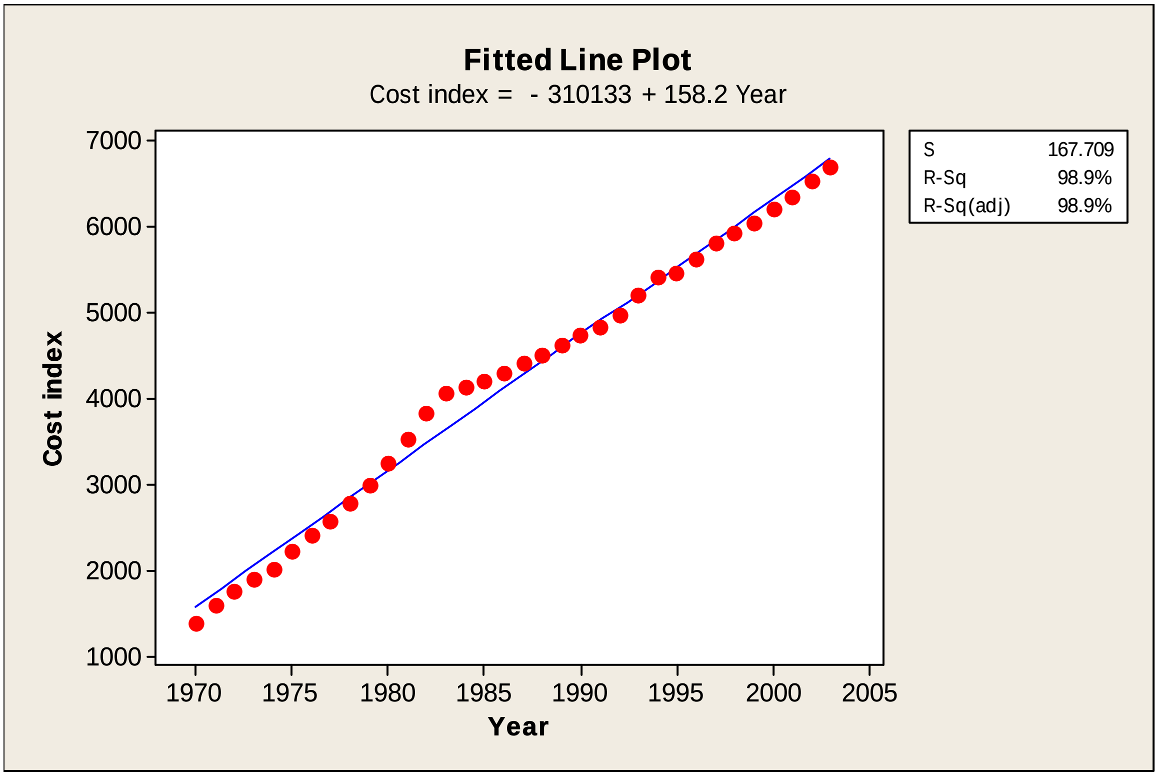

Figure C-1: Regression analysis for construction cost index

Table C-1: Construction cost index (ENR 2005)

Year	Cost Index	Year	Cost Index	Year	Cost Index
1913	100	1944	299	1975	2212
1914	89	1945	308	1976	2401
1915	93	1946	346	1977	2576
1916	130	1947	413	1978	2776
1917	181	1948	461	1979	3003
1918	189	1949	477	1980	3237
1919	198	1950	510	1981	3535
1920	251	1951	543	1982	3825
1921	202	1952	569	1983	4066
1922	174	1953	600	1984	4146
1923	214	1954	628	1985	4195
1924	215	1955	660	1986	4295
1925	207	1956	692	1987	4406
1926	208	1957	724	1988	4519
1927	206	1958	759	1989	4615
1928	207	1959	797	1990	4732
1929	207	1960	824	1991	4835
1930	203	1961	847	1992	4985
1931	181	1962	872	1993	5210
1932	157	1963	901	1994	5408
1933	170	1964	936	1995	5471
1934	198	1965	971	1996	5620
1935	196	1966	1019	1997	5826
1936	206	1967	1074	1998	5920
1937	235	1968	1155	1999	6059
1938	236	1969	1269	2000	6221
1939	236	1970	1381	2001	6343
1940	242	1971	1581	2002	6538
1941	258	1972	1753	2003	6694
1942	276	1973	1895	2004	7115
1943	290	1974	2020	2005	7446

Appendix D

Results of Dynamic Programming

Table D-1: Life cycle cost analysis for 8-inch cast iron pipe line

i	Last Stage											$V^{14}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	0	10										0	1
2	0	10	18.8	25.8	35.2							0	1
3			18.8	25.8	35.2	26.3	32.6	49.9				18.8	3
4						26.3	32.6	49.9	78.1	64.9	128.7	26.3	6
5									78.1	64.9	128.7	64.9	10
i	$V^{13}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{14}(j)\}$											$V^{13}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	0	10										0	1
2	12.80	22.80	18.8	25.8	35.2							12.80	1
3			19.69	26.69	36.09	26.3	32.6	49.9				19.69	3
4						27.19	33.49	50.79	78.1	64.9	128.7	27.19	6
5									78.1	64.9	128.7	64.9	10
i	$V^{12}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{13}(j)\}$											$V^{12}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	3.23	13.23										3.23	1
2	27.61	37.61	19.14	26.14	35.54							19.14	3
3			32.81	39.81	49.21	26.64	32.94	50.24				26.64	6
4						40.31	46.61	63.91	78.1	64.9	128.7	40.31	6
5									78.1	64.9	128.7	64.9	10
i	$V^{11}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{12}(j)\}$											$V^{11}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	8.8	18.8										8.8	1
2	48.12	58.12	22.81	29.81	39.21							22.81	3
3			52.31	59.31	68.71	30.31	36.61	53.91				30.31	6
4						59.81	66.11	83.41	81.33	68.13	131.93	59.81	6
5									81.33	68.13	131.93	68.13	10

Table D-1: Life cycle cost analysis for 8-inch cast iron pipe line (continued)

i	$V^{10}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{11}(j)\}$											$V^{10}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	18.98	28.98										18.98	1
2	71.97	81.97	31.98	38.98	48.38							31.98	3
3			75.47	82.47	91.87	39.48	45.78	63.08				39.48	6
4						82.97	89.27	106.57	90.13	76.93	140.73	76.93	10
5									90.13	76.93	140.73	76.93	10
i	$V^{9}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{10}(j)\}$											$V^{9}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	38.9	48.9										38.9	1
2	104.8	114.8	51.3	58.3	67.7							51.3	3
3			107.8	114.8	124.2	58.8	65.1	82.4				58.8	6
4						115.3	121.6	138.9	109.1	95.9	159.7	95.9	10
5									109.1	95.9	159.7	95.9	10
i	$V^{8}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{9}(j)\}$											$V^{8}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	78.5	88.5										78.5	1
2	156.9	166.9	90.6	97.6	107.0							90.6	3
3			159.5	166.5	175.9	98.1	104.4	121.7				98.1	6
4						167.0	173.3	190.6	148.0	134.8	198.6	134.8	10
5									148.0	134.8	198.6	66.59	10
i	$V^{7}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{8}(j)\}$											$V^{7}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	157.6	167.6										157.6	1
2	248.1	258.1	169.4	176.4	185.8							169.4	3
3			250.4	257.4	266.8	176.9	183.2	200.5				176.9	6
4						257.9	264.2	281.5	226.6	213.4	277.2	213.4	10
5									226.6	213.4	277.2	213.4	10

Table D-1: Life cycle cost analysis for 8-inch cast iron pipe line (continued)

i	$V^{6}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{7}(j)\}$											$V^{6}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	315.7	325.7										315.7	1
2	418.1	428.1	327.4	334.4	343.8							327.4	3
3			420.2	427.2	436.6	334.9	341.2	358.5				334.9	6
4						427.7	434	451.3	384.2	371.0	434.8	371.0	10
5									384.2	371.0	434.8	64.9	10
i	$V^{5}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{6}(j)\}$											$V^{5}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	631.7	641.7										631.7	1
2	746.1	756.1	643.4	650.4	659.8							643.4	3
3			749.9	754.9	764.3	650.9	657.2	674.5				650.9	6
4						755.4	761.7	779.0	699.9	686.7	750.5	686.7	10
5									699.9	686.7	750.5	686.7	10
i	$V^{4}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{5}(j)\}$											$V^{4}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	1264	1274										1264	1
2	1390	1400	1275	1282	1292							1275	3
3			1392	1399	1408	1283	1289	1307				1283	6
4						1399	1406	1423	1332	1318	1382	1318	10
5									1332	1318	1382	114.2	10
i	$V^{3}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{4}(j)\}$											$V^{3}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	2528	2538										2528	1
2	2666	2676	2539	2546	2556							2539	3
3			2667	2674	2684	2547	2553	2571				2547	6
4						2675	2681	2699	2595	2582	2646	2582	10
5									2595	2582	2646	166.7	10

Table D-1: Life cycle cost analysis for 8-inch cast iron pipe line (continued)

i	$V^2(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^3(j)\}$											$V^2(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	5056	5066										5056	1
2	5206	5216	5067	8074	5084							5067	3
3			5207	5214	5224	5075	5081	5099				5075	6
4						5215	5221	5238	5123	5110	5174	5110	10
5									5123	5110	5174	5110	10
i	$V^1(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^2(j)\}$											$V^1(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	10111	10121										10111	1
2	10274	10284	10123	10130	10140							10123	3
3			10275	10282	10291	10131	10137	10154				10131	6
4						10283	10289	10306	10179	10165	10229	10165	10
5									10179	10165	10229	10165	10
i	$V^0(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^1(j)\}$											$V^0(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	20223	20233										20223	1
2	20397	20407	20235	20242	20251							20235	3
3			20397	20406	20415	20242	20249	20266				20242	6
4						20406	20412	20430	20290	20277	20341	20277	10
5									20290	20277	20341	907	10

Table D-2: Life cycle cost analysis for 8-inch vitrified clay pipe line (SRV10)

i	Last Stage											$V^{11}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	0	10										0	1
2	0	10	18.8	25.8	35.2							0	1
3			18.8	25.8	35.2	26.3	32.6	49.9				18.8	3
4						26.3	32.6	49.9	78.1	64.9	128.7	26.3	6
5									78.1	64.9	128.7	64.9	10
i	$V^{10}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{11}(j)\}$											$V^{10}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	0	10										0	1
2	18.8	28.8	18.8	25.8	35.2							18.8	3
3			19.91	26.91	36.31	26.30	32.60	49.9				19.91	3
4						27.41	33.71	51.01	78.1	64.9	128.7	27.41	6
5									78.1	64.9	128.7	64.9	10
i	$V^{9}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{10}(j)\}$											$V^{9}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	13.18	23.18										13.18	1
2	38.38	48.38	19.45	26.45	35.85							19.45	3
3			38.78	45.78	55.18	26.95	33.25	50.55				26.95	6
4						46.28	52.58	69.88	78.1	64.9	128.7	46.28	6
5									78.1	64.9	128.7	64.9	10
i	$V^{8}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{9}(j)\}$											$V^{8}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	27.92	37.92										27.92	1
2	60.14	70.14	32.85	39.85	49.25							32.85	3
3			58.68	65.68	75.08	40.35	46.65	63.95				40.35	6
4						66.18	72.48	89.78	91.28	78.08	141.88	66.18	6
5									91.28	78.08	141.88	78.08	10

Table D-2: Life cycle cost analysis for 8-inch vitrified clay pipe line (continued)

i	$V^{7}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{8}(j)\}$											$V^{6}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	57	67										57	1
2	95	104	61	68	77							61	3
3			92	99	108	68	75	92				68	6
4						99	106	123	119	106	170	99	6
5									119	106	170	106	10
i	$V^{6}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{7}(j)\}$											$V^{6}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	113	123										113	1
2	157	167	118	125	134							118	3
3			153	160	170	125	131	149				125	6
4						161	167	184	176	163	226	161	6
5									176	163	226	163	10
i	$V^{5}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{6}(j)\}$											$V^{5}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	227	237										227	1
2	275	285	231	238	248							231	3
3			271	278	288	239	245	262				239	6
4						279	285	303	289	276	340	276	10
5									289	276	340	276	10
i	$V^{4}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{5}(j)\}$											$V^{4}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	454	464										454	1
2	507	517	458	465	475							458	3
3			503	510	519	466	472	489				466	6
4						511	517	534	516	503	567	503	10
5									516	503	567	503	10

Table D-2: Life cycle cost analysis for 8-inch vitrified clay pipe line (continued)

i	$V^3(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^4(j)\}$											$V^3(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	909	919										909	1
2	966	976	913	920	929							913	3
3			962	969	978	920	927	944				920	6
4						970	976	993	971	957	1021	957	10
5									971	957	1021	957	10
i	$V^2(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^3(j)\}$											$V^2(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	1818	1828										1818	1
2	1880	1890	1822	1829	1838							1822	3
3			1875	1882	1892	1829	1836	1853				1829	6
4						1883	1889	1906	1879	1866	1930	1866	10
5									1879	1866	1930	1866	10
i	$V^1(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^2(j)\}$											$V^1(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	3636	3646										3636	1
2	3703	3713	3640	3647	3656							3640	3
3			3698	3705	3714	3647	3654	3671				3647	6
4						3705	3711	3729	3697	3684	3748	3684	10
5									3697	3684	3748	3684	10
i	$V^0(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^1(j)\}$											$V^0(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	7272	7282										7272	1
2	7344	7354	7276	7283	7292							7276	3
3			7338	7345	7354	7283	7290	7307				7283	6
4						7345	7352	7369	7333	7320	7384	7320	10
5									7333	7320	7384	7320	10

Table D-3: Life cycle cost analysis for 8-inch concrete pipe line (SRV08a)

i	Last Stage											$V^{12}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	0	10										0	1
2	0	10	18.8	25.8	35.2							0	1
3			18.8	25.8	35.2	26.3	32.6	49.9				18.8	3
4						26.3	32.6	49.9	78.1	64.9	128.7	26.3	6
5									78.1	64.9	128.7	64.9	10
i	$V^{11}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{12}(j)\}$											$V^{11}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	0	10										0	1
2	18.8	28.8	18.8	25.8	35.2							18.8	1
3			19.76	26.76	36.16	26.30	32.60	49.90				19.76	3
4						27.26	33.56	50.86	78.1	64.9	128.7	27.26	6
5									78.1	64.9	128.7	64.9	10
i	$V^{10}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{11}(j)\}$											$V^{10}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	7.2	17.2										7.2	1
2	38.0	48.0	19.4	26.4	35.8							19.4	3
3			38.6	45.6	55.0	26.9	33.2	50.5				26.9	6
4						46.1	52.4	69.7	78.1	64.9	128.7	46.1	6
5									78.1	64.9	128.7	64.9	10
i	$V^{9}(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^{10}(j)\}$											$V^{9}(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	16.7	26.7										16.7	1
2	59.1	69.1	26.9	33.9	43.3							26.9	3
3			58.4	65.4	76.8	34.4	40.7	58.0				34.4	6
4						65.9	72.2	89.5	85.3	72.1	135.9	65.9	6
5									85.3	72.1	135.9	72.1	10

Table D-3: Life cycle cost analysis for 8-inch concrete pipe line (continued)

i	$V^8(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^9(j)\}$											$V^8(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	34.6	44.6										34.6	1
2	87.3	97.3	43.9	50.9	60.3							43.9	3
3			85.7	92.7	102.1	51.4	57.7	75.0				51.4	6
4						93.2	99.5	116.8	102	88.8	152.6	88.8	10
5									102	88.8	152.6	88.8	10

i	$V^7(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^8(j)\}$											$V^7(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	69.9	79.9										69.9	1
2	132.2	142.2	78.8	85.8	95.2							78.8	3
3			130	137	146	86.3	92.6	109.9				86.3	6
4						137.5	143.8	161.1	136.6	123.3	187.2	123.3	10
5									136.6	123.3	187.2	123.3	10

i	$V^6(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^7(j)\}$											$V^6(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	140.3	150.3										140.3	1
2	211.8	221.8	148.9	155.9	165.3							148.9	3
3			209.2	216.2	225.6	156.4	162.7	180				156.4	6
4						213.7	223	240.3	206.4	193.2	257.0	193.2	10
5									206.4	193.2	257.0	193.2	10

i	$V^5(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^6(j)\}$											$V^5(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	281	291										281	1
2	361.5	371.5	289.5	296.5	305.9							289.5	3
3			358.5	365.5	374.7	297	303.3	320.6				297	6
4						366	372.3	389.6	346.7	335.5	397.3	335.5	10
5									346.7	335.5	397.3	335.5	10

Table D-3: Life cycle cost analysis for 8-inch concrete pipe line (continued)

i	$V^4(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^5(j)\}$											$V^4(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	562	572										562	1
2	652	662	571	578	587							571	3
3			648	655	665	578	584	602				578	6
4						656	662	680	628	615	678	615	10
5									628	615	678	77.6	10
i	$V^3(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^4(j)\}$											$V^3(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	1125	1135										1125	1
2	1223	1233	1133	1140	1150							1133	3
3			1220	1227	1236	1141	1147	1164				1141	6
4						1227	1233	1251	1190	1177	1241	1177	10
5									1190	1177	1241	1177	10
i	$V^2(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^3(j)\}$											$V^2(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	2250	2260										2250	1
2	2357	2367	2258	2265	2275							2258	3
3			2353	2360	2370	2266	2272	2289				2266	6
4						2361	2367	2384	2315	2301	2365	2301	10
5									2315	2301	2365	2301	10
i	$V^1(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^2(j)\}$											$V^1(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	4499	4509										4499	1
2	4615	4625	4508	4515	4524							4508	3
3			4612	4619	4628	4515	4522	4539				4515	6
4						4619	4625	4643	4564	4551	4615	4551	10
5									4564	4551	4615	4551	10

Table D-3: Life cycle cost analysis for 8-inch concrete pipe line (continued)

i	$V^0(i) = Min\{g(i,k) + \alpha \sum_{j=1}^{5} p_{ij}^{(k)} V^1(j)\}$											$V^0(j)$	$k*$
	1	2	3	4	5	6	7	8	9	10	11		
1	8999	9009										8999	1
2	9123	9133	9008	9015	9024							9008	3
3			9120	9127	9136	9015	9021	9039				9015	6
4						9127	9134	9151	9063	9050	9114	9050	10
5									9063	9050	9114	9050	10

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