University of Alberta

Infrastructure Intermediate-Level Modelling and Optimization of Budget Allocation

By

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ABSTRACT

Aging infrastructure and a lack of available funding for maintenance and rehabilitation represent the greatest challenge for managing infrastructure within an acceptable level of performance. The main objective of this research is to provide a framework for optimizing budget allocation in scenarios with both constrained and unconstrained budgets. This research also proposes a new infrastructure modelling level which combines the network-level budget allocation concept and the project-level deterioration and rehabilitation strategies.

The proposed infrastructure intermediate-level satisfies both the strategic level, by providing an overall budget requirement based on the budgeting scenario, and the project level through the provision of a practical set of proposed projects. With this framework in place, the anticipated results on the network level would be achievable as there is no disconnect between the two levels.

The proposed framework could be used in two budget scenarios therefore, accordingly, the budget allocation objective is slightly different. In the first scenario, dealing with a constrained budget, the optimization objective is to maximize the resulting infrastructure performance levels. In the second scenario, dealing with an unconstrained budget, the optimization objective is to minimize the required budget to achieve the minimum acceptable performance levels.

The proposed model can be used and utilized in managing two types of assets: existing assets and new assets. The model manages existing assets by evaluating the required budget and associated rehabilitation actions (what, where and when). New assets are managed through building a sustainable funding strategy essential to the future management of said assets, without a heavy impact on the financial capability of the organization.

The concept of developing a set of infrastructure best practice guidelines is tested and explored within this research. The concept is researched for different types of assets, showing good potential for being able to produce some

guidelines for new assets. Depending on the asset deterioration and rehabilitation actions cost ratio, these guidelines could be used to answer the questions of which rehabilitation strategy should be employed by suggesting the ratio between the rehabilitation strategies, when they would be required, and how much of the assets value they would constitute.

This Thesis is dedicated with love and respect to my father, mother and my beloved family

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1.1 Background and Problem Statement

Aging infrastructures coupled with a deficit in the available rehabilitation and maintenance budget have been identified as major challenges that need immediate attention and remedy. A report assessing Canada's infrastructure needs, published in 2004, found that the increase in Canada's infrastructure budget required to get the infrastructure to an acceptable range is between $44 and $125 billion. The total present value of Canada's infrastructure has been estimated to be in the range of $3 to $5 trillion (Mirza 2003). This situation of aging and insufficient budget will only lead to an increase in required spending in the future.

A generic asset management system summarizes the components of any assets management system, including the establishment of goals and policies, assets inventory, condition assessment and performance modelling, budget allocation and alternatives evaluation, program implementation, and performance monitoring.

A solution to these infrastructure needs is to secure the required fund for maintenance and rehabilitation; however, this is not feasible because of the large amount of required funding. The only feasible advancement would be the proper distribution of the available budget in order to get the highest benefit and value from the spent money. The following sections will be devoted to discussing the following: 1) background, 2) proposed methodology, 3) research objectives, and 4) expected contribution.

Researchers and agencies have put in tremendous amounts of effort and time trying to understand, model, and establish rehabilitation policies for infrastructure. In looking into recent publications, one can find an adaptive optimization model for infrastructure management that was presented by Durango (2002) to develop maintenance and repair polices for modelling uncertainty and repair policies without modelling deterioration. This research relies on certain assumptions, such as the deterioration process of each facility within a network being a random variable. In 1999, Wirahadikusumah developed a decision-making framework for a large combined sewer. In this study, Markov chains are used to represent the system's deterioration and are integrated with prioritization criteria to obtain the optimal spending policy. Additionally, the uncertainty of the rehabilitation cost (based on life-cycle cost) was represented by simulating the selected optimal policy. Sanford (1997) focused on the infrastructure condition assessment to develop a model for representing data-related decisions for managing bridges. The objective of this study was to maximize the information gathered while minimizing data collection, cost, and resources. By conducting a multivariate analysis, Sheri (2002) was able to study the factors (e.g., political, citizen contact, racial, class, line-type, or location) affecting the prioritization of rehabilitation projects. Sadek et al. (2003) presented an integrated infrastructure management system for managing six transportation system components, using Solver for the optimization and GIS as a visual interface.

McKay et al. (1999) presented a method for evaluating the condition assessment of civil work with an end to establishing a consistent condition assessment procedure. Garaibeh et al. (1999) presented an integrated system of infrastructure management that includes the following: 1) investment trade-offs (network-level integration); 2) coordinating the implementation of highway infrastructure improvement projects (project-level integration); 3) a comprehensive evaluation of highway infrastructure performance (multiple concerns and performance measures); and 4) a single-system architecture software that ties data together with engineering, economic, and spatial analysis procedures.

Infrastructure deterioration modelling techniques can be divided into three main categories: 1) deterministic models; 2) stochastic models; and 3) artificial intelligence models. Deterministic modelling involves regression models.

Stochastic models are based on the Markovian processes and simulation models. Artificial intelligence models were presented using neural networks and case-based reasoning (Morcous et al. 2002).

Genetic Algorithms (GA) have helped to optimize many processes conducted regularly in the construction industry, such as the cost-time trade-off optimization, construction site layout optimization, design optimization, resource allocation and levelling, and schedule optimization. The cost-time trade-off problems arose from the fact that each project could have potentially hundreds of activities and each activity could be accomplished in several different ways with many combinations of crew size and equipment. Feng et al. (2000) and Hegazy (1999a) were able to present a solution to this problem using GA. The difficulties in site layout planning are another problem that has been solved using GA. The arrangement of a construction site should satisfy the site layout constraints and minimize the total traveling distance of site personnel and equipment. Li and Love (1998) and Hegazy and Elbeltagi (1999) used GA to solve this problem.

GA are also used in structural design; Rafiq and Southcombe (1998) used GA to optimize the design and to detail the reinforced concrete biaxial columns. Rajeev and Krishnamoorthy (1998) used GA to optimize the design of reinforced concrete frames. Resource allocation attempts to reschedule project tasks in order to utilize more efficiently the limited number of resources available, while minimizing the extension of the project schedule. Major contracting firms usually ensure that different types of labor, capable of performing several different construction activities, are kept available. Hegazy (1999b) worked with a GA model that addresses resource allocation and levelling simultaneously. Al-Tabtabai and Alex (1997) developed a GA model that deals with manpower scheduling optimization.

Budget allocation can be characterized as a multi-faceted problem in which the solution set for each element is limited but is quite large for the total system. The optimum solution, or near-optimum solution, is a combination of the sub-element solutions.

1.2 Research Objectives

Based on the discussion above, the general objective of this research is to develop tools that will facilitate a decision making process that ensures reliable and optimum decision regarding the allocation of resources to serve a specified purpose. This research has the following objectives:

1. Conduct a comparable study for the different infrastructure modelling levels.
2. Develop an optimal decision support system for budget allocation which will satisfy two main objectives: 1) maximizing the infrastructure performance index by distributing a limited budget; and 2) minimizing the total cost required to maintain the infrastructure at a specified condition index.
3. Establish best-practice guidelines for infrastructure rehabilitation and maintenance.

1.3 Proposed Methodology

This research begins with a literature review. The literature review covers research-related areas including infrastructure management systems (and within that the component of budget allocation and assessing the infrastructure needs),, various methodologies and techniques used in optimizing the infrastructure budget allocation, and also the use and implementation of GA.

The next step is the development of the intermediate-level framework which starts by introducing network and project level. The development of a decision support system for budget allocation that employs the intermediate-level framework will be explored for both constrained and unconstrained budget allocations.

The proposed methodology will be verified by comparing the results of the proposed model with a sample model from the literature. For the optimization component, convergence will be tested. The use of the model in both existing and new assets will be presented as a case study and implementation of the model.

The development of the infrastructure management best-practice guidelines concept will be introduced by solving the model of the new asset with variable rehabilitation and reconstruction cost ratio. This will include introducing the best-practice ratio between rehabilitation and reconstruction, and the required needs, as a percentage of the asset value.

1.4 Thesis Organization

This thesis is organized as follows: Chapter 2 provides a general overview of the existing infrastructure management system in terms of modelling and hierarchy, assets attributes, condition assessment, deterioration modelling, rehabilitation and replacement, and budget allocation techniques and methods. Chapter 3 will focus on the infrastructure rehabilitation and budget allocation component by introducing the different levels of allocation and work that has been done in that area.

Chapter 4 will be devoted to the introduction of GA, by highlighting various applications in which GA has been used as well as the implementation of GA in optimization. Chapter 5 will present the proposed infrastructure intermediate-level modelling and the optimization of budget allocation at that level. Also, the mathematical modelling of the optimization will be presented.

Chapter 6 will present the implementation of GA in optimizing the infrastructure budget allocation within an intermediate-level modelling framework. This chapter will include the system assumptions and problem inputs, an overview of the proposed infrastructure management system, and the implementation of GA (including chromosome encoding, genetic algorithm operators including fitness evaluation, crossover and mutation). The model validation will be presented by solving a problem from the literature presenting the state-of-the-art and comparing the results. An assessment of the model convergence by the Pareto-front surface and Rank-Histogram will be given and discussed.

Chapter 7 will demonstrate the application of the proposed model in two types of assets, existing assets and new assets. In addition to this, a concept for developing applicable best-practice guidelines for infrastructure maintenance and rehabilitation investment for new assets will be presented.

Chapter 8 presents the research findings, conclusions, contributions and recommendations for future research.

2. Infrastructure Management Systems: Infrastructure Modelling

2.1 Introduction

The purpose of this chapter is to review the existing infrastructure management systems in terms of modelling and hierarchy, assets attributes, condition assessment, deterioration modelling, rehabilitation and replacement, and budget allocation techniques and methods. The main objective is to present the point of departure between the state-of-the-art and this research in modelling the infrastructure and solving the budget allocation problem.

There are two main streams in modelling infrastructure: the first is the project level or the "bottom-up approach," in which each element in the hierarchy at the bottom level is assumed to be one project and has different rehabilitation actions, and the second is the network level or the "top-down approach," in which all the assets that share the same condition are assumed to be one element. Each of those approaches has its own advantages and disadvantages, which will be discussed later in this chapter. This research interposes an intermediate level between the two levels by utilizing a project level approach in the modelling deterioration and, a network level approach for budget allocation.

It is vital to underscore the objectives and components for infrastructure management systems. In general, those systems attempt to facilitate a proactive rather than reactive mode of infrastructure management. Also, they provide valuable information for decision makers in a timely fashion regarding the expected infrastructure condition, distribution, and expected required expenditure. Infrastructure management systems include the following components (FHWA 1999): 1) establishment of goals and policies; 2) assets inventory; 3) condition assessment and performance modelling; 4) budget allocation and alternatives evaluation; 5) program implementation; and 6) performance monitoring and feedback. Those components are shown in Figure 2-1.

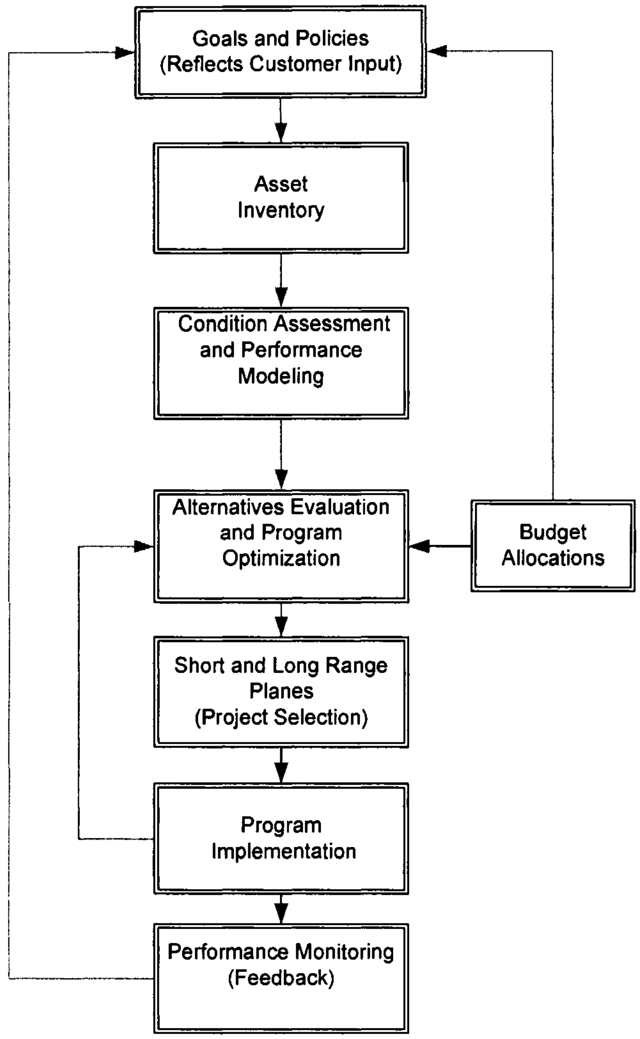


Figure 2-1 A generic asset management system (Adopted from FHWA 1999)

The following sections will focus on the definition of infrastructure and assets, infrastructure performance, deterioration modelling, infrastructure rehabilitation, infrastructure modelling, and infrastructure management systems.

2.2 What is Infrastructure & Asset?

If we search for the meaning of "asset" in the dictionary, we will find the following definitions:

- A useful and desirable thing or quality: *Organizational ability is an asset.*
- A single item of ownership having exchange value.
- Items of ownership convertible into cash; total resources of a person or business, as cash, notes and accounts receivable, securities, inventories, goodwill, fixtures, machinery, or real estate (opposed to liabilities).
- *Accounting.* The items detailed on a balance sheet, esp. in relation to liabilities and capital.
- All property available for the payment of debts, esp. of a bankrupt or insolvent firm or person.
- *Law.* Property in the hands of an heir, executor, or administrator, that is sufficient to pay the debts or legacies of a deceased person.

"Infrastructure" as a collection of those assets, can be defined as:

- An underlying base or foundation especially for an organization or system. Or
- The basic facilities, services, and installations needed for the functioning of a community or society, such as transportation and communications systems, water and power lines, and public institutions including schools, post offices, and prisons.

The City of Edmonton infrastructure strategy (2002) defined "Infrastructure" as: "*The physical assets developed and used by a municipality to support the community social and economical activities.*" City of Edmonton Assets is grouped into twelve classes as shown in Table 2-1.

The City of Huntington Beach, California defined infrastructure as: "*Capital assets owned by the city that require on-going maintenance and eventual replacement. It is the basic support structure for the community, which includes* *highways, streets, alleys, parking lots, bridges, sidewalks, curbs, parkway trees, landscaped median islands and parkway, block wall along arterial highways, traffic signals, street lights, flood control channels, storm drains and storm water pump stations, sewers, sewer manholes, sewer lift stations, public buildings, beach facilities, parks, sport fields, and the vehicles and equipment used for the operation , maintenance, and repair of infrastructure.*"

Table 2-1 City of Edmonton Assets (City of Edmonton 2004)

Class	Description
Drainage	Includes sanitary, storm and combined sewer, manholes, catchbasins, and wastewater treatment.
Road Right-of-way	Includes roads (arterials, collectors, local; and curb and gutter), sidewalks, bridges and auxiliary structures (such as gates, streetscapes, and others)
Parklands	Includes horticulture, trails, hardsurfaces, playgrounds, sportfiled, park infrastructure and parks.
Transit facilities and equipments	Includes Light Rail Transit (LRT) system facilities and equipment (including cars), transit centers, bus equipment and systems, trolley system.
Fleet	Including transit buses, city vehicles and shop equipment.
Buildings	Includes civic offices, public work and operation facilities (e.g. yards), emergency response buildings, police buildings and libraries.
Traffic control and street lighting	Includes traffic signals, signs, markings, street lighting and parking meters.
Recreation facilities	Includes major recreational facilities (e.g. arenas, leisure centers, Fort Edmonton) and amenities.
Affordable housing	Includes non-profit housing, community housing and senior lodges/cabins.
Waste management facilities	Includes operation and administration facilities, transfer stations and public facilities, processing facilities and operation landfills and appurtenances.
Technology equipments	Includes servers, network, all communication equipment.
Others	Includes emergency response and police equipment, and library content and material

Assets can be divided into two categories: 1) linear assets; and 2) composite assets. Linear assets such as road and drainage are distinguished by being independent from one segment or element to the other. For example the failure of 1km of road does not mean the failure of any other elements in the system. On the contrary, in the case of composite assets, the failure of one element might cause the failure of the whole system. An example might include a bridge or building, in which the failure of either one's foundation would cause the system failure. The present research will only focus on the independent assets.

Previous attempts at formulating a comprehensive infrastructure taxonomy were discussed (Casey 2003). Based on a review of other researchers in this field, infrastructure can be divided into:

1. Basic inter-urban infrastructure
2. Basic urban infrastructure
3. High-Tech infrastructure
4. Amenities
5. Knowledge-Based infrastructure
6. Health infrastructure

The objective of infrastructure classification and taxonomy is to facilitate the collection and classification of infrastructure information and inventory. This is the first step in the infrastructure management system, which helps the organization to establish the limits of what constitutes an identified asset of the organization, including the specific attributes of ownership and responsibility for rehabilitation and eventually replacement. After collecting the infrastructure information, the next step is to assess the infrastructure's current performance.

2.3 Infrastructure Performance

The measurement and description of asset performance depends on the assets's type and its organizational structure. In the literature some refer to it as Condition Index (C.I.) or Condition Rating, and in the pavement management (Haas 1997) system they refer to it as Pavement Quality Index (PQI), which is a combined index of other indices. We can define the asset performance in general as a qualitative measure of infrastructure integrity (AL-Battaienh et al. 2005).

The following is an illustration of the calculation of infrastructure performance and the methodology adopted in this research

2.3.1 Pavement Quality Index (PQI) in Alberta

PQI depends on roughness, deflection, and surface distress measurements; the evaluation of PQI is done by applying Equation 2-1.

$$PQI = 1.1607 + (0.596 * RCI * SDI) + (0.5264 * RCI * \log_{10} SAI) \quad \text{Equation 2-1}$$

Where:

$0 \leq PQI \leq 10$

RCI = Riding Comfort Index

SDI = Surface Distress Index

SAI = Structural Adequacy Index

The PQI is evaluated for each section, and for the network level a weighted average based on length would be used.

2.3.2 U.S. Army Crops (Condition Index Evaluation)

The combined condition index (McKay et al. 1999) is evaluated for each component based on the share of different distress, the authors presented an example of how to evaluate the condition index for steel sheet pile and lock miter gate inland navigation structures. Equation 2-2 is used to evaluate the combined condition index.

$$CI_{Combined} = \sum_{Distresses}(W_i)(CI_i) \qquad \text{Equation 2-2}$$

Where:

$0 \le CI_{Combined} \le 100$

W_i = The relative importance for Distress i

CI_i = Condition Index for Distress i

The first step of this procedure is to evaluate the distress condition index. The distress and its weights are found in a list. To evaluate CI_i, Equation 2-3 is used.

$$CI_i = 100(0.4)^{X_i / X_{i\max}} \qquad \text{Equation 2-3}$$

Where:

$0 \le X_i \le 100$

X_i = Distress measurement

$X_{i\max}$ = Distress limiting value

After evaluating the combined condition index, Table 2-2 is used to provide the expert definition associated with each condition index level, as well as the recommended rehabilitation strategy to be followed. This strategy is based on expert opinion and assume unlimited budget is available.

Table 2-2 Condition Index Scale

Condition Index	Condition Description	Recommendation
85 to 100	Excellent: No noticeable defects, Some aging or wear may be visible	Immediate action is not required
70 to 84	Good: Only minor deterioration or defects are evident	
55 to 69	Fair: Some deterioration or defects are evident, but function is not significantly affected	Economic analysis of repair alternative is recommended to determine appropriate action
40 to 54	Marginal: Moderate deterioration. Function is still adequate	
25 to 39	Poor: Serious deterioration in at least some portion of the structure. Function is adequate	Detailed evaluation is required to determine the need for repair, rehabilitation, or reconstruction, Safety revaluation is recommended
10 to 24	Very Poor: Extensive deterioration Barely functional	
0 to 9	Failed: No longer functions. General failure or complete failure of a major structural component	

2.3.3 City of San Diego's Wastewater Department

The Condition Rating is evaluated by computing the score using the assigned maintenance and structural points from the inspection. Next, by assigning the appropriate Condition Rating from Table 2-3, the score is evaluated using Equation 2-4:

$$Score = \frac{\sum SP \times SW + \sum MP \times MW}{LS} \qquad \text{Equation 2-4}$$

Where

SP= Structural points

SW= Structural weight

MP= Maintenance points

MW= Maintenance weight

LS= Length of segment

In this methodology, grade A and B are in the same range. The difference between the grades represents the existence of major defects. If there is at least one major defect, then the grade is B, and if there is no major defect then the grade is A. This grading system assumes A being the best condition and E, the worst.

Table 2-3 Score Range for Grades (Condition Rating)

Condition Rating	Grade	Score Range
1	A	0-2.5
2	B	0-2.5
3	C	2.5-4.0
4	D	4.0-6.0
5	E	Above 6.0

The standard defect list includes 108 criteria. This list indicating defect code, observation, description, and both maintenance and structural points.

2.3.4 City of Edmonton (Office of Infrastructure)

The Condition Index is inspected and assigned the appropriate physical condition using the information in Table 2-4.

Table 2-4 Description of assessment of physical condition

Mark	State	Explanation of condition
A	Very good	Element is structurally sound and is functional as intended when it was designed. Maintenance and operations costs are well within standards and norms. Element is new or recently undergone major rehabilitation. Its condition and function are practically equal to a new
B	Good	Element is structurally sound and is functional as intended when it was designed. Maintenance and operations costs are within acceptable levels but increasing with time. Typically such infrastructure would have reached its mid-life span or is functioning as if it has.
C	Fair	Element is showing signs of aging, small portions can be structurally deficient or the element is becoming functionally obsolete. Such an element is approaching the stage where expenditures beyond the original planned maintenance is being incurred to keep it useable.
D	Poor	Element is approaching a poor condition contributing. Signs of structural deficiency are becoming more pronounced and obvious. The element's physical condition may be contributing to safety hazards or negatively impacting safety, health, environment, or other areas.
F	Inadequate	Element is structurally unsound and/or is not functional anymore. It would be a matter of time for it to completely fail.

2.4 Deterioration modelling

Deterioration is a natural attribute of any asset, and is highly correlated to time. Specifically, it means that the asset's measurable conditions are getting worse with time, such as strength, appearance, or cost of maintenance. Modelling deterioration is an essential part for any asset management system to predict the asset's as well as its transition behaviour from one state (condition) to the other over time. Many researchers worked on deterioration modelling for different types of assets trying to improve and come to more accurate predictions, Morcous et al. (2002) categorized the methodologies used in deterioration modelling into three categories (see Figure 2-2).

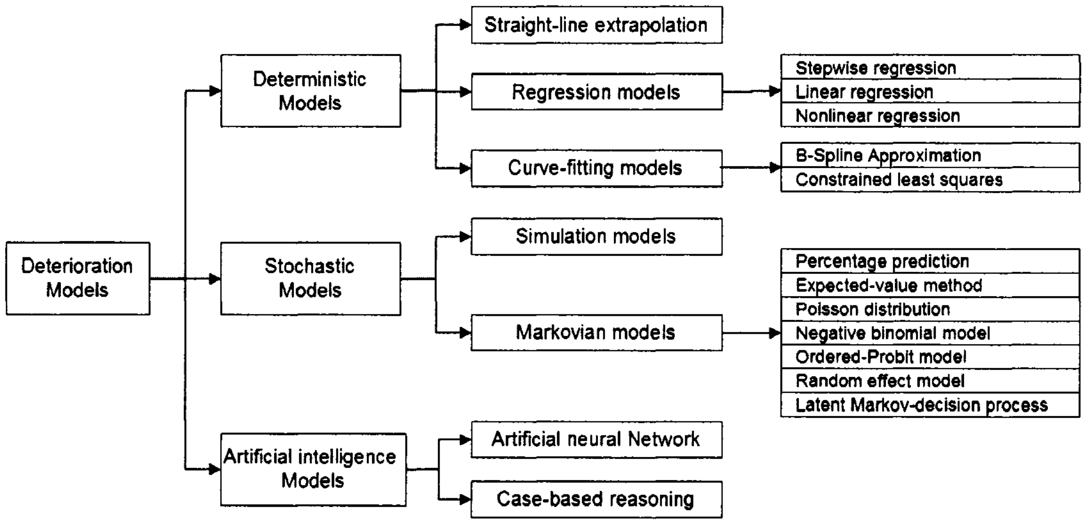


Figure 2-2 Deterioration Modelling Techniques

Deterministic modelling describes the relationship between the factor affecting facility deterioration (e.g., bridge age) and the facility condition using a mathematical or statistical formulation.

Stochastic models deal with the deterioration process as one or more random variables that capture the uncertainty and randomness of this process. Markovian models represent the most common stochastic technique.

Artificial intelligence models explore the application of artificial neural networks (Sobanjo 1997) and case-based reasoning.

Deterministic modelling is very efficient when analyzing a network with a large population. Morcous et al. (2002) list the following disadvantages:

1. The neglect of factors of uncertainty due to the inherent stochasticity of infrastructure deterioration;
2. They predict the average condition of a family of facilities regardless of the current condition and the condition history of individual facility;
3. The estimated facility deterioration only includes the "no maintenance" strategy;
4. They disregard the interaction between the facility's various components in the case of composite assets such as "bridge"; and
5. They are difficult to update when new data becomes available.

The last point in my opinion, is not accurate, since if a new information is acquired then the model could be re-created and incorporated in the system. The same disadvantages were justified in the case of using Markovian modelling. Black et al. (2005) presents a comparison study between the Markov model, the semi-Markov model and the delay-time model. The semi-Markov model extends the Markov model by allowing the distribution of survival time in a specified state.

Pavement deterioration prediction models and techniques were classified by Mahoney (1990), and mentioned by Haas et al. (1994). This classification is based on an earlier work done by Lytton (1987). The classification divides the models into deterministic and probabilistic, and indicates the system level in which the models were used, as shown in Table 2-5.

Table 2-5 Classification of Deterioration Models (Mahoney 1990)

	Deterministic Models				Probabilistic Models		
Levels of Pavement Management	Primary Response Deflection Stress Strain etc.	Structural Distress Pavement Condition	Functional PSI Safety etc.	Damage Load equivalent	Survivor Curves	Transition Process Models Markov	Semi-Markov
National Network				√	√	√	√
State Network		√	√	√	√	√	√
District Network		√	√	√	√	√	√
Project	√	√	√	√			

Purba et al. (1997) presented fault-tree analysis to model the interaction between the various components of a bridge. The author of that paper noted that the methodology is not intended to model deterioration, but to improve the deterioration prediction of an element due to the dependency in the bridge. The disadvantages of this methodology are that it would require numerous estimations of failure probability values for different events. Those types of assumption would add uncertainty to the results.

Reini et al. (2001) used a Markov-chains-based model in conjunction with nonlinear optimization for sewer systems. The authors utilized data collected in Indianapolis in 1996 for a combined sewer. A total of sixteen categories were identified based on the variations in material, ground water table, backfill soil type, and depth of cover. Due to limited number of available data points the authors were able to get the information for only 4 groups. Using regression analysis between age and OSG (Overall Structural Grade) the deterioration curves were produced and confirmed by the City of Indianapolis, as shown in Equation 2-5. For (group 2) flexible construction material and no corrosive backfill and low ground water table and non-typical depth of cover the deterioration curve is exponential, the coefficient of multiple determination r^2 estimated at 0.2669, 0.7829, 0.4209 and 0.6012 for group 1, 2, 9, and 10. This is not a good indication of the regression quality and only group 2 was presented.

$$OSG = e^{0.0143t} \qquad \text{Equation 2-5}$$

To estimate the probability value in transition matrices, a nonlinear optimization technique was adopted to minimize the sum of absolute difference between the regression curve and the predicted condition for the corresponding age generated by the Markov chain model. The objective function of the nonlinear optimization is represented in Equation 2-6.

$$Minimize = \sum_{t=1}^{N} |Y(t) - E[y(t,P)]| \qquad \text{Equation 2-6}$$

Where

$N =$ Total number of transition periods or stages (one transition period corresponds to a five year period)

$Y(t) =$ Sewer condition at stage *t* on the regression curve

$E[Y(t,P)] =$ Expected value of the sewer condition at stage *t* as predicted by the Markov chain model

Hyeon-Shik et al. (2006) presented another methodology to estimate the transition probabilities using the ordered probit model along with an incremental model. This model requires information such as depth of installation, soil conditions, groundwater level, and the frequency of sewage overflow. That information is not available for most of the cases thereby limiting the application of this methodology. Madanat et al. (1995) presented the rigorous econometric method for the estimation of infrastructure deterioration models and associated transition probabilities from condition rating data. This method was applied using a bridge inspection data set from Indiana. Micevski et al. (2002) presented a Markov model for the structural deterioration of storm water pipes, that model was calibrated using a Bayesian technique, to structural condition data from the storm water asset database of the Newcastle City Council (Australia). The deterioration process was found to be driven by pipe diameter, construction material, soil type, and exposure classification.

Markov chain is a discreet-time stochastic process and a special case of the Markov process, where the condition in the future depends only on the current condition and has nothing to do with the past history (Hyeon-Shik et al. 2006). The Markovian property can be expressed as in Equation 2-7, for all states $i_0, i_1, \ldots, i_{t-1}, i_t, i_{t+1}$ and all $t \geq 0$:

$$P(X_{t+1} = i_{t+1} | X_t = i_t, X_{t-1} = i_{t-1}, \dots, X_1 = i_1, X_0 = i_0)$$
$$= P(X_{t+1} = i_{t+1} | X_t = i_t) \qquad \text{Equation 2-7}$$
$$= P(X_{t+1} = j | X_t = i_t) = p_{ij}$$

Where p_{ij} = transition probability that, given the system is in State i at time t, it will be in State j at time $(t+1)$

The transition probabilities are commonly expressed as an $m * m$ matrix called the transition probability matrix P shown in Equation 2-8 and 2-9.

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mm} \end{bmatrix} \qquad \text{Equation 2-8}$$

$$\sum_{j=1}^{m} p_{ij} = 1 \qquad \text{for } i = 1,2,\dots,m \qquad \text{Equation 2-9}$$

The State j after n transitions can be expressed (Winston 1994) as in Equation 2-10:

$$Q^{(n)} = Q^{(0)} P^{(n)} \qquad \text{Equation 2-10}$$

Where:

$$P^{(n)} = P^n$$

$$Q^{(0)} = [q_1 \quad q_2 \quad \dots \quad q_m]$$

q_i = Probability of being in Stats i at Time 0.

Deterioration is to stay in the current state or to transfer to worse condition state. For illustration purposes, assume that there are five states for a certain asset in which are broken down as follow: 1-Excellent, 2-Good, 2-Fair, 4-Poor, and 5-Very Poor. If this is the case, then the Markovian transition matrix will be as represented by Equation 2-11.

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ 0 & P_{22} & P_{23} & P_{24} & P_{25} \\ 0 & 0 & P_{33} & P_{34} & P_{35} \\ 0 & 0 & 0 & P_{44} & P_{45} \\ 0 & 0 & 0 & 0 & P_{55} \end{bmatrix} \qquad \text{Equation 2-11}$$

The transition schema is shown in Figure 2-3.

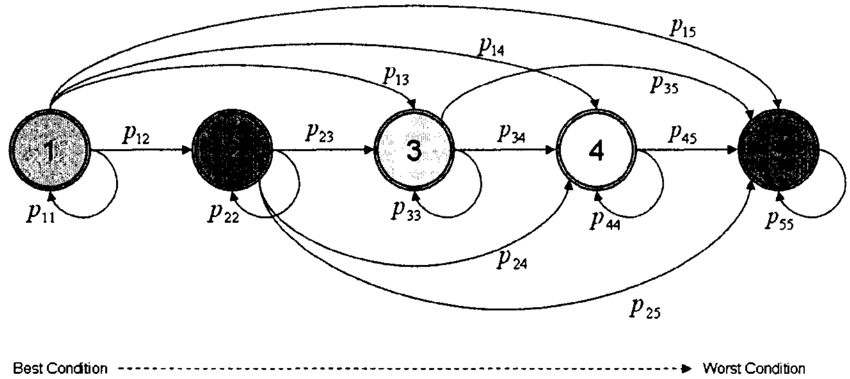


Figure 2-3 Assets Transition Schema

In this research, simulation was used to model deterioration. The process used is equivalent to the Markov chain process, in which a number of transition periods equal the asset life duration. The transition probability is 100% from one year to the following year, as shown in Figure 2-4.

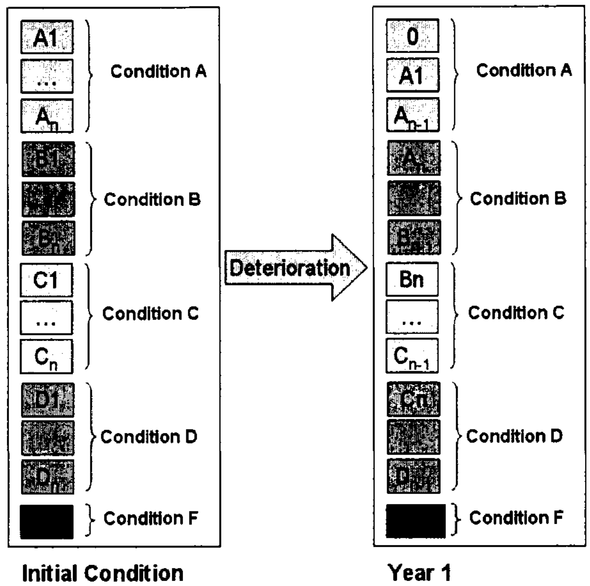


Figure 2-4 Modelling Deterioration Using Simulation

Assuming the asset lives a total of eight years, then the transition matrix will be as shown in Equation 2-12.

$$P = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \qquad \text{Equation 2-12}$$

2.5 Infrastructure Rehabilitation and Maintenance

Rehabilitation and maintenance have the same objective of extending the asset life span and maintaining a desirable level of service with different extent and associated cost and impact. Haas 1997 define pavement maintenance and rehabilitation as:

Maintenance: "Well timed and executed activities employed to extend pavement life, until deterioration of the pavement layers materials and subgrade is such that the minimum acceptable level of serviceability is reached".

Rehabilitation: "The application of appropriate measures including reconstruction, to extend the life of an existing pavement structure when roughness, lack of structural adequacy, or excessive surface distress results in unacceptable pavement".

Sewer rehabilitation is defined by ASCE 1994 as "upgrading the sewer structural and hydraulic aspects, Structural rehabilitation can include repair and renovation or renewal, while hydraulic rehabilitation can include replacement, reinforcement"

Successful rehabilitation strategy should be carried out on the right time and utilizing the appropriate methodology, each of those methods will have different cost and impact on the assets condition and performance (e.g. moving the asset from condition F to Condition A by replacement).

The following section will introduce different rehabilitation methods for both pavement (Haas 1997) and Sewer pipes (ASCE 1994); each of those methods is associated with cost and market availability as well as advantages and disadvantages.

2.5.1 Pavements Rehabilitation Methods

Pavement can be divided into three categories when considering rehabilitation methodology: 1) flexible pavement; 2) rigid pavement; and 3) surface treated pavement, Haas (1997) lists generic maintenance and rehabilitation methodologies and the expected gain in service life of the pavement. Those expected gains are uncertain due to the variable surrounding condition of the pavement which might lead to a shorter duration. Those actions are shown in Table 2-6 and 2-7.

Table 2-6 Flexible Pavement Rehabilitation Treatments and Expected Service Life

Type of Pavement	Methodology	Expected service life
Flexible Pavement	Reconstruction	up to 12 – 15
	Resurfacing (Thin Overlay)	up to 8 – 10
	Resurfacing (Thick Overlay)	up to 12 – 15
	Milling and Resurfacing	up to 10 – 12
	Hot In-Place Recycling	up to 10 – 12
	Cold In-Place Recycling	up to 10 – 12
	Full Depth Reclamation	up to 12 – 15
Rigid Pavement	Asphalt Concrete Surfacing	up to 12 – 15
	Diamond Grinding	up to 8 – 10
	Joint Stabilization	up to 5 – 10
	Crack, Seat and Resurfacing	up to 12 – 15
	Rubblizing and Resurfacing	up to 12 – 15
	Bonded Concrete Overlay	up to 15 – 20
	Unbonded Concrete Overlay	up to 25 – 30
Surface Treated Pavement	Surface Treatment Reapplication	up to 2 – 5
	Pulverization or Scarification and Resurfacing	up to 8 – 10

Table 2-7 Rigid Pavement Maintenance Treatments and Expected Service Life

Type of Pavement	Methodology	Expected service life
Flexible Pavement	Crack Sealing	up to 5 - 7
	Pothole Repair	up to 1 - 2
	Spray Patching	up to 2 - 3
	Shallow Patching	up to 3 - 5
	Drainage Improvement	up to 7 - 10
	Full Depth Patching	up to 7 - 10
	Heater Scarification	up to 6 - 8
	Texturization	up to 5 - 7
	Slurry Sealing	up to 3 - 5
	Micro-Surfacing	up to 7 - 9
	Chip Sealing	up to 5 - 7
Rigid Pavement	Crack and Joint Sealing	up to 7 - 10
	Spall Repair	up to 3 - 5
	Partial Slab Repair	up to 7 - 10
	Drainage Improvement	up to 7 - 10
	Full Depth Slab Repair	up to 12 - 15
	Texturization	up to 5 - 7
	Load Transfer Retrofit	up to 10 - 15
Surface Treated Pavement	Spray Patching	up to 2 - 3
	Chip Sealing	up to 2 - 4
	Levelling	up to 4 - 6
	Drainage Improvement	up to 5 - 7
	Full Depth Patching	up to 5 - 7

2.5.2 *Drainage Rehabilitation Methods*

Pipes rehabilitation (lining), replacement, and maintenance methods in a report by the ASCE (1994). It discusses advantages; disadvantages and the potential size of the application were discussed, as shown in Figure 2-5 and Table 2-8.

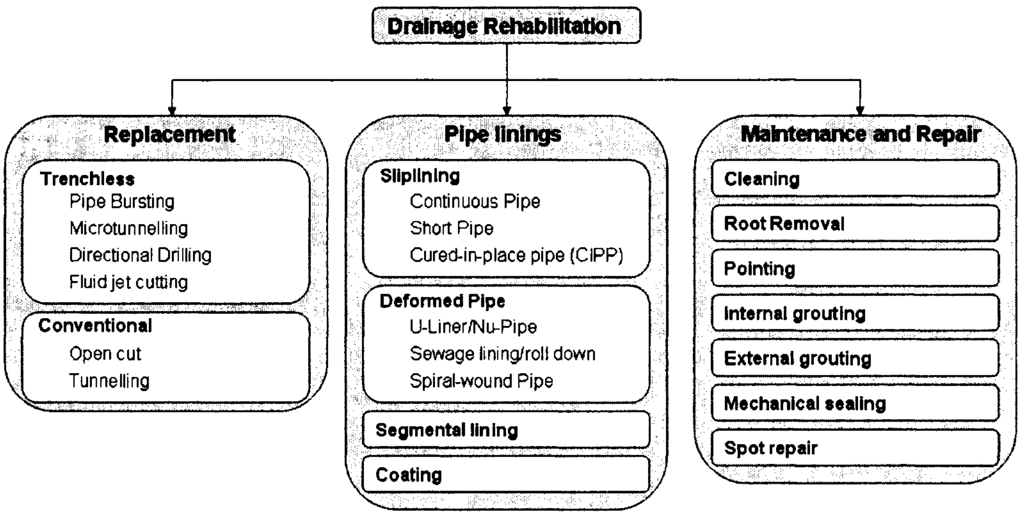


Figure 2-5 Drainage Rehabilitation Methodologies (ASCE 1994)

Table 2-8 Pipes Rehabilitation Options

Rehabilitation Option	Advantages	Disadvantages	Potential application
1.0 Pipe linings			
1.1 Sliplining			
1.1.1 Continuous pipe	1. Quick insertion 2. Large-radius bends accommodated	1. Circular cross section only 2. Insertion trench disruptive 3. High loss of area in smaller size 4. Less cost effective where deep	4 to 63 inch
1.1.2 Short Pipes	1. High strength-to-weight ratio 2. Varity of cress section can be manufactured 3. Minimal Disruption	1. Some material easily damaged during installation 2. Larger pipes may require temporary support during grouting 3. May involve labour intensive jointing	4 to 144 inch
1.1.3 Cured-In-Place Pipe (CIPP)	1. Rapid installation 2. No excavation 3. Accommodate bends and minor deformation 4. Maximize capacity 5. Grouting not normally necessary	1. Full bybass pumping necessary 2. Sole source often necessary 3. High set-up costs on small projects	4 to 108 inch
1.2 Deformed Pipe			
1.2.1 U-Liner/Nu-Pipe	1. Rapid installation 2. Continuous pipes 3. Maximizes capacity 4. No excavation 5. Grouting not required	1. Lateral relocation may be difficult 2. Relies on existing pipe for support	2.5 to 24 inch

Table 2-8 Pipes Rehabilitation Options

Rehabilitation Option	Advantages	Disadvantages	Potential application
1.2.2 Swage lining/roll down	1. Rapid installation 2. Maximizes capacity 3. Minimal excavation 4. Grouting not required	1. Lateral relocation may be difficult 2. Relies on existing pipe for support	3 to 24 inch
1.2.3 Spiral-wound Pipe	1. Tailor-made inside the conduit 2. No excavation required 3. Maximize capacity 4. Rapid installation 5. Noncircular available	1. Large number of joints 2. Relies on existing pipe for support 3. Required careful grouting of annulus	3 to 120 inch
1.3 Segmental lining	1. High strength-to-weight ratio 2. Variety of cross section can be manufactured 3. Minimal disruption	1. Some material easily damaged during installation 2. May require temporary support during installation 3. labour intensive 4. Requires person entry	36 in and larger
1.4 Coatings (Gunite/Shotcrete)	1. Connection easily accommodated 2. Minimal excavation	1. Difficult to supervise 2. May be labour intensive 3. Control of infiltration required	4 ft and larger
2.0 Replacement			
2.1 Trenchless replacement			
2.1.1 Pipe bursting	1. Can replace a variety of materials 2. Size for size or size increase 3. Not dependent of the condition of the conduit	1. Potential damage of adjacent services 2. Lateral connection required disconnection 3. Full bybass pumping required	4 to 20 inch

Table 2-8 Pipes Rehabilitation Options

Rehabilitation Option	Advantages	Disadvantages	Potential application
2.1.2 Microtunnelling	1. High groundwater head 2. Slurry can be water 3. Can deal with cobbles 4. Small diameter shafts 5. Can excavate plain, weak concrete	1. Service connections 2. Bentonite slurry required treatment 3. Off-line only	6 to 36 inch
2.1.3 Directional drilling	1. Rapid installation 2. Long distance 3. Can be used in tidal or surf zone and underwater 4. Variety of pipe materials	1. Service disruption 2. Generally not suitable for gravity lines 3. Difficult to use in sandy/granular material 4. Off-line only	3 to 36 Inch
2.1.4 Fluid jet cutting	1. Range of up to 400 ft 2. Accurate steering 3. Capable of steering around obstructions	1. Possible of service damage 2. Operation difficult in sandy or granular soils 3. Not Suitable for gravity lines 4. Off-line only	2 to 14 inch
2.2 Conventional Replacement			
2.2.1 Open cut	1. Removes all problem on length 2. Traditional design	1. Expensive, particular if deep 2. Disruptive	Any
2.2.2 Tunnelling	1. Removes all problems on length 2. Traditional design 3. Reduce disruption 4. Flexibility on line/elevation	1. Usually more expensive than open cut 2. May need expensive ancillary works	Greater than 3 ft

Table 2-8 Pipes Rehabilitation Options

Rehabilitation Option	Advantages	Disadvantages	Potential application
3.0 Maintenance and repair			
3.1 Cleaning	1. Increase effective capacity 2. May resolve localized problems	1. May be costly and cause damages 2. May become a routine requirements	Any
3.2 Root removal	1. May increase effective capacity 2. May resolve localized problem	1. May be costly 2. Problems likely to recur	Any
3.3 Pointing	1. Restores original condition cheaply 2. Minimal disruption 3. Increase capacity	1. Person-entry 2. Sewer must be structurally sound	Greater than 3 ft
3.4 Internal grouting	1. Seals leaking joints and minor cracks 2. Low cost and causes minimal disruption 3. Can reduce infiltration 4. Can include root inhibitor	1. Infiltration may find other routs of entry 2. Existing sewer must be structurally sound 3. May recur/become routine requirement	Any
3.6 Mechanical sealing	1. Seals leaking joints and minor cracks 2. Prevent soil loss 3. Low cost and causes minimal disruption	1. Infiltration may find another routs 2. Existing sewer must be structurally sound 3. Suitable for person-entry only	Person-entry only
3.7 Spot Repair	1. Deals with isolated problems	1. Required excavation for small conduits	Any

2.5.3 Modelling Rehabilitation

The concept of modelling rehabilitation in this research is based on the impact that rehabilitation will have on the asset condition rating. By assuming five conditions (A, B, C, D, and F), then there are ten possible rehabilitation actions, as shown in Figure 2-6.

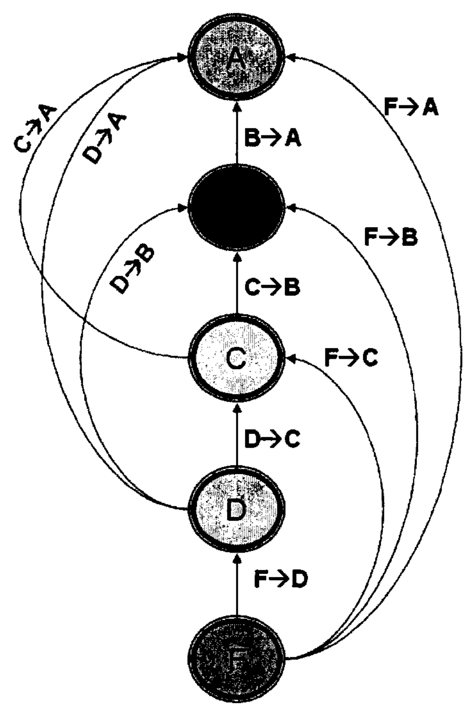


Figure 2-6 Rehabilitation Actions Impact

Each asset does not have to involve those ten actions. An illustration of the rehabilitation mechanism and deterioration simulation is shown in Figure 2-7. Assuming an asset that lives 3 years in A, 4 years in B, 3 years in C, 4 years in D, and 3 years in F, and assuming that the practical rehabilitation actions for this asset are as follows: F→A, D→A, D→B, and C→B, the number inside the boxes will represent the length of the asset in that condition.

The approach adopted applies rehabilitation then deterioration, if the length rehabilitation for each option is F→A=20, D→A= 5, D→B=15, and C→B=3 then the asset new condition will be as shown.

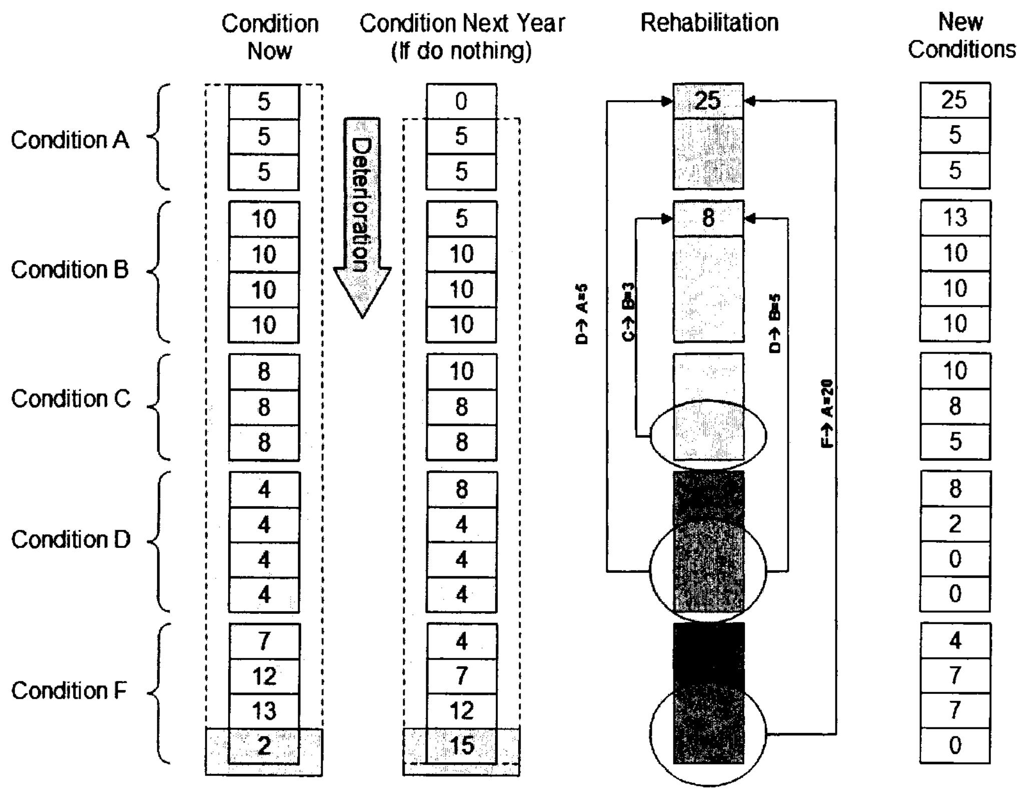


Figure 2-7 Deterioration and Rehabilitation Simulation

2.6 Infrastructure Modelling

As mentioned earlier, there are two modelling approaches which are inspired from work done in the transportation field. These are the network level, or "top-bottom approach", and project level "bottom-up approach". As described for pavement management systems (Haas et al. 1994), the project level includes design, construction maintenance, rehabilitation and for the network level it includes programming, planning and budgeting, and the use of existing information for research and special studies as shown in Figure 2-8.

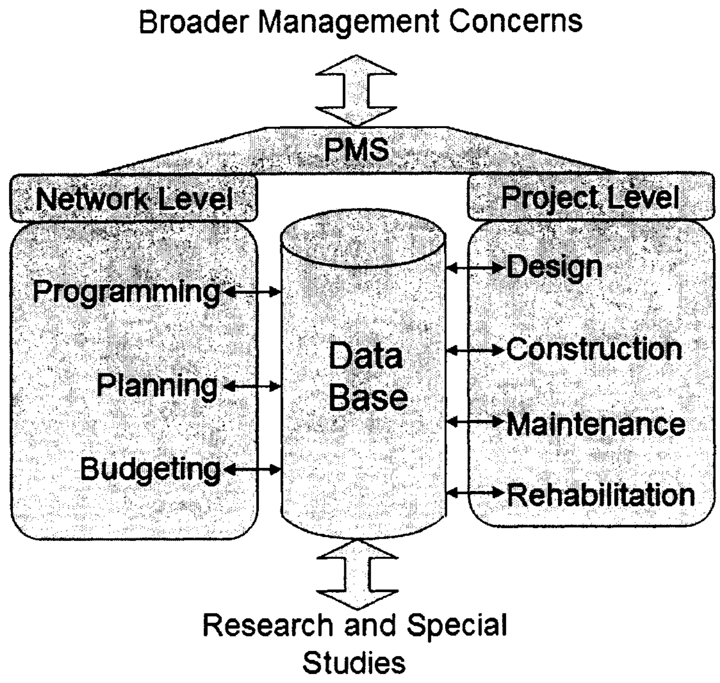


Figure 2-8 Infrastructure Modelling Level within the Pavement Management Systems Context (Adopted from Haas et al. 1994)

Haas et al. (1994) mention the three-level concept including project level, project selection level, and network level. This concept is advanced in order to clarify the terminology that is often used in the literature by referring to the project selection level, which could be either the network level or the project level. In Figure 2-9, the lower-left triangle represents an area of unreliability because too little information is available at the project level, and the upper right triangle is an area infeasible for modelling due to the size and complexity of the required models.

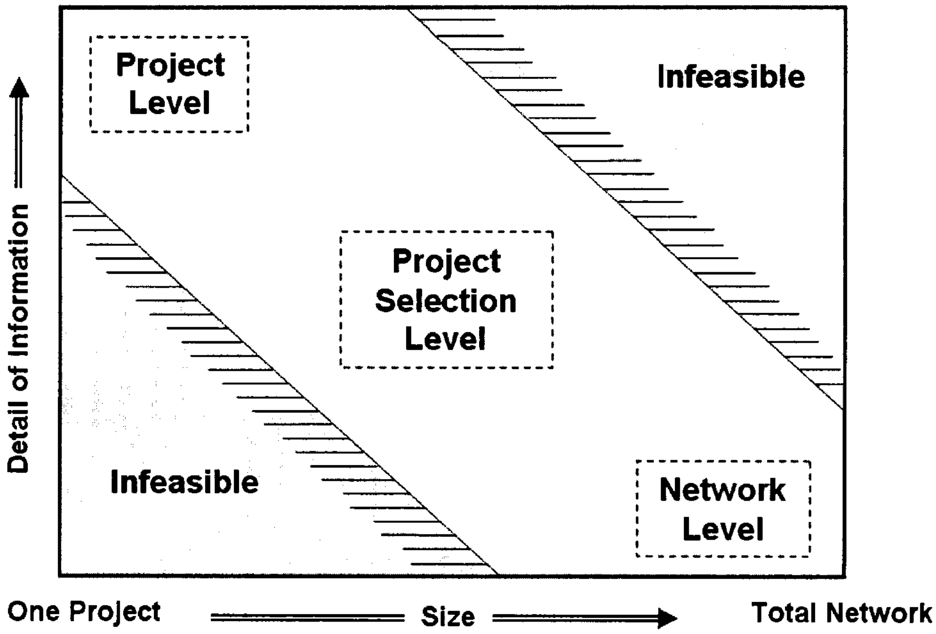


Figure 2-9 Information Level and Complexity Level for Infrastructure Modelling

The main objective of modelling the infrastructure is to group all the assets that belong to one type under one element, thereby facilitating any further modelling actions done to that asset. A typical infrastructure model is composed, in the lower level, of category, systems, components, and elements. These components can vary in name or arrangement but are the same in terms of scheme. See Figure 2-10 for a typical infrastructure model utilizing project level or bottom-up approach.

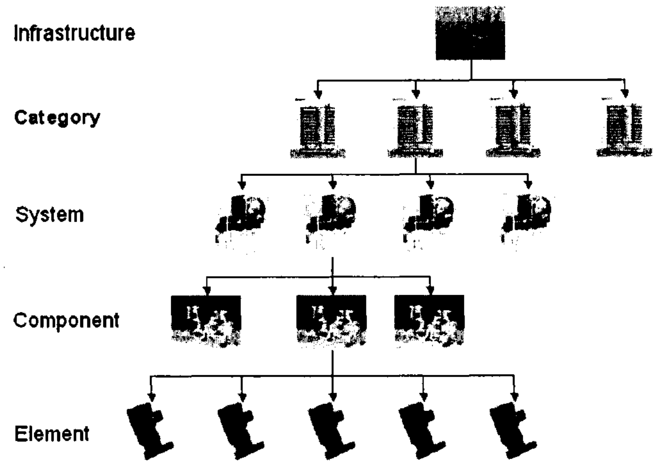


Figure 2-10 Typical Infrastructure Model

The evaluation of the condition index is carried out by the following procedure:

1- For each element evaluate element condition index using Equation 2-13.

$$EP = EW * VEC \qquad \text{Equation 2-13}$$

2- For each component evaluate condition index using Equation 2-14:

$$CP = \sum_{i=1}^{i=NE} EW_i * EP_i \qquad \text{Equation 2-14}$$

2- For each system evaluate condition index using Equation 2-15:

$$SP = \sum_{i=1}^{i=NC} CW_i * CP_i \qquad \text{Equation 2-15}$$

4- For each category evaluate condition index using Equation 2-16:

$$CAP = \sum_{i=1}^{i=NS} SW_i * SP_i \qquad \text{Equation 2-16}$$

5- Calculate infrastructure condition Index (CI) using Equation 2-17:

$$CI = \sum_{i=1}^{i=NCA} CAW_i * CAP_i$$ Equation 2-17

Where:

CI: Condition Index

CAP: Category condition Index

SP: System condition Index

CP: Component condition Index

EP: Element condition Index

NCA: Number of Categories

NS: Number of Systems in each Category

NC: Number of Components in each System

NE: Number of Elements in Each Component

CAW: Category weights relative to all categories

SW: System weight relative to all systems within the same category

CW: Component weight relative to all components within the same system

EW: Element weight relative to other elements within the same component

VEC: Value of element condition (i.e. A= 5, B= 4, C= 3, D= 2, F= 1)

2.7 Infrastructure Management Systems

The role of infrastructure management systems is the identification of optimum strategies at various management levels and the implementation of those strategies. It could also be defined as the optimum use of management tools and techniques to maintain the infrastructure network at an acceptable level of performance.

This section will provide review of previous work that has been conducted by other researchers in the area of infrastructure management systems including pavement, drainages, bridges, and overall infrastructure systems. Zimmerman (1993) summarizes the factors that influenced the evolution of pavement management systems. First, there was recognition by federal agencies of the benefits made possible through the implementation of the pavement management systems, and further support represented by legislation that mandates the use of those systems to be eligible for funding. Second, the strong influence and acceptance by various organizations resulted by realizing the benefits of using those systems. Furthermore, the limitations on budgets and the increase in users demands also facilitate the need for optimum use of the available resources.

The FHWA set the policy that each state highway agency should implement and adopt a pavement management system by 1993 (Irrgang et al 1993). Many researchers have worked to develop and advance higher performance infrastructure management systems. Several of these advancements are listed below.

Mooney et al. (2005) presented a web-based pavement infrastructure management system adopted by Oklahoma Aeronautics Commission (OAC) to oversee state aviation needs and to guide the distribution of the state and federal funds towards 88 statewide general aviation airports. This model is trying to breach the separation between the network level and the project level.

Lee et al. (1995) discussed expanding the existing pavement management systems toward infrastructure management system by introducing other types of assets and incorporating those models into one system. Other issues such as the graphical representation of the asset, were discussed in relation to processes such as automated mapping (AM) and geographical information systems (GIS). This model was applied in the small community of Cronwall, Ontario, Canada. In this system the budget allocation is done based on user input.

Sadek et al. (2003) presented a case study for applying an integrated infrastructure management system for the City of South Burlington, Vermont. This system includes the following assets: pavement, nonmotorized paths, sidewalks, signal controllers, signal heads, loop detectors, transit vehicles, and transit shelters. Utilizing MicroPAVER to determine the improvement in the overall network condition for each budget level, regression analysis was then used to develop a relationship between budget levels and the overall network condition. An example is given in Equation 2-18.

$$C_{pav} = 73.35 + 1.848 * b + 1.845 * 10^{-4} * b^2 \qquad \text{Equation 2-18}$$

Where:

C_{pav} =Pavement Condition

b =Budget in unites of 100,000 dollar

This methodology can only be applied for special cases. The relationship should be updated at each step of the analysis. The authors realized the limitations of the suggested model in terms of the deterioration model and the budget allocation methodology.

Karydas et al. (2006) introduced the methodology for the infrastructure renewal program adopted at Massachusetts Institute of Technology (MIT) which involved several projects with an overall estimated value of $1 billion. This methodology is a basic prioritization process utilizing the Analytical Hierarchy Process (AHP).

The criteria used includes the minimization of risk, the optimization of economic impact, and the coordination with academic policies, programs, and operations of the MIT.

PAVER and MicroPAVER were developed by the U.S. Army Construction Engineering Research Laboratory. Starting in 1970 these systems were developed for use in the military installations (Shahin et al. 1982).

The Illinois Interstate Highway system rehabilitation requirement was established utilizing the ILLINET program. This program is linked with the Illinois Pavement Feedback System (IPFS). This system produces the required rehabilitation strategies (Hall et al. 1994). The Arizona Network Optimization System is based on cost-minimization using linear programming (Wang et al.)

FHWA utilizes PONTIS (Latin for Bridge) for network-level bridge management systems. Deterioration prediction is done using a Markov process. The benefit/cost analysis is uses for the prioritization of projects (Walls et al. 1993)

The main component of any infrastructure management system is the budget allocation and alternatives evaluation, which constitutes the primary output of the infrastructure management system. Figure 2-11 shows the budget allocation schematics in which an asset will deteriorate with time and, at certain point of time, the overall performance measure will fall under the minimum acceptable level of performance. At that point, there are two scenarios possible: first, a rehabilitation action is performed which can involve more than one option; the second scenario involves deferring the rehabilitation.

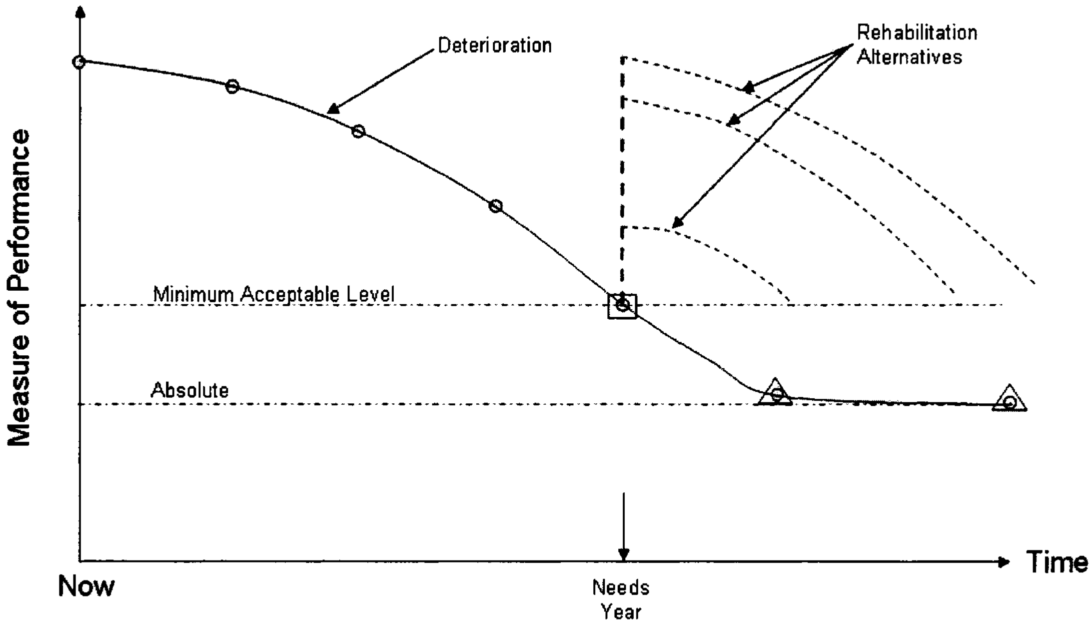


Figure 2-11 Deterioration and Rehabilitation Needs

Those two scenarios will have implication on the assets condition, safety, public services, and preservation of assets, and after certain time the only feasible rehabilitation option is reconstruction.

2.8 Summary

This chapter presents the major components of infrastructure management systems and the modelling levels of infrastructure. The major outcome of the modelling review indicates the need for breaching the gap between the network level and project level by introducing an intermediate level model, which combines the deterioration of the project level and budget allocation of network level. The main reason behind this suggestion is the benefit achieved by being able to solve a network level with practical results that can be used at the project level. The intermediate model component and assumption will be introduced in Chapter 3. The budget allocation and the selection of rehabilitation actions methodologies will also be introduced.

3. Infrastructure Rehabilitation Needs: Modelling and Optimization

3.1 Introduction

The primary output for a successful infrastructure management system is the assessment of infrastructure needs and the distribution of those needs among the asset components in a timely manner. Asset rehabilitation could be proactive, so that the future needs are known or we have a good estimate for those needs, and many of the adopted rehabilitation action will tend to be preventive measures. On the other hand, reactive management mode is the mode in which reactions to failures and the descent of assets controls the whole operation; and the majority of rehabilitation actions will be corrective measures such as reconstruction. Hicks et al. (1997) listed those modes as preventive, corrective, and emergency maintenance actions.

Infrastructure can be divided into two broad categories based on its existence. The first one is the new assets, those assets do not exist at the time and they will be built as a result of new development and then transferred to their ultimate owner. The other type is the existing assets, those assets already exist and their condition mainly depends on their deterioration and previous rehabilitation that took place. On different government levels there are discussions for attaining "Sustainable Infrastructure Strategies". This research will discuss how to develop a sustainable infrastructure strategy for those types of assets.

This chapter will focus on the topic of infrastructure rehabilitation and budget allocation, presenting the work completed in the field of budget allocation, along with associated advantages, limitations and level of modelling.

The first step in asset management is to identify the goals and policies of the system, including the minimum acceptable level of performance of the infrastructure, and the trigger on which an action would be required by the agency in order to satisfy the stakeholder's desires and requirements.

3.2 Minimum Acceptable Level of Performance

The organization size, risk acceptance, financial capability, and stakeholder's involvement are the major factors affecting the minimum acceptable level of performance. The majority of cases deals with limited budget situations and attempts to allocate that budget in such a way as to maximize the benefit gained from a given task.

Defining the minimum acceptable level of performance commences with two major steps. The first one is to define the performance measures by answering the question, what are the performance measures to be considered? The second is to determine the minimum acceptable level for each of the performance measures. For roads one must consider the following performance measures (Haas, 1997):

1. Surface Roughness, or an index such as Riding Comfort Index (RCI), Ride Condition Rating (RCR), or International Roughness Index (IRI),

2. Surface distress or an index such as Surface Distress Index (SDI), Distress Manifestation Index (DMI),

3. Surface Deflection, or Structural Adequacy Index (SAI),

4. Surface friction or skid resistance,

5. Composite measure, such as Pavement Quality Index (PQI), or Ontario's Pavement Condition Index (PCI),

The first Canadian Pavement Management Guide (RTAC 1977) recommended the use of Riding Comfort Index (RCI) in relation to age to measure pavement performance. The minimum desirable Riding Comfort Index (RCI) depends on the pavements functional use, as shown in Table 3-1. RCI is a scale from 0-10 and divided into 5 intervals: (0-2: very poor; 2-4: poor; 4-6: fair; 6-8: good; and 8-10: very good) (RTAC 1977).

Table 3-1 Minimum Desirable Riding Comfort Index (RCI) (RTAC 1977)

Pavement Type	RCI
Freeways and primary highways	RCI ≥ 5.5
Secondary, rural highways	RCI ≥ 4.5
Minor rural highways	RCI ≥ 4.5

Karan (1983) used recursive regression to develop an equation to evaluate RCI based on the information provided by Alberta Transportation; the equation evaluates the RCI with respect to age as shown in Equation 3-1.

$$RCI = \begin{array}{l} -5.998 + 6.870 * LOG_e(RCI_B) - 0.162 * LOG_e(AGE^2 + 1) \\ + 0.185 * AGE - 0.084 * AGE * LOG_e(RCI_B) - 0.093 * \Delta AGE \end{array} \quad \text{Equation 3-1}$$

Where:

RCI = Riding Comfort Index at any AGE

RCI_B = Previous RCI (initially the as-built or 0 age RCI)

AGE = age in years

ΔAGE = 4 years (for the above equation but could be 1, 2, 3, etc.)

Haas et al. (1994) listed a minimum (desirable) acceptable level for different performance measures and pavement functional use, as shown in Table 3-2.

Table 3-2 Minimum Desirable Performance Measures (Adapted from Haas et al. 1994)

Performance Measure	Freeway	Arterial	Collector	Local	Remarks
1. Roughness	Variable	Variable	Variable	Variable	Depends on how measured
a) PSI	3.0	2.5	1.5	1.5	
b) IRI	*	*	*	*	Remains to be established by IRI
c) RCI	6.0	5.0	4.0	3.0	
2. Surface Distress	Variable	Variable	Variable	Variable	Depends on distress type
a) SDI (scale of 0 to 10)	6.0	5.0	4.0	3.0	
b) PCI (scale of 0 to 100)	60	50	40	30	
3. Deflection	Variable	Variable	Variable	Variable	Depends on how measured
a) SAI (scale of 0 to 10)	7.0	6.0	5.0	4.0	
4. Surface friction	Variable	Variable	Variable	Variable	Depends on how measured
a) Skid number (ASTM)	*	*	*	*	Not specified by hwy agencies
5. Combined index					
a) PQI (scale of 0 to 10)	6.0	5.0	4.0	3.0	
6. Traffic delays (Veh. hours)	*	*	*	*	Remains to be established
7. Vehicle operating costs	*	*	*	*	Remains to be established

The specified minimum performance measures and the targeted performance measure would have a considerable impact on the required level of investment by the organization. The literature makes a strong case that a gap exists between the required level of investment to maintain the minimum desirable performance and the available budget. A recent study carried out by Infrastructure Canada estimated the infrastructure needs ranging between $44 billion to $125 billion (Infrastructure Canada 2004), which is an alarming figure. The range is especially broad because of the variations in methodology and in the included assets. It is essential to invest more time in order to achieve an understanding of the asset value and the required investment level. These assets deteriorate with time so that a greater delay will translate into higher needs and investment.

The main purpose of this section was served by exposing different performance measures and their minimum acceptable levels, to be adopted and developed by the infrastructure owner. These values are very sensitive and have a direct impact on the required level of investment; (this issue will be discussed later in the sensitivity analysis).

This will lead to an investigation of the work and methodologies that have been developed in the area of budget modelling, estimation, allocation, and optimization. A key contribution of this research is to aid in implementing intermediate level modelling so as to optimize "project level". The research adopts the simulation of deterioration based on project level and budget optimization from the network level by optimizing the number of units in the rehabilitation action.

3.3 Infrastructure Budget Allocation

Infrastructure investment and budget allocation vary in complexity from simple project prioritization exercises to project level optimization, decision trees, and expert systems used in budget allocation. Each of those methodologies offer advantages in terms of accuracy, simplification, and the ability to produce near optimum solutions.

Abraham et al. (1998) presented a deterministic dynamic programming optimization model for large combined sewers in the City of Indianapolis; the proposed model utilizes Markovian process with respect to deterioration, and assumes the total life of the sewer to be about 50 years. The budget allocation is a rule-based process in which each pipe section is modelled within a time interval of 5 years, and the condition of the pipe could be in one of five states (1, 2, 3, 4, and 5), in this scale 5 is the worst condition.

Depending on each state, feasible rehabilitation is determined and the option with a higher benefit/cost ratio is selected. At the same time expert opinion is utilized to asses the benefits. This procedure is only useful when dealing with a small number of pipe sections, where the budget is not constrained. In case the budget is violated, the authors suggest the development of a prioritization schema to meet the budget constraints. Additional research in the area of combined sewer rehabilitation in Indianapolis was conducted by Greeley et al. (1996) which involved simple selection process shown in Figure 3-1.

Lee et al. (2004), presented a development pavement management system for the town of West Warwick, Rhode Island, using MicroPAVER 3.2. In the pavement management system, budget allocation is carried out using a rule-based decision for each of the road section based on the pavement condition index. Next the required action for each section on the pavement management system is implemented. Those rules as shown in Table 3-3.

Table 3-3 Rehabilitation Strategy for Town of West Warwick (Adopted from Lee et al. 2004)

Primary and Secondary Roads PCI	Tertiary PCI	Rehabilitation Strategy
0 - 10	0 - 10	Reconstruction
11 - 25	11 - 25	Recycling of Bituminous Overlay
26 - 55	26 - 40	Bituminous Overlay
	41 - 55	Surface Treatment (Chip/Stone Seal)
56 - 70	56 - 70	Minor Repair/Routine maintenance
71 - 85	71 - 85	Routine maintenance
86 – 100	86 - 100	None

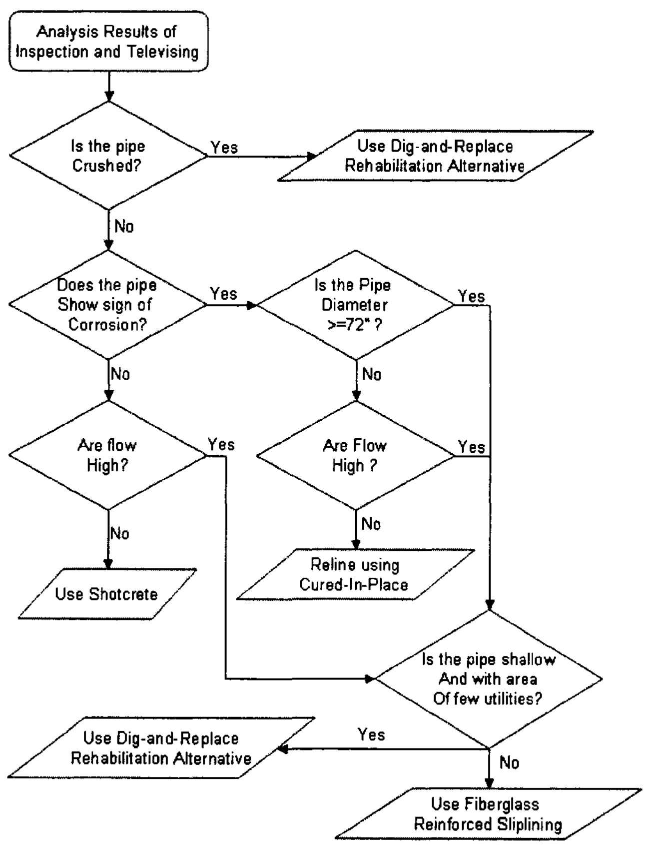


Figure 3-1 Selection Process of Sewer Rehabilitation Alternatives ***(Adopted from Greeley et al. 1996)***

Hicks et al. (1997) introduced a decision tree for the selection of an effective preventive maintenance treatment for flexible pavement. This decision tree is based on the type of distress, distress characteristics, and the roads Average Daily Traffic (ADT). The following preventive maintenance measures are considered: crack sealing, fog seal, chip seal, thin cold-mix seal, and thin hot-mix overlays.

Five types of distress were considered in this research including roughness, rutting, cracking, bleeding, and weathering/ravelling. The decision tree for preventive maintenance for rutting is shown in Figure 3-2.

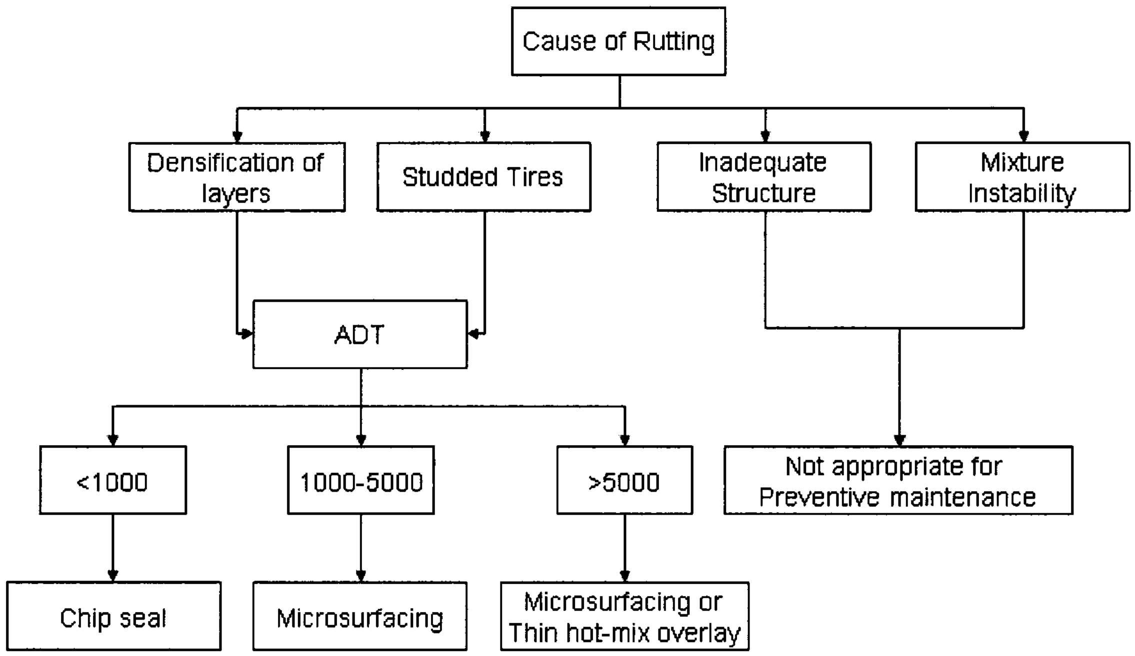


Figure 3-2 Preventive Maintenance for Rutting (Adopted from Hicks et al. 1997)

Guignier et al. (1999) integrated maintenance and reconstruction through the use of an integer optimization model. The authors specifically mentioned the difficulty associated with optimizing a large infrastructure network. The conclusion of this research shows that combining maintenance actions with rehabilitation actions tends to results in significant savings.

Decision tree for the selection of rehabilitation action was presented by Hall et al. (1987). The decision process depends on the identification of the distress characteristics; then, based on the extent of the distress, an appropriate rehabilitation action is proposed. These actions include reconstruction, restoration, and overlay of one or both lanes (see Figure 3-3).

Regarding the Network level for ranking and the project selection process, Su et al. (2006) presented a methodology for ranking a major transportation project in Taiwan. The ranking process utilized AHP (Analytical Hierarchy Process); in the process of evaluating the weight of each project, the different input from each evaluator was transferred into a probability distribution, with scores falling in 95th percentile being selected.

Gabrial et al. (2006) introduced another network level for budget allocation in infrastructure projects. This research presents case study of 15 project, providing such information as cost as a normal distribution and project rank. The adopted approach sets out to minimize the total expected cost, maximize the total value (rank) of the selected projects, both within the available budget. The formulation of the optimization formulation is shown in Equation 3-2.

$$Min\ w_1 \sum_{i=1}^{n} \bar{c}_i * x_i - w_2 \sum_{i=1}^{n} r_i * x_i \qquad \text{Equation 3-2}$$

Where

$\sum_{i=1}^{n} \bar{c}_i * x_i$ = Expected cost

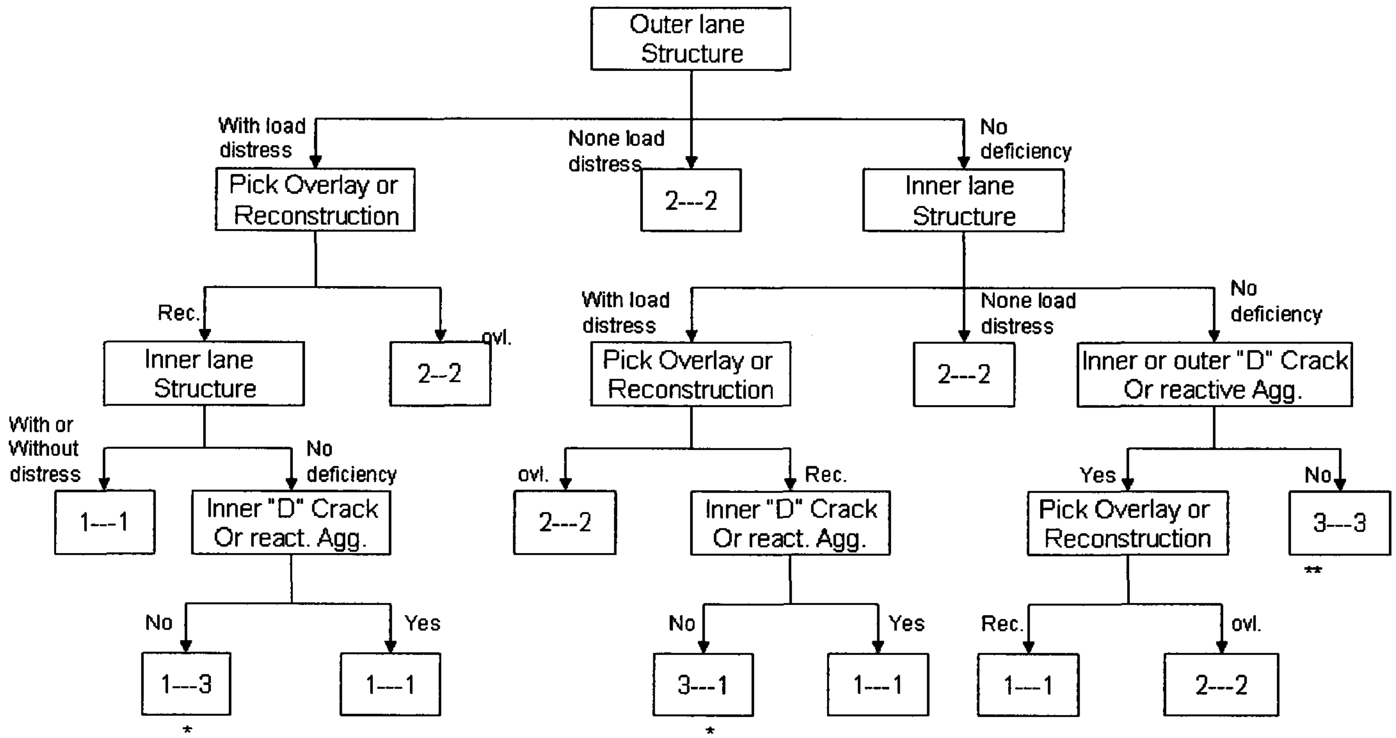
$\sum_{i=1}^{n} r_i * x_i$ =Expected Rank or value

This problem was solved by a weighting method in which it is feasible to find the Pareto optimal points by varying the weights w_1 (Note that $w_1 + w_2 = 1$). A grid of values for w_1 from ranging 0.01 to 0.99 in increments of 0.01 was utilized in the study.

Perng et. al (2007) discussed the use of a Genetic Algorithm (GA) in the optimization of budget allocation for historical buildings in Tainan City, Taiwan. The model represents each work package in a building as one project, and the objective of the optimization is to maximize a total score while maintaining a total cost which falls within the budget constraints. The total score takes into account two issues: the work priority level and the synergy score.

Hsieh et al. (2004) presented the use of a Genetic Algorithm (GA) in order to optimize infrastructure investment under time/resources constraints. The optimization objective maximizes a utility function subject to time constraints, resource consumption constraints, and time-logic constraints. This model does not select different approaches of executing the projects. Essentially, this research offers a scheduling and resource allocation solution.

Jawad (2003), presented a life cycle cost optimization for infrastructure, in which he highlighted the potential of using GA to optimize infrastructure budget allocation. This research also noted the limitations of the life cycle cost approach, in which the process is intended to identify which of those strategies is the best. Simply identifying the best option serves only to limit the discovery of an optimal solution.



1---1 Reconstruction Both Lanes

1---3 Reconstruction Outer, Restore Inner

3---1 Restore Outer, Reconstruct Inner

3---3 Restore Both Lanes

2---2 Overlay Both Lanes

* Option to Go to 1---1 Provided

** Option to Go to 1---1, 1---3, or 2---2 Provided

Figure 3-3 Decision Tree for Selection of Rehabilitation approach (Adopted from Hall 87)

Haas et al. (1994) and (1997) presented a general integer programming model for infrastructure optimization, the objective of which is to maximize the present value of m pavement improvement projects, each with k within-project alternatives, for a T years programming period, as shown in Equations 3-3, 3-4, 3-5, and 3-6.

$$Maximize \sum_{i=1}^{m}\sum_{j=1}^{k}\sum_{t=1}^{T} X_{ijt} * B_{ijt}$$ Equation 3-3

Subject to $\sum_{t=1}^{T}\sum_{j=1}^{k} X_{ijt} \leq 1$ for $i = 1,2,...,m$ Equation 3-4

$$\sum_{i=1}^{m}\sum_{j=1}^{k} X_{ijt} * D_{ijtt'} \leq B_t \text{ for } t = 1,2,...,T$$ Equation 3-5

$$X_{ijt} \geq 0$$ Equation 3-6

Where

X_{ijt} = section i (of m total section) with alternative j (of k total treatment alternatives) in year t (of the T years in the program period), could take the value of 1 or 0.

B_{ijt} = present value of annual benefits (including salvage value) of section i, with alternative j, built in year t, all discounted to base year at a discount rate R

$D_{ijtt'}$ = the actual construction and/or maintenance cost of section i, with alternative j, built in year t, incurred in year t'

B_t = budget of year t

In the field of infrastructure rehabilitation optimization, both pavement and drainage researchers utilized almost all types of optimization algorithms, linear and non-linear programming, integer programming, heuristic methods, goal programming, dynamic programming, and genetic algorithms. Table 3-4 summarizes the most common optimization methods used in pavement management systems, along with their general features and weaknesses adopted from Nunno, (2001).

Table 3-4 Optimization Techniques Characteristics (Adapted from Nunno, 2001)

Optimization Method	Features	Weaknesses
Linear Programming (LP)	- Objective function and constraints are formulated as linear functions - Most common programming method in PMS	-Cannot handle a large number of decision variables -Suffers from combinatorial explosion problem - Difficulty in maintaining identity of individual pavement section
Non-Linear Programming (NLP)	-Objective function and constraints are formulated as non-linear functions	-Cannot handle a large number of decision variables -Suffers from combinatorial explosion problem - Difficulty in maintaining identity of individual pavement section
Integer Programming (IP)	-Decision variables are forced to take the value of integer, the most common of which 0 for do-nothing and 1 for do-something -Formulated in manner similar to linear or non-linear programming - Considered a realistic approach to most pavement management problems	-Cannot handle a large number of decision variables -Suffers from combinatorial explosion problem
Dynamic Programming (DP)	- Used when number of decisions must be made in sequence and earlier decisions affect later decisions - Each node represents a decision point, and the connecting line represent the cost of making each choice - Used to determine the least cost associated with each decisions	- Difficulty in maintaining identity of individual pavement section

Table 3-4 Optimization Techniques Characteristics (Adapted from Nunno, 2001)

Optimization Method	Features	Weaknesses
Heuristic Methods	- Used in place of true integer programming because of the limitations on the size of the problem that can be handled by true integer programming - Gives close answers	-Dose not produce a true optimum solution
Markov Decision Process (MDP)	-Extension of Markovian prediction models - Has been applied in pavement rehabilitation programming successfully	- Approach is primarily a financial planning approach and directly applicable to program planning - Difficulty in maintaining identity of individual pavement section - Translation of the optimal M&R network strategy into a workable program of specific M&R projects is considered a non-trivial task

3.4 Summary

This chapter has presented the various methodologies used in assessing infrastructure needs. In most id not all cases the available funding is less than the needs, which translated into the search for optimization technique to maximize the value of that investment. These methods vary from expert and heuristic methods to complex optimization technique.

Each of the methods has its own advantages and appropriate field of application. From the literature review there is lack in the available methodology to consider the network level and project level in the same model, and considering the optimization of a multi-system infrastructure model. For the case in which only one asset is considered at a time, this may lead to deviation from the overall optimum solution.

The other note to be made regarding the interaction between different types of assets has to do with the relationship between different types of assets either within the same category (e.g. local roads and sidewalks) or in different categories (e.g. local combined sewer pipe and local roads) those relationships should be incorporated and modelled within same the infrastructure management system, this integration will facilitate coordination at the project level where opportunities to maximize or conserve resources may realized.

Level of investment in infrastructure is highly driven by the minimum acceptable level of performance, and the relationship between this minimum level of performance and amount of investment should be further investigated and certified.

There are different maintenance and rehabilitation methods, which vary in cost and effect from minimal maintenance actions to reconstruction of the asset. Establishing the relationship between asset deterioration and cost ratio between major rehabilitation and minor rehabilitation for typical types of asset would open the opportunity to establish an optimal guide for infrastructure rehabilitation.

There is a need to distinguish between existing assets and new assets, for the new assets to be built in the future the ultimate owner should consider the establishment of a sustainable infrastructure strategy which would produce the expected cost of maintenance and rehabilitation during the asset life duration. This research will establish some of these rules.

Existing infrastructure should be considered separately, as the assets distribution and condition would vary from one site to another. If an asset's condition fall short of the acceptable minimum performance then, based on the financial capacity of the organization and the available contractual capacity of the market, a plan should be adopted such that these factors can be integrated into the model. Infrastructure budget allocation and condition optimization is a combinatory problem, the numerous associated constraints of which make it an excellent candidate for the application of genetic algorithms. Genetic algorithms will be discussed further in Chapter 4.

4. Genetic Algorithms

4.1 Introduction

Genetic Algorithms (GA) are based on evolution theory by Darwin. They have been developed and used in many area of research in the past fifty years, Although the specifics of the chromosomal encoding and decoding are not fully understood, here are some general features of the theory of evolution that are widely accepted (Davis, 1991).

1. Evolution is a process that operates on chromosomes, not on the living beings themselves.

2. Natural selection is the link between the chromosomes and the performance of their decoded structures. The process of natural selection causes those chromosomes that encode successful structures to reproduce more frequently than those that do not.

3. Reproduction is the process in where evolution takes place. Mutations may cause chromosomes of offspring to be different from those of their parents, and the crossover or recombination process may create quite different chromosomes of the offspring by combining material from the parents' chromosomes.

In the early 1970s, these features inspired Dr. John Holland. In his research he believed that incorporating them in an algorithm might yield a technique that could be suitable for solving difficult problems in the way nature does through evolution. He began to work with binary strings of 0's and 1's that he called chromosomes. The algorithm he developed carried out simulated evolution on populations of such chromosomes.

As in nature, the algorithm solves the problem of finding efficient chromosomes by manipulating the material in the chromosomes blindly. Like nature, the algorithm had no pre-knowledge of the problem to be solved. The only information given to the algorithm would be a fitness value of each chromosome in the population. The information required to assemble full solution is built in the chromosome encoding. The evaluation of fitness is based on the collection of knowledge by defining a very basic concept “what make one solution better than the other”?

The advance from one generation to another is done through selection, crossover and mutation; selection of the chromosomes is based on their fitness values. Chromosomes with higher fitness values would have the chance to reproduce more often than those with lower fitness values. In reference to the algorithm’s origin, Holland named the field “Genetic Algorithm.”

4.2 Previous Work Using Genetic Algorithm

GA is a search algorithm developed by Dr. John Holland in the 1970s that is based on the mechanics of natural selection and genetics to search through the decision space for optimal solutions (Goldberg, 1989). It was invented to mimic some of the processes observed in natural evolution (Davis, 1991). GA was successfully used in real-world problems as well as a number of civil engineering applications that were hard to solve.

GA was successfully used in construction time-cost trade-off analysis. Feng et al. (2000) and Hegazy (1999a) used GA in solving this problem. Feng et al. (2000) successfully used GA along with the simulation techniques to imitate the probabilistic nature of project networks throughout the search for optimal solutions; they were able to solve the time-cost trade-off problem that included uncertainty. Difficulties of such a problem arise due to the hundreds of activities of a project and because there are various options for completing these activities using different crew sizes or equipment. These conditions created a combinatorial search problem for construction engineers to identify the best selection of crew size or equipment that produces the minimum cost possible to finish the project in reasonable time. As in combinatorial optimization problems, finding optimal decisions is difficult and time-consuming considering the number of permutations involved (Hegazy, 1999a). Using GA, Hegazy (1999a) was able to develop a model that minimizes the total project cost as an objective function and account for project-specific constraints on time and cost.

GA was also successfully used in Site Layout Planning of construction projects. Li and Love (1998) and Hegazy and Elbeltagi (1999) used GA in solving the problem. Arranging a set of predetermined facilities into appropriate locations while satisfying a set of layout constraints is a difficult problem as there are many possible alternatives (Li & Love, 1998). The objective of the problem is to minimize the total traveling distance of site personnel between facilities. Appropriate site layout of temporary facilities is crucial for enhancing the productivity and safety on construction sites. Site layout is a complex problem (Hegazy & Elbeltagi, 1999). In their GA model, they took the facility closeness relationships into account, which represents the project manager's preference in having the facilities close or apart from each other. They used a site layout model with more flexible site and facility representation that can accept any user-specified shape.

GA was used in structural design; Rafiq and Southcombe (1998) used GA in optimizing the design and detailing reinforced concrete biaxial columns. In the model, GA searched to identify optimal bar sizes and the bar detailing arrangement. There is a large number of alternatives for designing and detailing a specific biaxial column. The optimal bar sizes and bar detailing arrangements satisfied the maximum bending capacity about both axes of the column section and minimized the area of reinforcements, which led to an economical design.

Rajeev and Krishnamoorthy (1998) used GA in the design optimization of reinforced concrete (RC) frames. The GA model considered the RC structures main cost components that are due to concrete, steel reinforcement, and formwork. As a result, the problem is a combinatorial one that ultimately ends with selecting a combination of design variables for beam and column section dimensions and quantity of reinforcement so that the cost of the frame is a minimum (Rajeev & Krishnamoorthy, 1998).

Hegazy (1999b) worked with a GA model that deals with resource allocation and levelling simultaneously. Resource allocation attempts to reschedule the project tasks so that a limited number of resources are efficiently utilized while keeping the time extension to a minimum. Resource leveling attempts to reduce the sharp variations among the peaks and valleys in the resource demand histogram while maintaining the original project duration. A multi-objective GA model was used to search for near-optimal solutions considering both aspects simultaneously.

Al-Tabtabai and Alex (1997) developed a GA model that deals with manpower scheduling optimization. Major contracting firms usually maintain different types of labour that are capable of performing a multitude of construction activities. These firms are typically involved in multiple construction projects and eventually will have to address their manpower requirements and allocate the manpower resources efficiently. The computation gets more complex when multiple manpower resources are to be allocated to multiple construction projects with various stages of execution at the same time (Al-Tabtabai & Alex, 1997). As the number of possibilities increases, the solution space increases factorially. GA is being considered as an efficient approach for solving these combinatorial-type scheduling problems (Al-Tabtabai & Alex, 1997).

GA has been used in other civil engineering applications. Liu and Hammad (1997) used GA in the multi-objective optimization of bridge deck rehabilitation, aiming to minimize the total rehabilitation cost and deterioration degree. Haidar et al. (1999) developed a GA model using a hybrid knowledge-based system and GA for the selection of the excavating and hauling equipment in opencast mining. Chan et al. (1994) used GA in developing a model for road-maintenance planning that could overcome the problem of combinatorial explosion as the solution space of this problem could be quite astronomical. In a situation like this, GA has been proven a useful tool to provide a good and acceptable solution within practical time periods (Goldberg, 1989).

GA has been used successfully to reach optimal or near optimal solutions for a number of civil engineering applications. The most common theme of these applications is that they mainly deal with combinatorial problems, each having a huge number of combinations or alternatives such that it is not feasible to explore each one of them. In these conditions and by exploring only a fraction of the solution space, GA excelled in reaching effective solutions.

Some of the limitations when using genetic algorithms are:

1. Have trouble finding the exact global optimum.
2. Require large number of response (fitness) function evaluations.
3. Configuration is not straightforward.

4.3 Genetic Algorithm Implementation

The implementation of genetic algorithm starts with the identification of a number of components, including chromosome encoding, re-production including crossover and mutation, and fitness calculation. A chromosome is set of codes which composed a solution for the problem. Each of the significant parameters in the desired solution is represented by a gene. Each chromosome consists of a number of genes. Furthermore, each population consists of a pre-specified number of chromosomes.

The algorithm relies on the collective learning process within a population of individuals or chromosomes. Each of these chromosomes represents a search point in the space of potential solutions. Each chromosome by itself represents a possible complete solution to the problem. The population eventually evolves towards better regions in the solution space by means of a randomized process of selection, crossover, and mutation. When forming a new population, the selection mechanism favours individuals or chromosomes of higher fitness values to reproduce more often than the less efficient chromosomes. The crossover, or recombination, allows mixing of the parents' information which is then passed to the children chromosomes. Mutation introduces information that might not exist in the parents, and this information is passed to the children chromosomes. Usually, the initial population is randomly initialized. Then, the evolution process continues until a time limit is reached, a certain number of populations evolve, or some error level is achieved (Khalifa, 1997). A flowchart of a simple GA is shown in Figure 4-1.

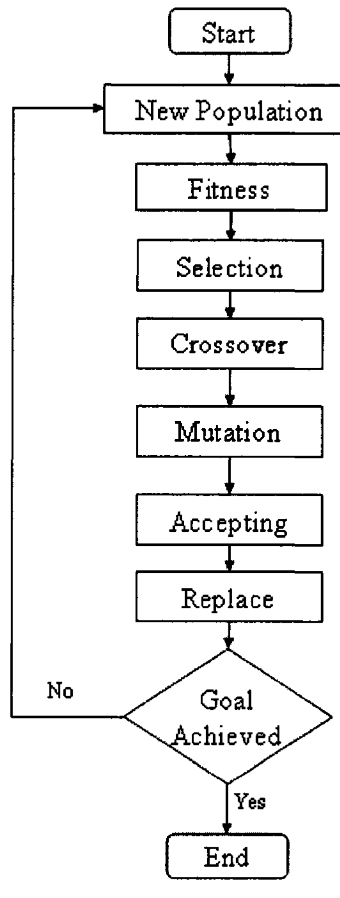


Figure 4-1 Simplified Genetic Algorithm Flowchart

4.3.2 Chromosome Encoding

GA usually works on strings (chromosomes) of binary encoding, permutation encoding, value encoding, tree encoding, or any set of encoding that serve the purpose of the chromosome.

Consider, for instance, the Traveling Salesman Problem (TSP), in which there are 9 cities with specified distances between them; the salesman must visit each of them, but he does not like to travel. One must find a sequence of cities which minimize the distance; the chromosome encoding could be a permutation encoding in which the chromosome structure represents the sequence of travel between those cities, as shown in Figure 4-2.

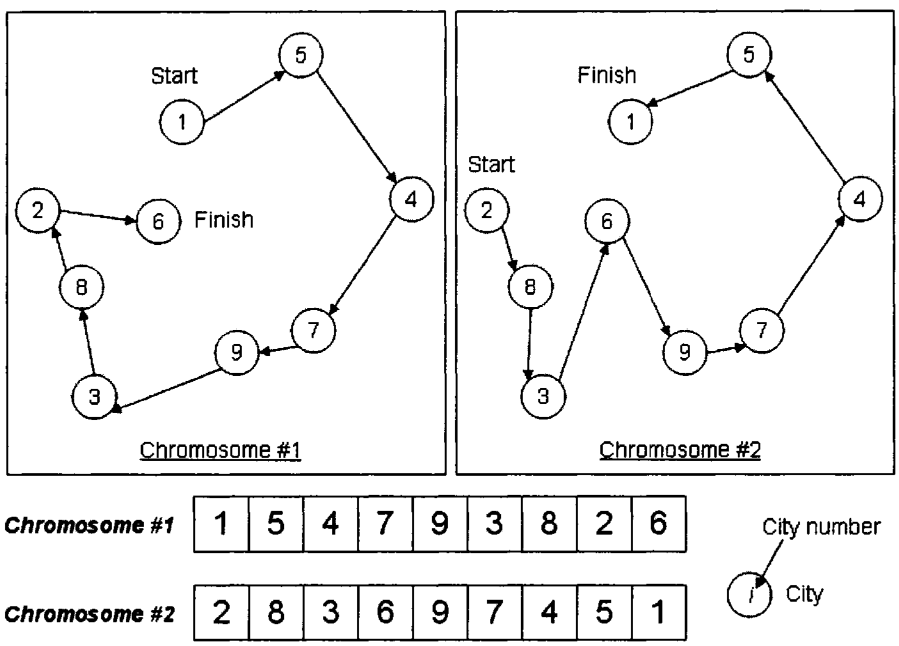
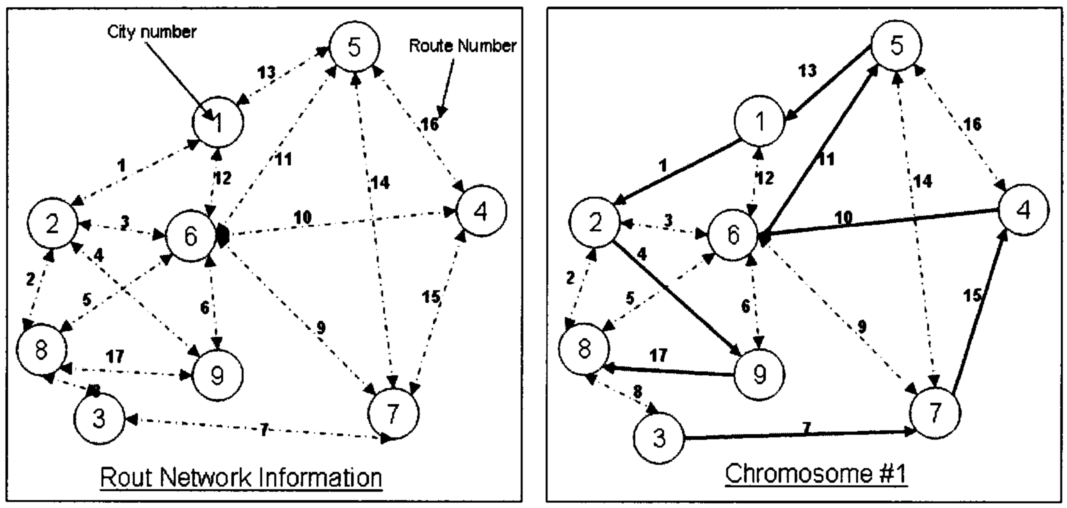


Figure 4-2 Chromosome Permutation Encoding Structure Sample-1

Chromosomes, also called *individuals* could vary in their complexity depending on the problem requirements and development of encoding, for the same problem different ideas and prospective could change the encoding, for example considering the TSP, if the given information indicated the available routes between those cites, and the starting points to be city number 3, then another permutation chromosome could be suggested as in Figure 4-3.



Chromosome #1	7	15	10	11	13	1	4	17

Figure 4-3 Chromosome Permutation Encoding Structure Sample-2

4.3.3 Fitness Evaluation

The fitness of a chromosome is a measure of the chromosome's efficiency, or suitability, to meet the objectives of the problem. It could be an objective function value that needs to be maximized, or it may be a complicated function that includes many constraints. It is up to the designer to specify a suitable evaluation function that would judge the suitability of the chromosomes.

The information in each chromosome is passed on to the evaluation function as input. The evaluation function generates an evaluation value that is assigned to the chromosome and would express the efficiency of the current chromosome in meeting the objectives of the problem. The higher the evaluation values of the chromosome, the better the chromosome.

It should be noted that nowhere, except in the evaluation function, is there any information about the problem being solved. As far as the algorithm is concerned, it is just reproducing and operating on chromosomes so that those with higher fitness values are inclined to reproduce more often. For the TSP problem the fitness evaluation, utilizing the second chromosome encoding in Figure 3-6, could be formulated as in Equation 4-1 and 4-2:

$if\ n_{ch} = n\ Then$

$$F = \sum_{i=1}^{R} X_i D_i \qquad \text{Equation 4-1}$$

$Else$

$$F = D_{\max} * (17 - n_{nch}) + \sum_{i=1}^{R} X_i D_i \qquad \text{Equation 4-2}$$

$End\ if$

Where

n = total number of cities to be visited by the sale man

n_{ch} = number of cities visited by the chromosome

R = route code for R=1 to 17

X_i = an integer number 1 if the route is selected, and 0 if the route is not selected

D_i = distance associated with rout R

The fitness equation evaluates the total distance for the route selected by the chromosome, so that when a chromosome violate the problem objective in visiting all the cities it is penalties by multiplying the distance to large factor which depend of the number of selected routes; in this case the worst expected case with the chromosome select only one route and keep moving between two cities and to give the highest penalty the chromosome will inherit the route maximum distance multiplied by the number of remaining routs.

4.3.4 Genetic Algorithm Operators

The GA mimics biological operation in nature, where the main operators are selection, crossover, and mutation (Khalifa, 1997). These operators to performed and fine-tuned based on the problem domain and logic.

4.3.4.1 Chromosome Selection

The selection operation is performed on the current population to choose the parents of the next population. The most widely used selection technique is the “roulette-wheel” method of parent selection.

It is very important that the selection operation leans towards selecting the chromosomes with higher fitness values so that these chromosomes are selected more frequently over those that are less efficient. In the roulette-wheel parent selection technique, selection is performed randomly over the current population; the probability of selecting any chromosome is proportional to the chromosome’s fitness. For a specific chromosome, the probability that it would be chosen to be a parent to the next population is equal to its fitness value divided by the cumulative fitness of the current population.

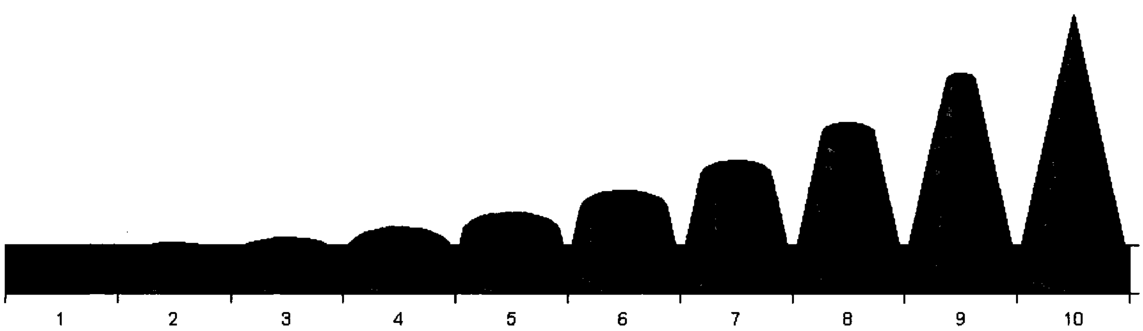
The result is that chromosomes with higher fitness values have a better chance of being selected as parents to the next generation, and at the same time, a low number of chromosomes with relatively low fitness values will also be selected to be parents of the next generation.

The roulette-wheel method gives the highest scoring chromosome higher probability to be selected in the future, the selection process start by ranking the chromosomes in the population base on there fitness, and then the weighted rank score is evaluated and probability associated with a length on the roulette-wheel is assigned. As shown in Table 4-1 and Figure 4-4.

Table 4-1 Roulette-Wheel Selection

Chromosome #	Rank	Rank^2	Cumulative Rank^2	Probability
1	1	1	1	0.26%
2	2	4	5	1.30%
3	3	9	14	3.64%
4	4	16	30	7.79%
5	5	25	55	14.29%
6	6	36	91	23.64%
7	7	49	140	36.36%
8	8	64	204	52.99%
9	9	81	285	74.03%
10	10	100	385	100.00%

In this example chromosome number 10 is the best chromosome and the probability that this chromosome will be selected as one of the parents in the new population is 31.82%, on the other hand, chromosome number 2 has only a probability of 0.41% to be selected, those probabilities are shown in Figure 4.5. The selection process executed by producing a random number $x \in [0,1]$ and select the chromosome that hold the number x (for example if the random number x=0.55 then select chromosome number 9, if the number x= 0.12 then select chromosome number 5)



1	2	3	4	5	6	7	8	9	10
0.26%	1.30%	3.64%	7.79%	14.29%	23.64%	36.36%	52.99%	74.03%	100.00%

Figure 4-4 "Roulette-Wheel" Selection

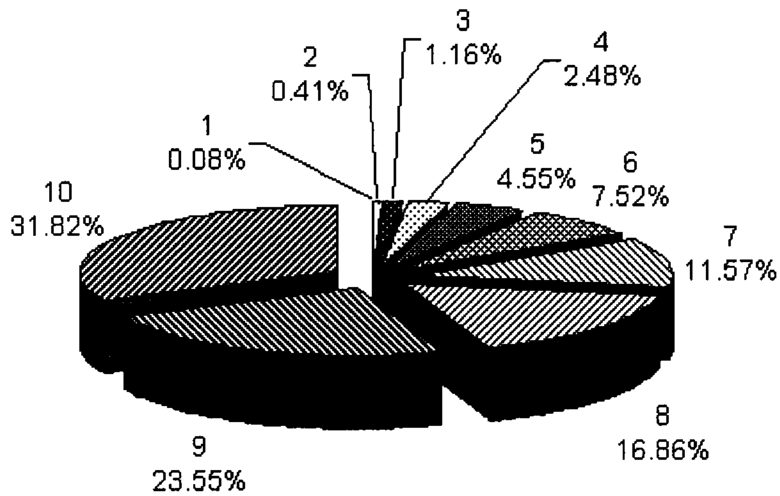


Figure 4-5 Selection Probability based on "Roulette-Wheel"

4.3.4.2 Crossover

Crossover is an extremely important component of a GA. Many researchers believe that, if the crossover operator is eliminated from the GA, the result would no longer be a GA (Davis, 1991).

In nature, crossover occurs when two parents exchange parts of their corresponding chromosomes. In GA, the crossover operator recombines the genetic material of two parent chromosomes to give two offspring chromosomes.

The simplest form of crossover is one-point crossover. For every pair of chromosomes of length L, a random point along L is chosen, which results in dividing each parent chromosome into two parts, the corresponding parts are swapped between the two chromosomes, resulting in two new offspring chromosomes as shown in Figure 4-6.

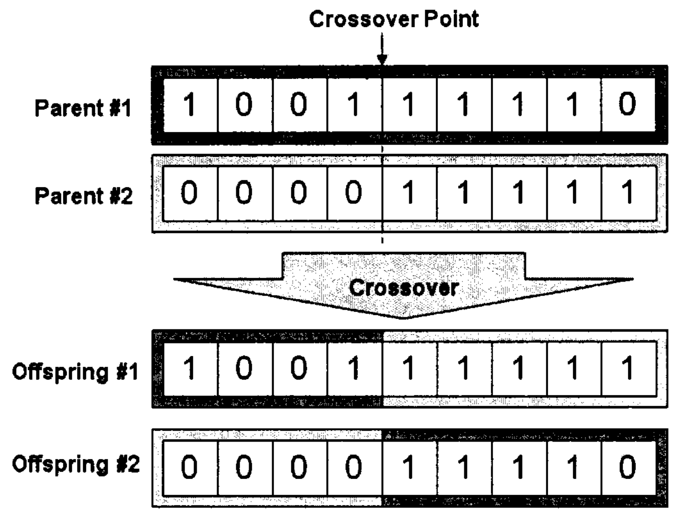


Figure 4-6 One-Point Crossover

Two-point crossover will be used in this research, two random points are chosen within the chromosome length (L). As shown in Figure 4-7, the genetic material between those two points is swapped between the parent chromosomes to form the two offspring chromosomes.

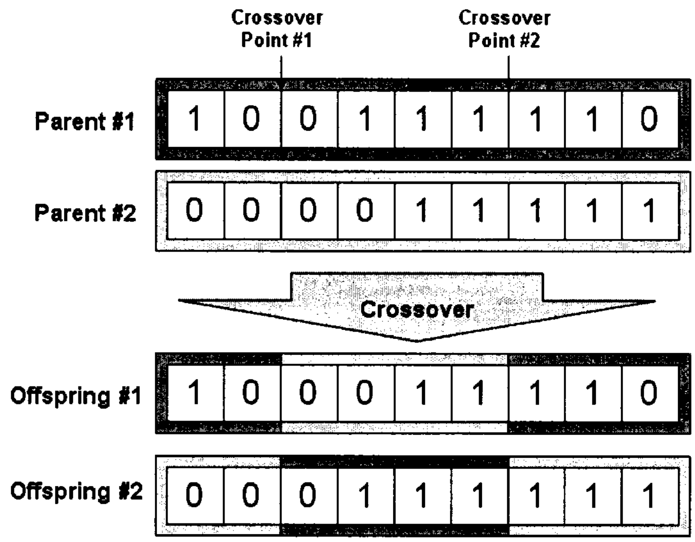


Figure 4-7 Two-Point Crossover

Crossover can produce children that are different from their parents, which is true in cases where the swapped parts are very different in both parents. In cases where some of the swapped positions in both parents have the same value, crossover will not introduce differences for those positions.

4.3.4.3 Mutation

Mutation is a genetic operator that changes the offspring chromosome bits with a certain probability. When the mutation operator is applied to a bit string, it sweeps down the list of bits of that chromosome, replacing each by a randomly selected bit if the probability test for the bit under consideration passes. For every bit, the mutation test can be simply applied by generating a random number between 0 and 1 and the random number is less than a predefined rate (mutation rate), then the mutation test passes for that bit.

Mutation helps in introducing genetic diversity into the new generation. It also helps in preventing the algorithm from being stuck in local optima. In nature, the probability of mutation is low, so the offspring is not too much different from the parents. As in nature, mutation rates are typically kept low. Generally, for chromosomes of length L, Khuri et al. (1994) recommend a mutation rate equal to 1/L which is suitable for a variety of problems.

One way of applying bit mutation is to invert the value of the passing bit as shown in Figure 4-8. Another way for applying mutation is to substitute the value in the passing bit by a randomly generated value.

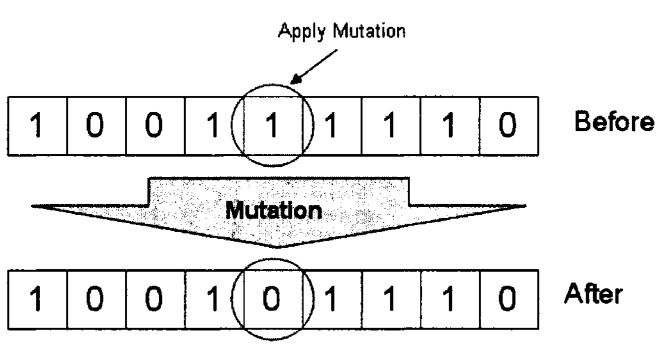


Figure 4-8 Mutation Operation

4.4 Principal Attractions of GA

GA has many attractions that make it very appealing for implementing. Khalifa (1997) summarized some of those attractions that will be mentioned in the following sections.

4.4.1 Domain independence

As mentioned before, the only two links between the algorithm and the problem it is solving are the encoding of the problem and the methodology of evaluating the performance of chromosomes to assign a fitness value to each of them. Therefore, it is easy to write one general software code that would work on many different problems. The only modifications needed in most cases are the way of encoding each problem and the way of calculating the fitness values of the chromosomes.

4.4.2 Non-linearity

Unlike many other conventional techniques that depend on unrealistic assumptions of linearity, differentiability, convexity, etc., none of these assumptions is needed by the GA. The only requirement is a way to calculate a measurement of performance, which may be highly complicated and non-linear, or depending on many stages of analysis and compilation.

4.4.3 Ease of modification

Even minor modifications to a particular problem may cause severe difficulties to many heuristics. In contrast, it is easy to modify a GA to model changes to the original problem, and it is easy to add any new constrain or requirement to the fitness calculations.

4.4.4 Parallel nature

In GA, parallelism can be divided into two separate features. The GA manipulates a large number of schemata (building blocks) in parallel, which is known as "Intrinsic Parallelism." The reproduction mechanism together with crossover causes the best schemata to proliferate in the population, combining and recombining to produce high-quality combinations of schemata on single chromosomes. In a sense, it is like having multiple search points that search the solution space for high-quality solutions.

4.4.5 Robustness

The GA is a very robust technique. It can work on a variety of problems. It can work with highly non-linear problems. Although it is possible to fine-tune a GA to work better on a particular problem, it is true that a wide range of parameter settings (selection technique, mutation rate, population size, etc.) will give acceptable results.

4.5 Summary

This chapter introduced the concepts and outlines the implementation of genetic algorithms, GA has been used successfully in optimising complex combinatory problems and the results show that it is robust and superior in terms of modelling logical constraints and can be easily modified.

Chapter 5 will introduce the proposed modelling and the implementation of GA in order to optimize infrastructure budget allocation with respect to intermediate level modelling.

5. Intermediate-Level Modelling and Optimization of Budget Allocation:

5.1 Introduction

This chapter will present a framework for developing an infrastructure management system for budget allocation using intermediate level modelling and the optimization of budget allocation. Budget allocation for infrastructure is a combinatory problem which will be solved utilizing Genetic Algorithms (GA).

The next sections will present the adopted infrastructure model hierarchy and required input, infrastructure deterioration, infrastructure performance measures, and rehabilitation strategies. There are two types of budget allocation problems which depend on the objective function and the organization requirement: the first is the problem of how to maximize the performance of infrastructure given a limited budget, and the second is the problem of attempting to minimize the required budget in order to achieve certain performance levels. These variations in the objectives could be utilized to show the flexibility of modifying the formulation of GA.

5.2 Infrastructure Model Hierarchy

In general, infrastructure models are composed of different levels and categories depending on the available information including the organization hierarchy, the assets functionality, and the characteristics of the assets. Infrastructure inventory information is one of the major challenges faced when developing an infrastructure management system. In particular, infrastructure assets are generally built at various times as the organization evolves. This fact creates challenges related to availability of information as well as its uniformity.

Another challenge caused by the organization hierarchy which would be one of the major players in determining the infrastructure hierarchy. For example, if one department is responsible for drainage and water services, the infrastructure hierarchy will inherit one category called “Drainage and water services” and this category will include two systems the first one drainage and second one is water services. The fact that many systems belong to the same hierarchy creates challenges when aggregating results.

Functionality and characteristics of the assets would have large impact on the infrastructure hierarchy. In general terms, it would be advantageous to group assets with same functionality as one system. For example when dealing with combined sewers if all the combined sewer have the same life duration, same deterioration behaviour, same rehabilitation strategies then it is reasonable to have all of the combined sewers in one component. However, if there are different deterioration behaviour based on the pipe size then we might need to have different categories depending on the size.

The hierarchy we used in this research is composed of five levels as shown in Figure 5-1, those levels start with the infrastructure level (e.g. City of Edmonton), then the category level (e.g. road) , then the system level (e.g. collectors system), then the component level (e.g. collector roads with soil cement base), and at the bottom the element level (e.g. an element located at Alberta Avenue, with a length of 1037 m and PQI=3.5).

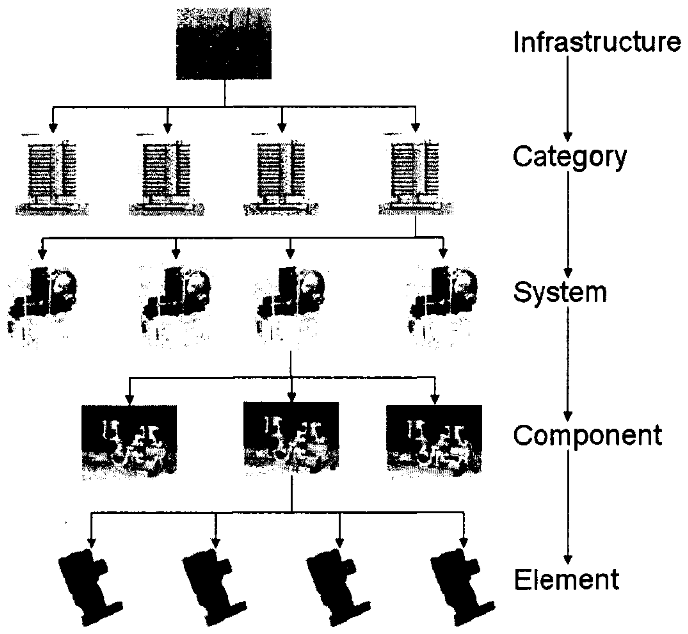


Figure 5-1 Infrastructure Model Hierarchy

5.2.1 Infrastructure Hierarchy Identification Process

Identifying the assets for each organization could be done by following the process shown in Figure 5-2.

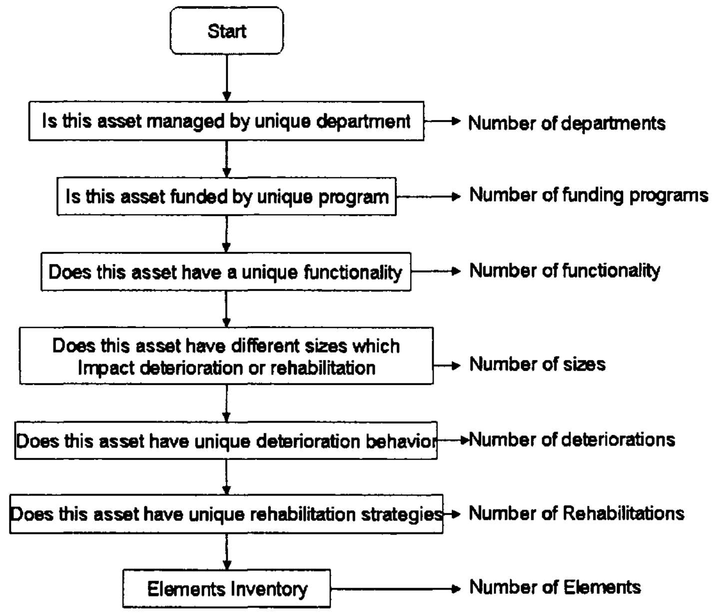


Figure 5-2 Identifying Infrastructure Model Hierarchy Process

The process divides the assets based on:

- The department that manages the asset;
- Funding program which is dictated to asset category (for example in sewer rehabilitation local sewer is funded by neighbourhood program and large trunks are funded by large trunk program);
- Asset functionality such as combined sewer or storm pipes;
- Different asset sizes that have impact on either deterioration or rehabilitation;
- Deterioration behaviour or deterioration curve is an important factor this variation for the same size or geometry of the asset could occur because of different types of construction materials which have different life spans, and;
- Rehabilitation strategies, this variation could exist because of different cost and actions.

5.3 Network Level Modelling

This research will focus only on linear assets including roads and drainage. The City of Edmonton (Office Infrastructure 2004) divided the City infrastructure into twelve categories, when modelling infrastructure at the network level. The model will include only infrastructure and category information of the drainage and roads as shown in Figure 5-3.

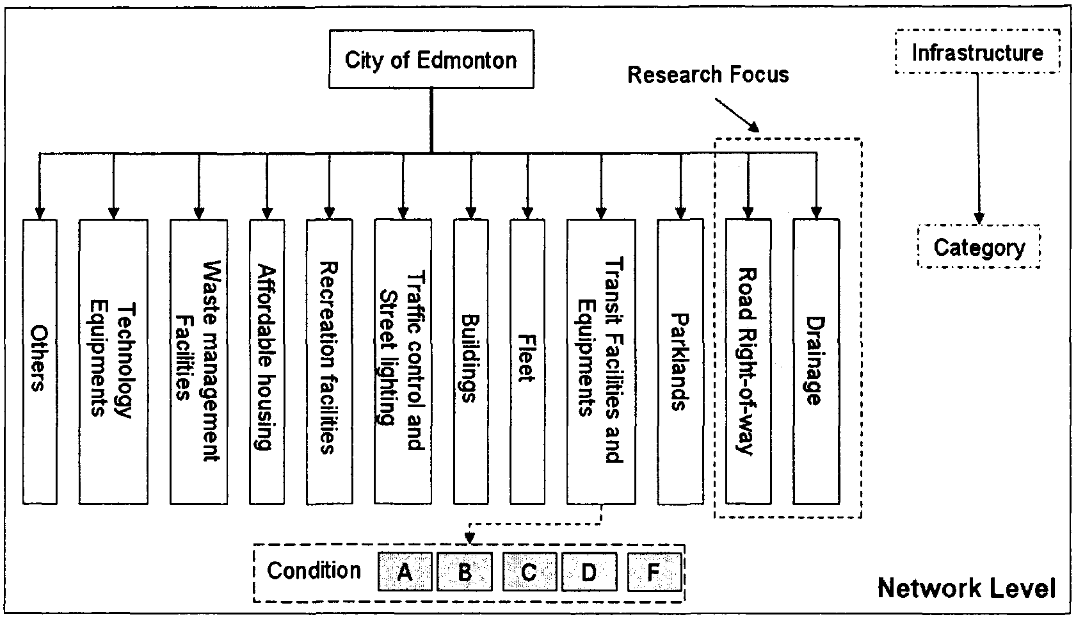


Figure 5-3 Network Level Model (City of Edmonton)

The detailed information for each individual asset does not exist at the network level, the only information available is the inventory breakdown within the conditions (A, B, C, D, and F, for e.g. 20 km of road in condition A, 70 km in condition B, etc.). Budget allocation and analysis carried out at this level of analysis would be useful only for strategic planning and will not help in identifying practical projects.

5.3.1 Network Level Modelling

Road Right-of-way includes pavement, sidewalks and bridges. Each of those categories could be divided further, for example pavement includes alleys, arterial roads, local roads, sidewalks includes mature and suburban. Bridges includes channels, culverts, grade separation, rail and river crossing. The high level model is shown in Figure 5-4.

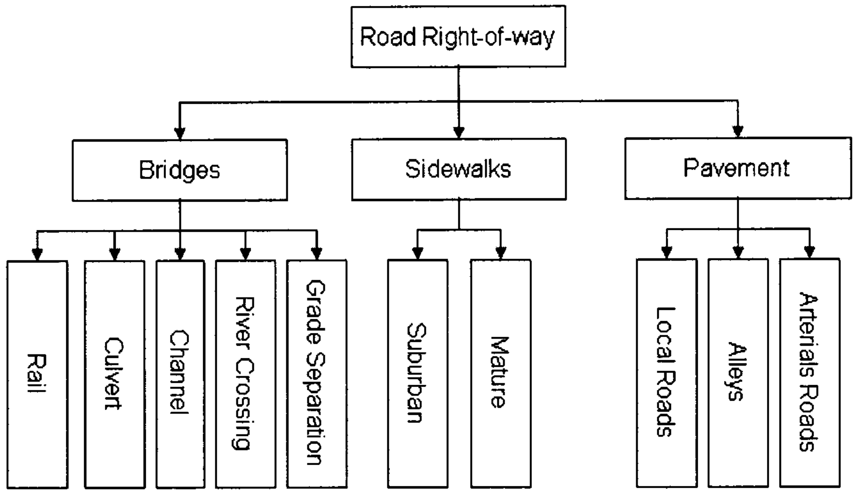


Figure 5-4 Network Level (City of Edmonton- Road Right-of-way)

Drainage at the Network level includes wastewater treatment facilities, pipe network (including combined system, sanitary system, and storm system), service connections, and pump stations. The network level is shown in Figure 5-5.

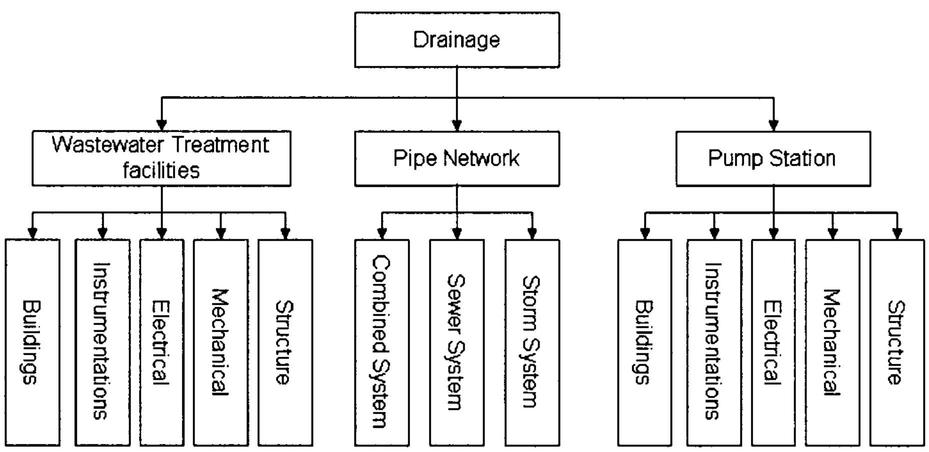


Figure 5-5 Network Level (City of Edmonton- Drainage)

5.3.2 Network Level Modelling Required Input

Network level modelling input data includes the network components, deterioration behaviour for each category, cost for rehabilitation and replacement, and the inventory of assets in each condition.

The following assumption is usually adopted in the network level modelling:

- All the assets under one category will follow the same deterioration behaviour.
- Deterioration behaviour is generally modeled using Markovian process in which all assets belonging to one category are assumed to be one collection. This will results in a uniform distribution of assets within the condition total life span, and there will be no distinction for the asset being at the start or the tail end of the condition.
- The budget allocation task will provide the category needs only, within the category further analysis will be required to define projects for rehabilitation.

5.4 Project Level Modelling

Project level model is more extensive hierarchy than the network level. The model includes all the categories, systems, components and elements, and usually the hierarchy terminate at the bottom level were the basic information are available for the each element or section for each asset as shown in Figure 5-6.

Figure 5-6 illustrate an example for road right-of-way. In this model pavement includes three systems, one of them the local roads, which includes residential, collectors and industrial roads. For residential roads there are two sub-components based on the road base which has impact on the deterioration behaviour. Those are granular base and soil cement base. For each of those sub-categories there are many elements or sections consisting of different characteristic in the pavement management system.

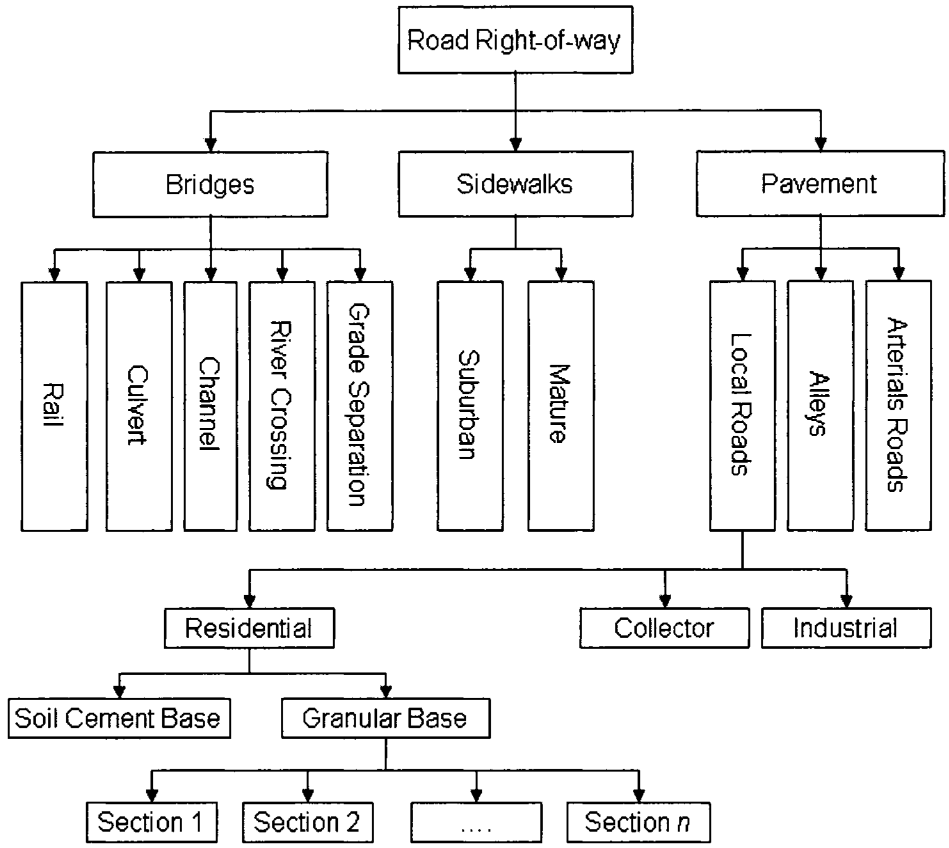


Figure 5-6 Project level Model

The element/section information includes:

- Neighbourhood
- Length (m)
- Current PQI (Pavement Quality Index) (scale 0 to 10)
- Year of construction
- Pervious rehabilitations or maintenance
- Pavement Type
- Road type.

This information may vary from one system to another but all of them should include the element condition, element geometry (e.g. size and length).

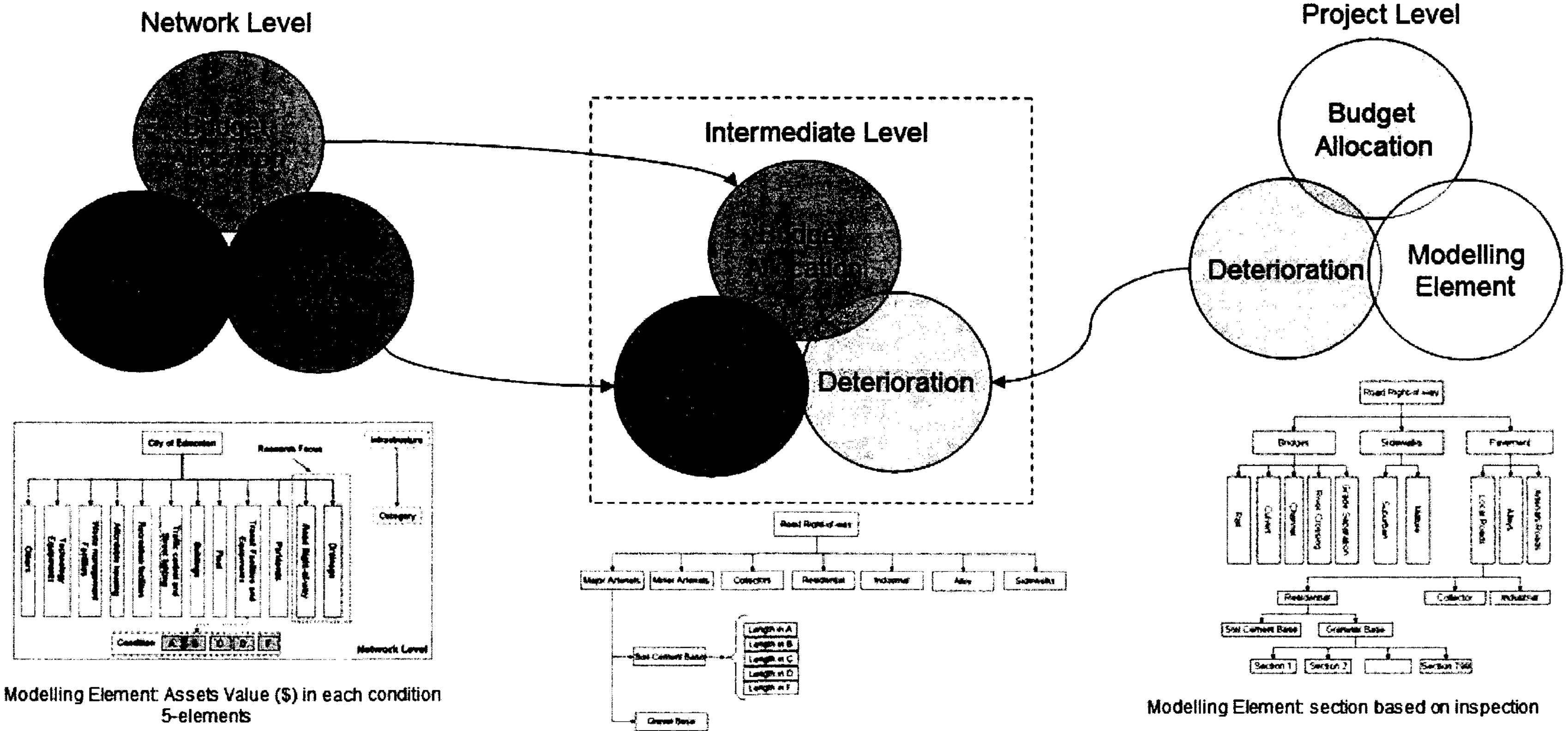
At this level, deterioration could be modelled to reflect the inventory total life span and the distribution of the assets over that life span. The representation of the elements at this level could be done by the asset unit of measurements (km, or m). This level is more practical since each element would be defined as one project and the rehabilitation action for that particular element would be known as a result of the budget allocation task.

It is obvious that the expected size of the budget allocation problem is rather large and then a combinatorial explosion problem might occur if an inappropriate technique was used in the budget allocation task.

At the network level, the Markovian transition probability matrix should be interpreted at the expected percentage of the facility (category) in a certain state that will deteriorate to another state in one time period. On the other hand, at the project level it should be interpreted as one element deteriorating from one state to another.

5.5 Intermediate Level modelling

The intermediate level modelling is a hybrid modelling level in which budget allocation is performed at the network-level and the asset deterioration is performed at the project-level. The budget allocation optimization objective is to optimize the percentage of the total asset length that will be subjected to collection of applicable rehabilitation strategies as shown in Figure 5-7.



Modelling Element: Assets Value ($) in each condition 5-elements

Deterioration: Percentage of assets value move from one condition to the other

Budget Allocation: enhance %of the assets value or element by applying certain action

Modelling Element: Assets inventory in each condition 5-elements

Deterioration: each length (inventory) follow deterioration curve representing the asset life duration

Budget Allocation: enhance %of the assets inventory element by applying certain action

Modelling Element: section based on inspection

Deterioration: each section follow deterioration curve representing the asset life duration

Budget Allocation: apply an action on that section to achieve the minimum level of performance for that section

Figure 5-7 Intermediate-Level mechanics

The next section will discuss the intermediate-level model hierarchy, deterioration mechanism, rehabilitation actions, and budget allocation formulation.

5.5.1 Intermediate-Level Model Hierarchy

In the intermediate-level model the hierarchy is reduced to include only three levels as shown in Figure 5-8.

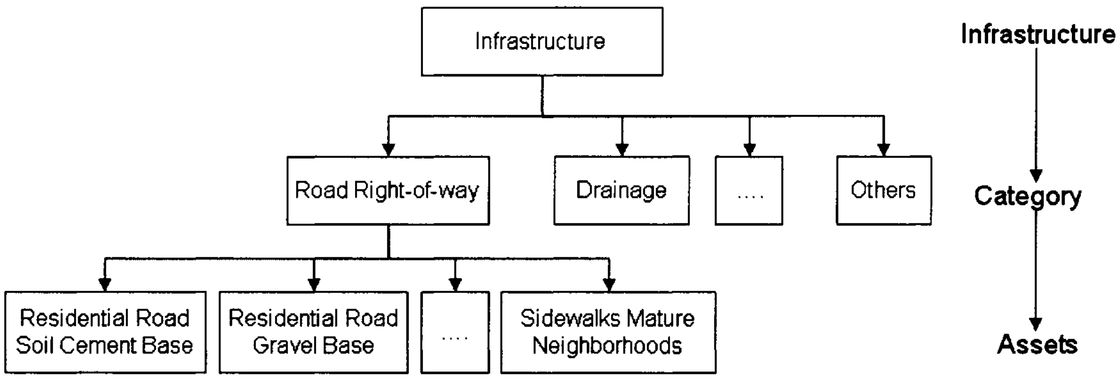


Figure 5-8 Intermediate-Level Model Hierarchy

The asset element in the intermediate-level model is a summation of all the elements of the same type. In this element the lengths in each age is added and placed together in the element collection. The model assumes that there the elements have the same importance. Later on, the weight for each asset will be defined as the weight of its value to the total value of the assets. The deterioration of the assets can be carried in a deterministic manner or using Markovian chain.

5.5.2 Intermediate-Level Model Input and Deterioration

Deterioration in this research will use deterministic simulation methodology (or equivalent Markovian process with transition probability equal to 100% where the number of states equal the asset life duration). For example, if an asset such as residential roads soil cement base with 40 years life span can be represented as shown in Table 5-1.

Table 5-1 Residential Road Soil Cement Base Life Span Duration

Condition	Total Years	VCI Range
A	9	10 - 8
B	6	8 – 6
C	10	6 – 4
D	13	4 – 2
F	2	2 – 0
Total	40	

The relationship between age and pavement rating can be represented as shown in Figure 5-9. This figure reflects the transition path in which the lengths in each year will flow and its associated rating value (Condition value).

Figure 5-9 Residential Road Soil Cement Base Condition Rating Vs. Age

To illustrate, the local residential roads inventory in Edmonton is about 948.8 km distributed over 1696 section (City of Edmonton, Transportation department 2007). The intermediate-level representation for those elements would be only one element representing all sections with an array of 40 cells each one holding the length at that age. The residential roads current and future distribution is presented in Table 5-2. Which shows the asset deterioration without any rehabilitation. This can also be achieved by using Markovian process as explained in Section 2-4.

Table 5-2 Deterioration Example (residential roads)

Condition	Age	Current	2008	2009	2010	2011
	1	9,252	0	0	0	0
	3	1,179	9,252	0	0	0
	4	4,225	1,179	9,252	0	0
A	5	1,589	4,225	1,179	9,252	0
	6	5,403	1,589	4,225	1,179	9,252
	7	8,905	5,403	1,589	4,225	1,179
	8	620	8,905	5,403	1,589	4,225
	9	10,609	620	8,905	5,403	1,589
	10	21,707	10,609	620	8,905	5,403
	11	30,061	21,707	10,609	620	8,905
B	12---13	.....	.....	.....	.....	.....
	14	49,194	39,302	49,989	30,061	21,707
	15	62,965	49,194	39,302	49,989	30,061
	16	53,177	62,965	49,194	39,302	49,989
	17--22	.....	.....	.....	.....	.....
C	23	52,885	35,171	48,283	42,831	39,280
	24	39,295	52,885	35,171	48,283	42,831
	25	31,523	39,295	52,885	35,171	48,283
	26	25,292	31,523	39,295	52,885	35,171
	27	14,163	25,292	31,523	39,295	52,885
	28	33,531	14,163	25,292	31,523	39,295
D	29	24,107	33,531	14,163	25,292	31,523
	30---35	.....	.....	.....	.....	.....
	36	4,812	13,108	15,732	10,009	6,989
	37	13,669	4,812	13,108	15,732	10,009
	38	4,856	13,669	4,812	13,108	15,732
F	39	6,405	4,856	13,669	4,812	13,108
	40	28,012	34,417	39,273	52,942	57,754

5.5.3 *Intermediate-Level Model Rehabilitation Actions*

In this research we represented the asset condition in five distinct states A,B,C,D, and F (as per the ASCE guidelines). The rehabilitation actions affecting the assets simply represent a transition of the asset from one state to the other. The possible transitions we considered are shown in Figure 5-10.

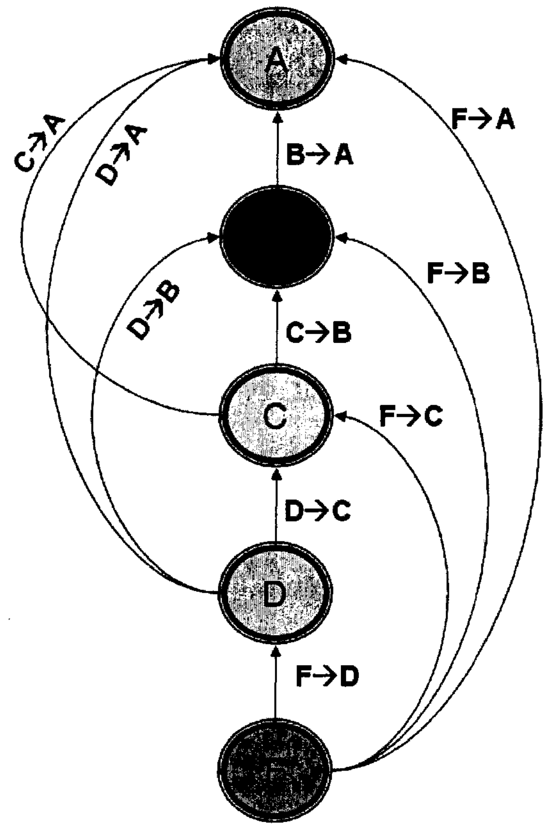


Figure 5-10 Rehabilitation Actions

In the formulation of the budget allocation, these actions will be noted through the length of action and associated cost as:

C_{ij} = cost of rehabilitation strategy j asset i (the cost of applying rehabilitation strategy j for asset i.

L_{ij} = length of asset i to be rehabilitated using strategy j

The rehabilitation strategies are shown in Table 5-3, and they include the possible actions for any asset (Note that not all of these actions may be applicable in all cases).

Table 5-3 Rehabilitation Actions

Strategy (*j*)	Action
1	Transferring the Asset from B→A
2	Transferring the Asset from C→A
3	Transferring the Asset from C→B
4	Transferring the Asset from D→A
5	Transferring the Asset from D→B
6	Transferring the Asset from D→C
7	Transferring the Asset from F→A
8	Transferring the Asset from F→B
9	Transferring the Asset from F→C
10	Transferring the Asset from F→D

5.5.4 Intermediate-Level Model Performance Measures

This section will introduce the performance measures that will be used in this research to set the minimum performance levels. The performance measures including Condition Index (CI) and percentage of critical assets. The condition index uses a 5 point scale where 5 being the best condition and 1 is the worst.

The reason behind the consideration of the percentages of the critical assets is that, in general, the evaluation of the condition index of performance index of the pavement visual performance level is an average which does not represent the distribution of the assets over its conditions. For example, if we limited only the condition index to be 3.00, then infinite number of distribution will satisfy this condition index some of them might be not acceptable. See Table 5-4 and Figure 5-11, where three scenarios were presented and all of them resulted in a condition index equal to 3.00.

Table 5-4 Condition Index Scenarios

Condition	Scenario #1	Scenario #2	Scenario #3
A	1.00	2.50	1.50
B	1.00	0.00	0.00
C	1.00	0.00	2.00
D	1.00	0.00	0.00
F	1.00	2.50	1.50
Condition Index	3.00	3.00	3.00

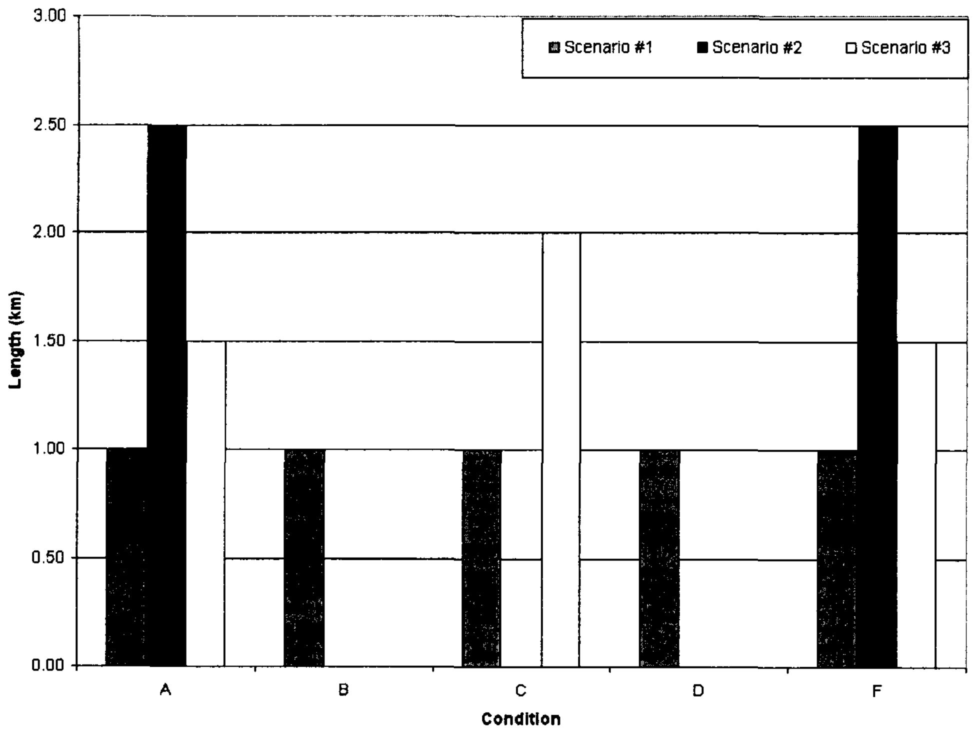


Figure 5-11 Condition index with variable Scenarios

As shown in Figure 5-11 a condition index of 3.00 could be the minimum acceptable level for certain assets, and still 50% of the asset could be in condition F, which will not be acceptable, this is why controlling the critical assets is important.

5.5 Intermediate-Level Model: Optimization of Budget Allocation

This section will present the formulation of the budget allocation problem for the intermediate-Level model in two cases the first one when the objective is to find the minimum budget which is constraint by minimum performance level and the second one is to allocate available budget to maximize the resulting performance levels. The GA approach will demonstrate flexibility in modelling this optimization problem as the only change in the GA will be the fitness formula as will be demonstrated later on.

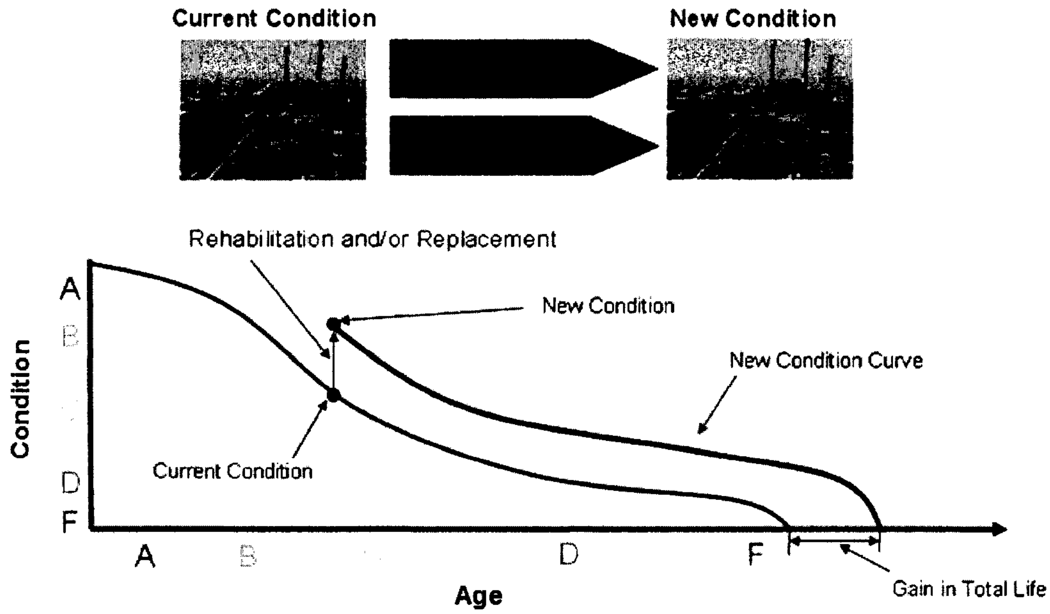


Figure 5-12 Budget Allocation Task

An overview of the budget allocation problem is presented in Figure 5-12, in this Figure the asset deteriorates with time and the objective is to find the optimum budget allocation to maximize the performance and maximize the gain in the infrastructure expected life span or find the minimum budget to achieve certain performance levels.

5.5.5 Budget Allocation: Unconstrained Budget

With an unconstrained budget "cost minimization" the objective of the optimization is to minimize the required budget at time t to get the maximum condition Index CI, minimum percentage in condition D and F, and the minimum percentage in condition F. In defining the optimization problem the following notation will be used:

N = number of assets in composing the infrastructure

T = total planning horizon

t = time interval (t=1, 2, 3... T)

D_i = asset i total life duration

$D_{i(X)}$ = asset life duration in condition X (X =A, B, C, D, or F)

C_{ij} = cost of rehabilitation strategy j asset i (the cost of applying rehabilitation strategy j for asset i.

B^t =Available total budget at time t

L_{ij} = length of asset i to be rehabilitated using strategy j

l_{id} = total asset i length at age d

v_{id} =asset i condition index value associated with age d

$l_{i(Y)}$ = total asset i length in condition Y (Y= B, C, D, or F) time t and the expected length transferred to condition Y (Y= B, C, D, or F) at time $t+1$

j = rehabilitation strategy (j =1, 2, 3...10 as shown in Table 5-3)

w = asset relative importance weight based on asset value

CI^t_{INF} = infrastructure condition index at time t

CI^t_i = asset i condition index at time t

PFD^t_{INF} = infrastructure percentage in conditions (D and F) at time t

PF^t_{INF} = infrastructure percentage in conditions (F) at time t

P^t_{iFD} = asset i percentage in condition (D and F) at time t

P^t_{iF} = asset i percentage in condition (F) at time t

The optimization objectives are:

$$Min \sum_{i=1}^{N} \sum_{j=1}^{10} L_{ij} * C_{ij} \quad \text{Equation 5-1}$$

$$Max \sum_{i=1}^{N} CI^t_i * w_i \quad \text{Equation 5-2}$$

$$Min \sum_{i=1}^{N} P^t_{iFD} * w_i \quad \text{Equation 5-3}$$

$$Min \sum_{i=1}^{N} P^t_{iF} * w_i \quad \text{Equation 5-4}$$

Equation 5-1 objective is used to minimize the adopted strategy budget at time t for the infrastructure. Equation 5-2 is used to maximize the infrastructure condition index, Equation 5-3 and 5-4 are used to minimize the percentages of critical assets in condition D and F. Critical assets contribute the most in increasing the risk of failure, although, %F+D and %F and CI are constrained it is obvious that at some point of time only of those constraints will control the optimization and it could be that two solution will satisfy that condition but one of them would tend to have better results for the other two performance measures.

Subject to:

$$CI_{INF}^{t} \geq CI_{INF_{\min}}^{t}$$ Equation 5-5

$$PFD_{INF}^{t} \leq PFD_{INF_{\min}}^{t}$$ Equation 5-6

$$PF_{INF}^{t} \leq PF_{INF_{\min}}^{t}$$ Equation 5-7

$$CI_{i}^{t} \geq CI_{i_{\min}}^{t}$$ Equation 5-8

$$P_{iFD}^{t} \leq P_{iFD_{\min}}^{t}$$ Equation 5-9

$$P_{iF}^{t} \leq P_{iF_{\min}}^{t}$$ Equation 5-10

$$L_{i1} \leq l_{iB}$$ Equation 5-11

$$\sum_{j=2}^{3} L_{ij} \leq l_{iC}$$ Equation 5-12

$$\sum_{j=4}^{6} L_{ij} \leq l_{iD}$$ Equation 5-13

$$\sum_{j=7}^{10} L_{ij} \leq l_{iF}$$ Equation 5-14

Equations 5-5, 5-6 and 5-7 set the acceptable level of performance for the infrastructure at time t Equations 5-8, 5-9 and 5-10 set the constraints for the assets performance levels. Equations 5-11, 5-12, 5-13 and 5-14 constrain maximum rehabilitation length up to the existing length in that condition and the expected length that will deteriorate at time $t+1$.

Where:

$$CI_i^t = \sum_{d=1}^{D_i} l_{id} * v_{id}$$ Equation 5-15

$$w_i = \frac{\sum_{d=1}^{D_i} l_{id} * C_{i7}}{\sum_{i=1}^{N}\sum_{d=1}^{D_i} l_{id} * C_{i7}}$$ Equation 5-16

$$P_{iFD}^t = \frac{\sum_{k=D_{iA}+D_{iB}+D_{iC}+1}^{D_i} l_{ik}}{\sum_{k=1}^{D} l_{ik}}$$ Equation 5-17

$$P_{iF}^t = \frac{\sum_{k=D_{iA}+D_{iB}+D_{iC}+D_{iD}+1}^{D_i} l_{ik}}{\sum_{k=1}^{D} l_{ik}}$$ Equation 5-18

$$CI_{INF}^t = \sum_{i=1}^{N} CI_i^t * w_i$$ Equation 5-19

$$PFD_{INF}^t = \sum_{i=1}^{N} P_{iFD}^t * w_i$$ Equation 5-20

$$PF_{INF}^t = \sum_{i=1}^{N} P_{iF}^t * w_i$$ Equation 5-21

$$l_{iB} = \sum_{d=D_A}^{D_A+D_B} l_{id}$$ Equation 5-22

$$l_{iD} = \sum_{d=D_{iA}+D_{iB}}^{D_{iA}+D_{iB}+D_{iC}} l_{id}$$ Equation 5-23

$$l_{iC} = \sum_{d=D_{iA}+D_{iB}+D_{iC}}^{D_{iA}+D_{iB}+D_{iC}+D_{iD}} l_{id}$$ Equation 5-24

$$l_{iF} = \sum_{d=D_{iA}+D_{iB}+D_{iC}+D_{iD}}^{D_i} l_{id}$$ Equation 5-25

5.5.6 Budget Allocation: Constrained Budget

Once the available budget is decided the optimization objective would be to get the maximum condition Index CI , minimum percentage in condition D and F; in other words to maximize the gained benefit from the spent money.

The optimization objectives are:

$$Max \sum_{i=1}^{N} CI_i^t * w_i$$ Equation 5-26

$$Min \sum_{i=1}^{N} P_{iFD}^t * w_i$$ Equation 5-27

$$Min \sum_{i=1}^{N} P_{iF}^t * w_i$$ Equation 5-28

Equation 5-26 is to maximize the infrastructure condition index, Equation 5-27 and 5-28 are to minimize the percentages of critical assets in condition D and F.

Subject to:

$$\sum_{i=1}^{N} \sum_{j=1}^{10} L_{ij} * C_{ij} \le B^t$$ Equation 5-29

$$L_{i1} \le l_{iB}$$ Equation 5-30

$$\sum_{j=2}^{3} L_{ij} \le l_{iC}$$ Equation 5-31

$$\sum_{j=4}^{6} L_{ij} \le l_{iD}$$ Equation 5-32

$$\sum_{j=7}^{10} L_{ij} \leq l_{iF}$$ Equation 5-34

5.6 Summary

This chapter presented the concept behind the intermediate-level modelling for infrastructure. This level is a hybrid between the network level and project level. It utilizes the network level budget allocation scheme and project level deterioration and collection of modelling elements in one element for each asset type.

The model component and mechanics including performance measures, deterioration, rehabilitation and budget allocation was introduced in conjunction with the formulation of budget allocation optimization. The next chapter will introduce the framework implementation and the use of Genetic Algorithm in optimizing the budget allocation.

6. Optimization of Intermediate-Level Budget Allocation Using Genetic Algorithm (GA)

6.1 Introduction

This chapter will present the implementation of Genetic Algorithm (GA) in optimizing infrastructure budget allocation within an intermediate-level modelling framework. The first section will deal with the system assumptions and problem inputs, followed by an overview of the proposed infrastructure management system; the section will also deal with system components, their objectives and logic, and the interconnection between those components.

Next, the implementation of GA will be presented, as defined by three major components: chromosome encoding, genetic algorithm operators including fitness evaluation, and crossover and mutation. This illustration will cover both constrained and unconstrained budget optimization.

Model validation will be presented by solving a problem from the literature and comparing the results, then assessing the model convergence by Pareto-front surface and Rank-Histogram.

6.2 System Assumptions and Inputs

The proposed system has the following assumptions, limitations, and features:

1. Each asset follows one deterioration curve, which does not change during the optimization:
2. The number of assets in the infrastructure is unlimited.
3. The relative weight between the assets is based on their replacement value ratio to the whole infrastructure replacement value.

4. Each asset is represented by an array. The number of cells in the array is equal to the asset life duration, and each cell contains the asset length at that age.

5. The system is capable of modelling new construction or added inventory to the asset during the analysis.

6. The deterioration curve is represented by constant Markovian process in which the probability of transition between a given age and the next is 100%.

7. Neither uncertainty in deterioration nor sudden failure is modelled in this system.

8. Practical rehabilitation strategy along with associated costs is an input to the system. If the cost for any strategy is set at "0" then the strategy is not applicable.

The system input includes the following components:

1. Number of assets

2. Asset deterioration curve information including number of years in each condition and condition value associated with each age.

3. Asset inventory (length) distribution over the asset's life duration.

4. Asset rehabilitation strategies and their associated costs per km.

5. Expected new inventory to be added each year. This added new inventory could vary depending on the expected new construction.

6.3 Infrastructure Management System Overview

The proposed system overview is shown in Figure 6-1, includes the following components:

- The read-Input component reads the infrastructure input file; it first acquires the number of assets included in the infrastructure model, and then read and store all the input in the program for later use.

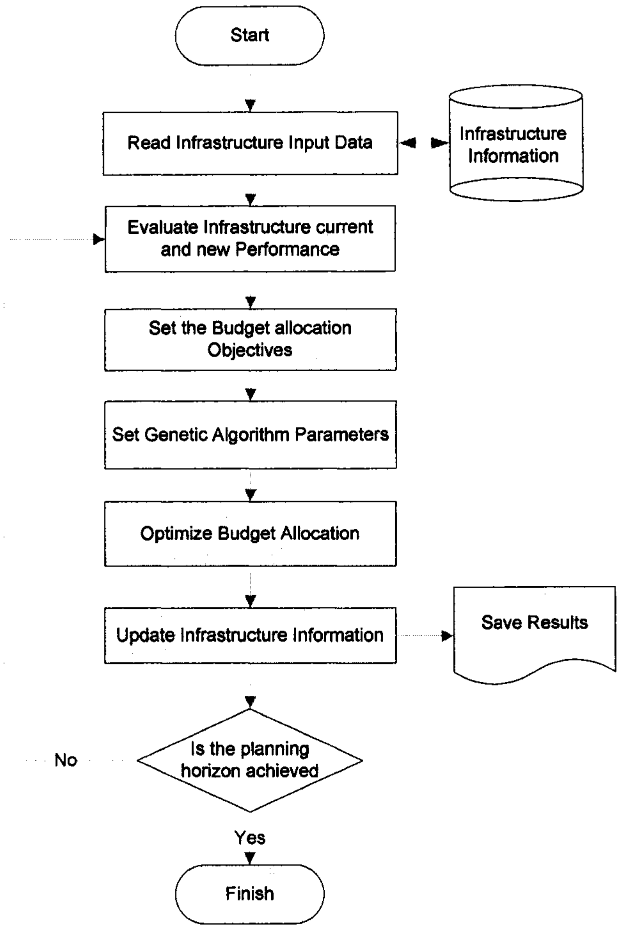


Figure 6-1 Proposed System Overview Flowchart

- The infrastructure performance evaluation component evaluates the condition index and (%F+D, %F) for each current asset as well as for the following period time assuming "No Actions"; this information is used later during the budget allocation optimization.

- The main purpose of the budget allocation objective component is to identify the infrastructure/asset minimum acceptable levels of performance including condition index, (%F+D and %F), and to identify the planning horizon for which the optimization will be performed, (for example, 30 years). The other important factor is the performance enhancement duration in which the minimum target will be achieved (Figure 6-2).

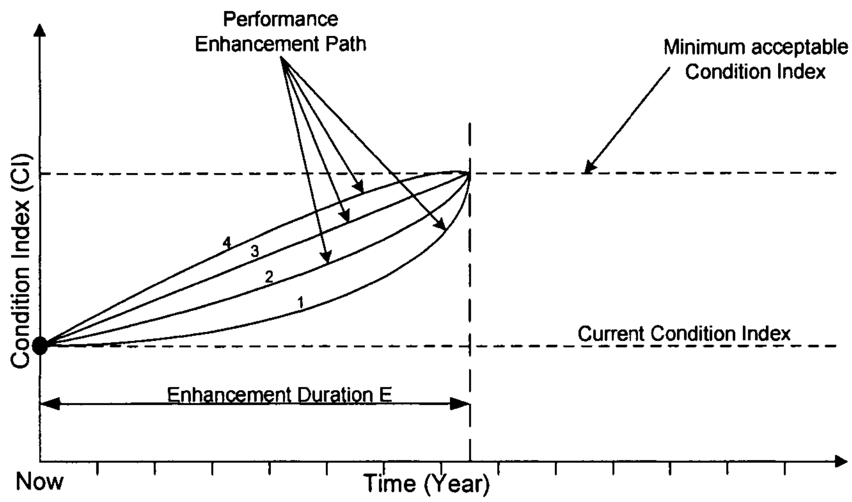


Figure 6-2 Performance Enhancement Duration and Trends

The selection of the enhancement duration and path would be selected by the organization to meet their requirements, and would be associated with different financial needs over the enhancement duration. Setting the GA parameters, including number of generations, number of chromosome in each population, percentage of crossover, percentage of mutation and mutation rate is also an important step, and those parameters will be discussed in detail in this chapter.

- Optimization budget allocation is the component responsible for identifying the optimum strategy to be followed in order to achieve the stated optimization objectives for that particular period of time.

Updating the infrastructure information is carried out once the optimum strategy has been developed and applied to the infrastructure.

6.4 Implementation of Genetic Algorithm

This section will present and discuss the formulation and use of GA in optimizing infrastructure budget allocation for intermediate-level. First the terminology to be used in the formulation will be presented, then the main components of GA including chromosome encoding, fitness calculation, and finally cross-over and mutation.

The third part of the section will discuss the optimization framework and each of the operations executed during the optimization process.

6.4.1 GA Terminology

There are three important terms which will be referred to frequently in this section: gene, chromosome and, population or generation. The simplest one is the gene, which usually includes the parent information; and the intermediate level is the chromosome, which is the collection of all the genes and which represents an independent solution for the problem. The highest level is the population or generation; a generation is a collection of many chromosomes, as shown in Figure 6-3.

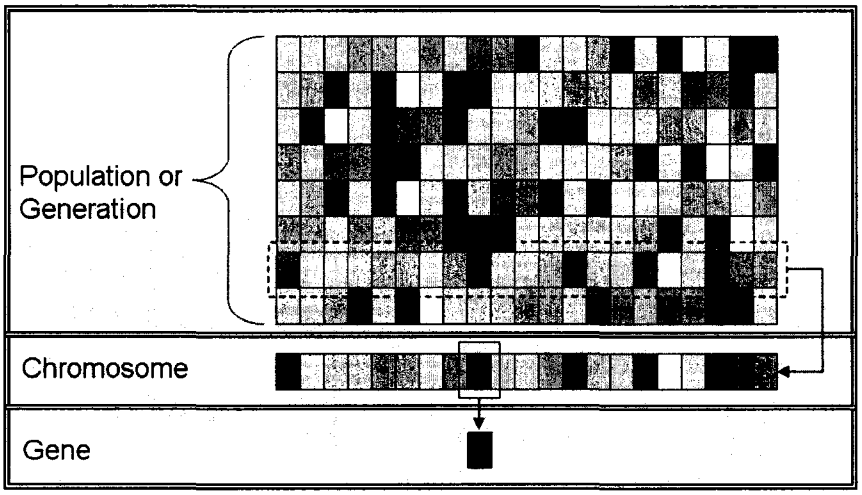


Figure 6-3 Genetic Algorithms-Terminologies

6.4.2 Chromosome Encoding

The selected chromosome encoding is a real value encoding chromosome in which each asset is represented by 10 cells or "genes" each of which contains, the number of units to be rehabilitated using different rehabilitation strategies (Figure 6-4); the total number of cells in each chromosome is equal to 10 times the number of assets in the infrastructure model.

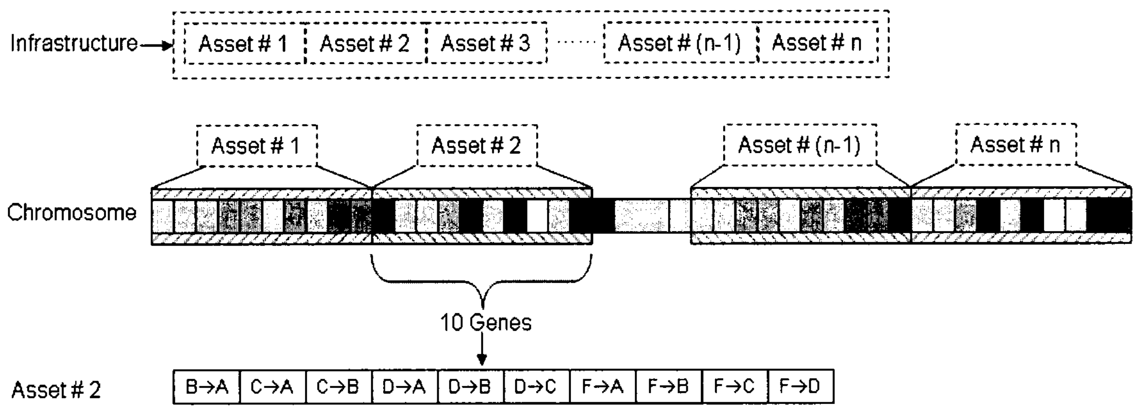


Figure 6-4 Proposed Chromosome Encoding

When this encoding was implemented, the numbers included in the cells were real number leading to an infinite search domain; this was replaced with an integer representing the number of units to be rehabilitated according to the appropriate strategy. For example, if an asset has 50 km in condition B, and assuming that the unit length was selected to be 0.1 Km, then the number of units in condition B is 500, and the cell representing B→A would have an integer number $X \in [0, 500]$.

For the given example in Figure 6-5, the asset inventory is given as 70 km in condition A, 50 km in condition B, 40 km in condition C, 10 km in condition D, and 10 km in condition F, and the cost of the rehabilitation action is given as well. If the unit length =0.01 then the number of units available in each condition is given in the figure. The chromosome should not violate the conditions of rehabilitation and if any rehabilitation is not applicable it should be eliminated from the proposed strategy by the chromosome.

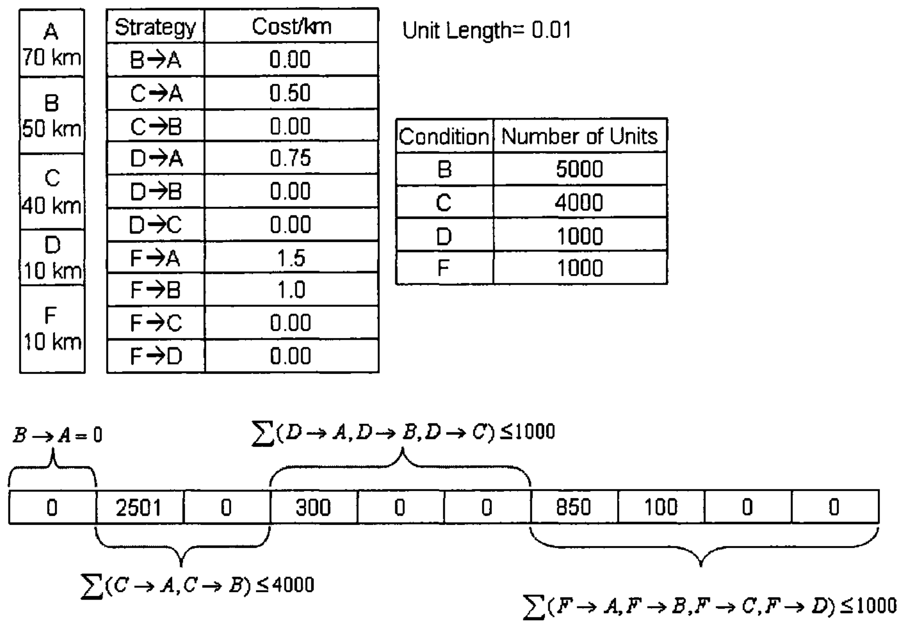


Figure 6-5 Chromosome Example

The number of elements and the rehabilitation action applicability conditions will be checked once the chromosome is created (to be discussed in subsequent sections).

6.4.3 Reducing Chromosome Length

In the previous section the chromosome encoding process was presented. The notion of reducing the chromosome length in order to minimize the computation time and memory usage comes from the fact that not all the expected rehabilitation actions (maximum 10) would be practical, depending on the asset type and current practice for that asset.

For example combined sewer pipes could be re-lined, replaced or open-cut and spot-repaired. This reduces the number of actions from 10 to just three, which means that seven genes should carry a value equal to 0.

The process of reducing the chromosome length is begun by deciding the number of applicable rehabilitation actions for each asset by reading the input data. This means that each asset will have the number of genes in the chromosome that represents its applicable rehabilitation actions, as shown in Figure 6-6.

Strategy	Asset #1	Asset #2	Asset # *n*
B→A	X	X	X
C→A	■	■	■
C→B	X	X	X
D→A	■	■	■
D→B	X	X	X
D→C	X	■	X
F→A	■	■	■
F→B	X	X	X
F→C	X	X	■
F→D	X	X	■

X : Not Applicable
■ : Applicable

Final Chromosome Encoding

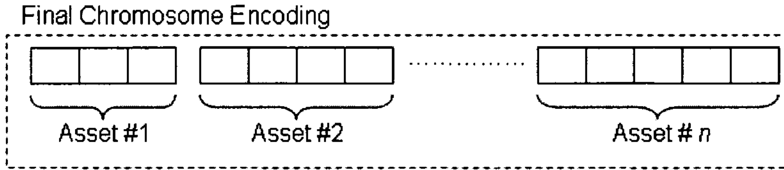


Figure 6-6 Final Chromosome Encoding (Reduced length)

6.4.4 Fitness Evaluation

Once the population is created, each of the chromosomes would be assigned a fitness value. This value is an indication of how suitable this chromosome is relative to the whole population. In the context of minimizing the required budget to achieve certain performance levels, the lower the budget proposed by the chromosome, the more fit the solution, if and only if the associated condition index, %F+D and %F fails within the constrained value. If the chromosome violates one of the constraints, then its fitness value will be penalized so as to reduce its fitness.

Fitness evaluation should consider the problem logic, and is the only component in the system that would be changed if any new constraint were added. Two types of budget allocation will be presented, the first with an unconstrained budget and the second with budget constraints.

6.4.4.1 Fitness Evaluation for Unconstrained Budget Optimization

The purpose of optimization is to minimize the required budget at time t in order to achieve the maximum condition Index CI, minimum percentage in condition D and F, and minimum percentages in condition F.

The algorithm for evaluating the chromosome fitness can be characterized as follows:

1. Find the maximum and minimum budget value for all chromosomes that satisfy all the optimization constraints (Equation 5-5 through 5-15), as shown in Figure 6-7.

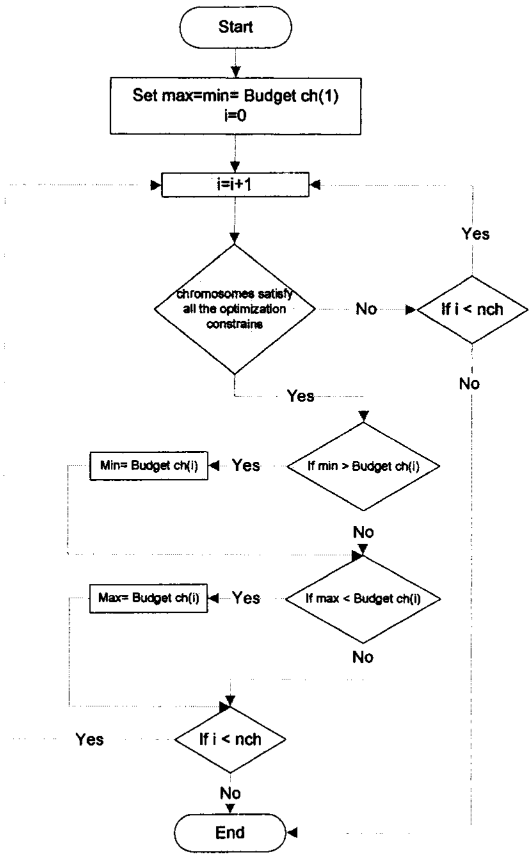


Figure 6-7 Evaluation of Minimum and Maximum Budget

2. For each of the chromosomes in the population, if the chromosome satisfies the optimization constraints then use Equations 6-1 through 6-6 to evaluate the fitness.

$$Fitness = B_f + CI_f + FD_f + F_f$$ Equation 6-1

Where:

$$B_f = \left(\left(\frac{B_{\max} - B_{ch}}{B_{\max} - B_{\min}}\right) + 1\right) * 10$$ Equation 6-2

$$CI_f = (CI_{ch} - CI_t)$$ Equation 6-3

$$FD_f = (\%(F + D)_t - \%(F + D)_{ch})$$ Equation 6-4

$$F_f = (\%(F)_t - \%(F)_{ch})$$ Equation 6-5

$$where\ B_{\max} \neq B_{\min} \neq 0$$ Equation 6-6

If a chromosome budget is equal to zero and the performance constraints are satisfied, then stop the optimization and select the solution “Do Nothing”.

Where:

B_f = fitness value based on chromosome budget

$B_{\max}$ = maximum budget registered in the population of the chromosomes that satisfies the optimization constraints (evaluated as shown in Figure 6-6)

$B_{\min}$ = minimum budget registered in the population of the chromosomes that satisfies the optimization constraints (evaluated as shown in Figure 6-6)

B_{ch} = budget proposed by the chromosomes under consideration

CI_f = fitness value based on chromosome condition index

CI_t = minimum acceptable condition index at time t

CI_{ch} = condition index proposed by the chromosomes under consideration

FD_f = fitness value based on chromosome percentage (F+D)

FD_t = maximum acceptable percentage (F+D) at time t

FD_{ch} = percentage (F+D) proposed by the chromosomes under consideration

F_f = fitness value based on chromosome percentage F

F_t = maximum acceptable percentage F at time t

F_{ch} = percentage F proposed by the chromosomes under consideration

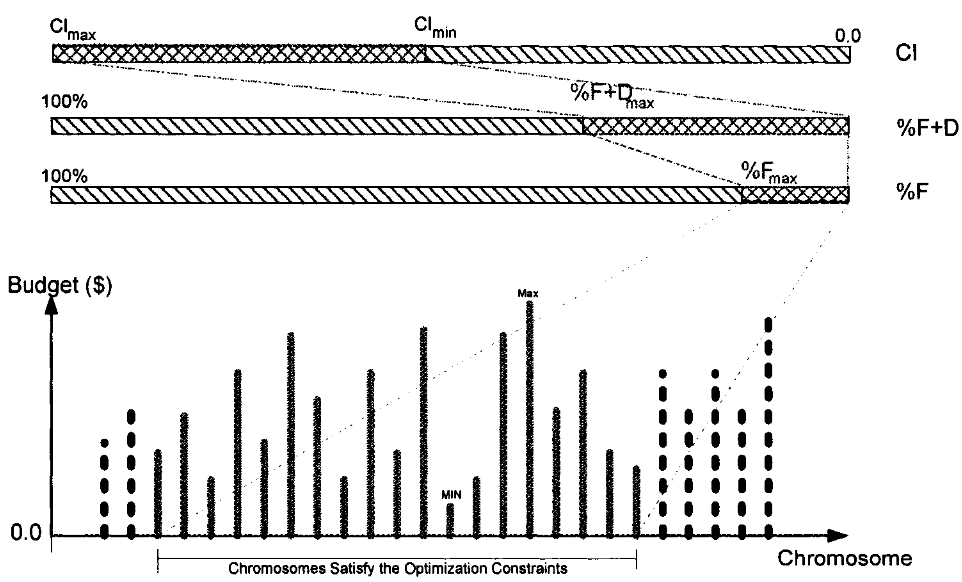


Figure 6-8 Chromosomes Expected Distribution Schema

As shown in Figure 6-8, the chromosomes could be distributed over two regions, such that the chromosome within the accepted region meet all the optimization constraints. Later, those chromosomes will be assigned a fitness-value relative to the other accepted chromosomes. The second region is the rejection region, in which at least one of the constraints is violated by each of the chromosomes.

3. For each of the chromosomes in the population, if the chromosome violates any of the optimization constraints then use Equation 6-7 to evaluate the fitness.

$$Fitness = 0.01 * CI_{ch} \qquad \text{Equation 6-7}$$

Equations 6-1 and 6-2 show that the highest weight of the fitness equation is associated with minimizing the budget. A geometrical concept was used to develop equation 6-2. A minimum share of the budget would occur in the case of a maximum budget and the fitness value would be 10. On the other hand, the maximum expected fitness value is associated with the chromosome with minimum budget and that share would be 20. See Figure 6-9.

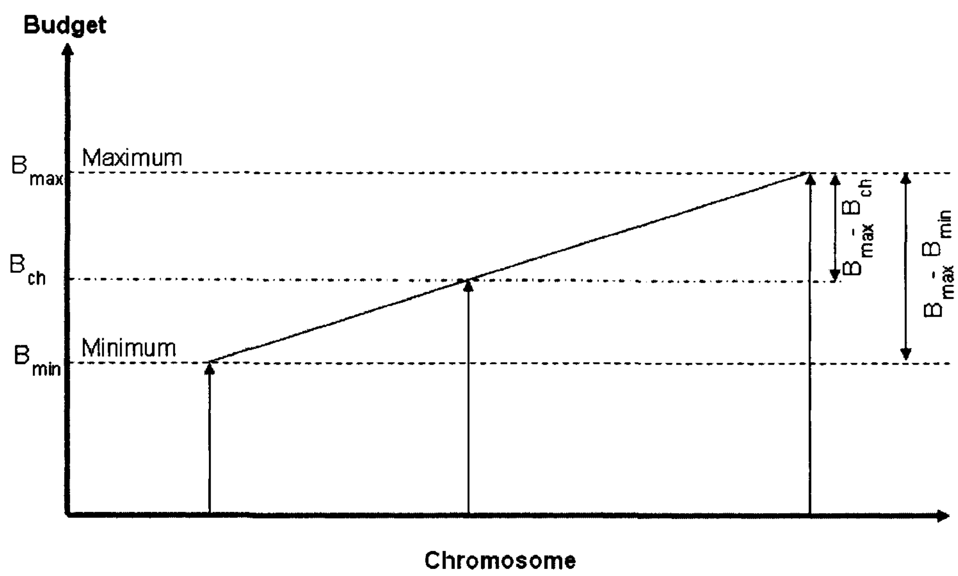


Figure 6-9 Evaluating the Budget Fitness Share

6.4.4.2 Fitness Evaluation for Constrained Budget Optimization

The purpose of the optimization is reach the maximum condition Index CI, minimum percentage for conditions D and F, and minimum percentage in condition F, all within a proposed budget equal to or less than the available budget.

The algorithm for evaluating the chromosome fitness can be characterized as follows:

1. For the group of all chromosomes that satisfy the optimization constraints, find the maximum and minimum condition index, percentage in condition F and D, and percentages in condition F. The same algorithm described in Figure 6-7 can be utilized.

2. For each of the chromosomes in the population, if the chromosome satisfies the optimization constraints then apply Equations 6-8 through 6-14 to evaluate the fitness.

$$Fitness = CI'_f + FD'_f + F'_f$$ Equation 6-8

Where:

$$CI'_f = \left(\left(\frac{CI_{ch} - CI_{min}}{CI_{max} - CI_{min}} \right) + 1 \right) * 10$$ Equation 6-9

$$FD'_f = \left(\left(\frac{FD_{max} - FD_{ch}}{FD_{max} - FD_{min}} \right) + 1 \right) * 5$$ Equation 6-10

$$F'_f = \left(\left(\frac{F_{max} - F_{ch}}{F_{max} - F_{min}} \right) + 1 \right) * 5$$ Equation 6-11

$$where\ CI_{max} \neq CI_{min} \neq 0$$

$$where\ CI_{max} \neq CI_{min} \neq 0$$ Equation 6-12

$and\ FD_{max} \neq FD_{min} \neq 0$ Equation 6-13

$and\ F_{max} \neq F_{min} \neq 0$ Equation 6-14

If any of Equations 6-12, 6-13, and 6-14 is not satisfied, then the associated fitness will be assigned the total share value equal to 20; this situation may occur when there are only one or two chromosomes that satisfy the budget constraint.

Where:

CI'_f = fitness value based on chromosome condition index

CI_{max} = maximum condition index in the accepted chromosome's group

CI_{min} = minimum condition index in the accepted chromosome's group

CI_{ch} = condition index of the chromosomes under consideration

FD'_f = fitness value based on chromosome asset's percentage in condition F&D

FD_{max} = maximum percentage for conditions F&D in the accepted chromosome's group

FD_{min} = minimum percentage for conditions F&D in the accepted chromosome's group

FD_{ch} = percentage in condition F&D of the chromosome's under consideration

F'_f = fitness value based on chromosome assets percentage in condition F

F_{max} = maximum percentage for condition F in the accepted chromosome's group

F_{min} = minimum percentage for condition F in the accepted chromosome's group

F_{ch} = percentage in condition F of the chromosomes under consideration

3. For each of the chromosomes in the population, if the chromosome violates the available budget constrain then use Equation 6-15 to evaluate the fitness.

$$Fitness = CI_{ch} \qquad \text{Equation 6-15}$$

6.4.5 Crossover and Mutation

Two points crossover will be adopted in which after selecting two parents from the existing population, two randomly selected crossing points will be sampled and two offspring generated as a result of the crossover, Figure 6-10 demonstrates the crossover process.

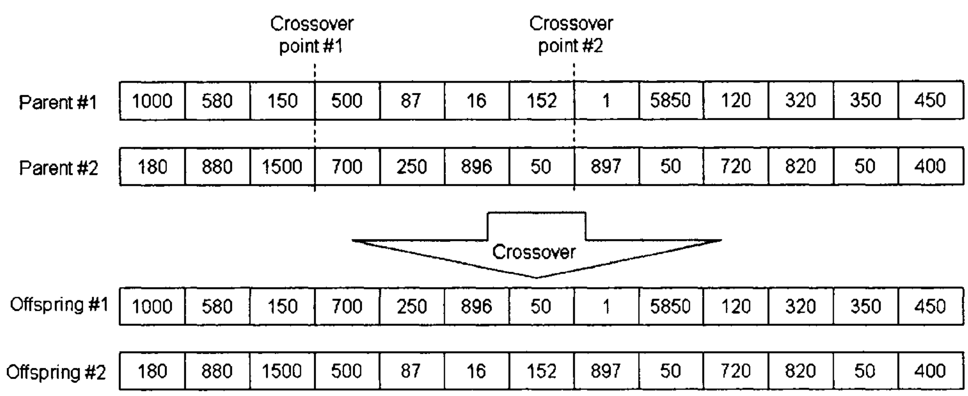


Figure 6-10 Two-Points Crossover

The next step after Crossover is mutation, which is created by sampling a new random number of elements to be rehabilitated and replacing the gene content with this new number. Before the number is replaced, a check will be carried out to ensure that the total number to be rehabilitated is equal to or less than the existing number of units.

Figure 6-11 illustrates the mutation action. In this example, three genes were selected to be mutated, based on a random probability which determines mutation rate. The selected genes were mutated by introducing a new rehabilitation quantity or number of elements; next, they were checked to determine whether or not they were applicable. If not, then a new number was randomly selected within the applicable range.

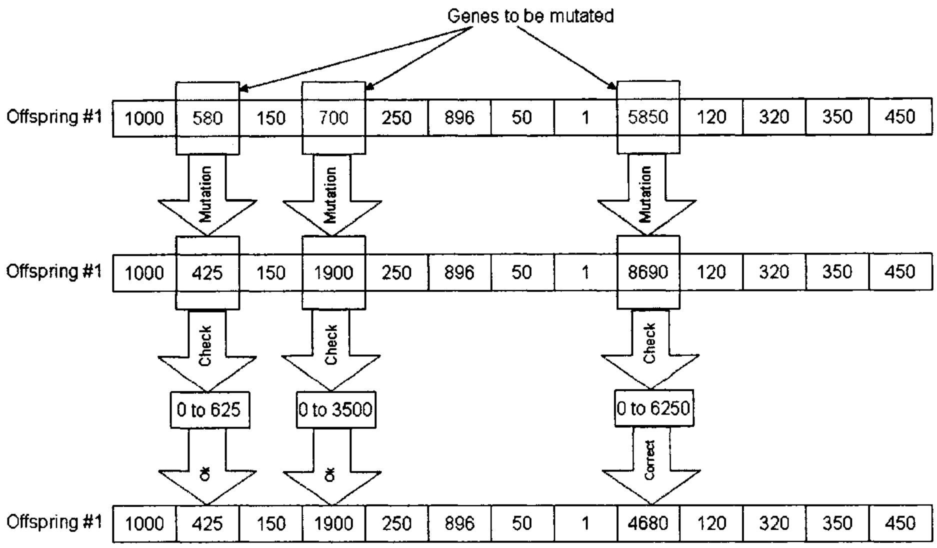


Figure 6-11 Mutation Process

6.4.5.1 Controlling Crossover and Mutation

The application of crossover and mutation is a random process controlled by given parameters which are given as a percentage of crossover, percentage of mutation, and mutation rate. Percentage of crossover is the probability of the occurrence of crossover once the parents are selected and this number is usually quite high, In this research, a probability equal to 95% was selected, meaning that 95% of the time crossover will occur.

Once the crossover stage has been completed for each offspring a certain proportion, called percentage of mutation, will be mutated. In nature, mutation is rare so the mutation rate has a very small probability to occur.

It is also worth noting that crossover and mutation are the search mechanisms in GA, Typically crossover leads near the beginning of the optimization while at later stages mutation drives the search. Depending on the problem and search domain the speed of getting the optimum solution or converging toward the optimum or near optimum solution is variable.

6.5 Intermediate-Level Budget Optimization Using GA

This section will present the process of applying GA in optimizing budget allocation for the infrastructure intermediate-level model. Optimization includes the following steps: 1) initialization; 2) application of actions; 3) fitness evaluation; 4) arrange; 5) elitism; 6) selection ; 7) crossover; 8) mutation; 9) acceptance; and 10) updating of the model. These actions will be presented in this section.

6.5.1 Population Initialization

The first step is to determine the population size or the number of chromosomes in each generation; there is no formula to evaluate the optimum number of chromosomes. The role of-thump is that the higher the number of chromosomes, the higher the chance to achieve more rapid convergence; a value between 50 and 200 is commonly suggested (Goldberg 1997), in this research, 500 chromosomes were selected for each population.

As discussed above with respect to chromosome encoding, each gene or cell contains an integer number which represents the number of units of rehabilitation strategy to be applied on the asset. This number is randomly selected by sampling a random number between 0 and 1 and multiplying that number by the available number of units in the condition, given that the total number of rehabilitated units should be less than or equal to the existing number of units in that condition.

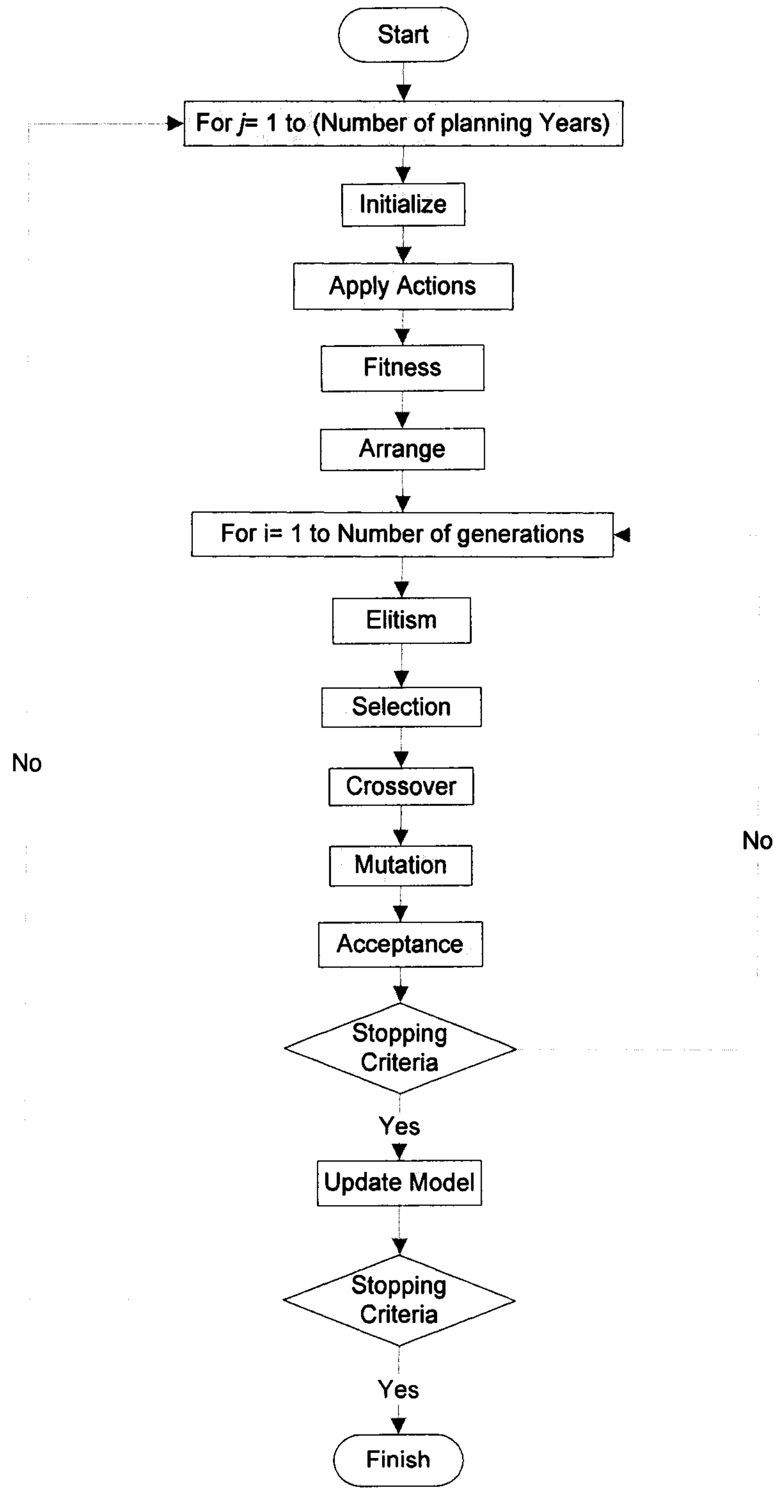


Figure 6-12 Budget Allocation Flowchart

In order to facilitate the optimization algorithm the initial population was divided into four categories in which the initialization was guided to some degree. these four categories are as follows:

1. Purely random initialized chromosomes.
2. Full rehabilitation and replacement: for each condition apply all applicable rehabilitation strategies. This applies to conditions B, C, D, and F.
3. Only reconstruction: reconstruct all the assets in condition D and F.
4. Do nothing: don't apply any rehabilitation actions.

The probability that a chromosome will follow one of the above schemes is (70%, 10%, 10%, and 10%) respectively (Figure 6-13).

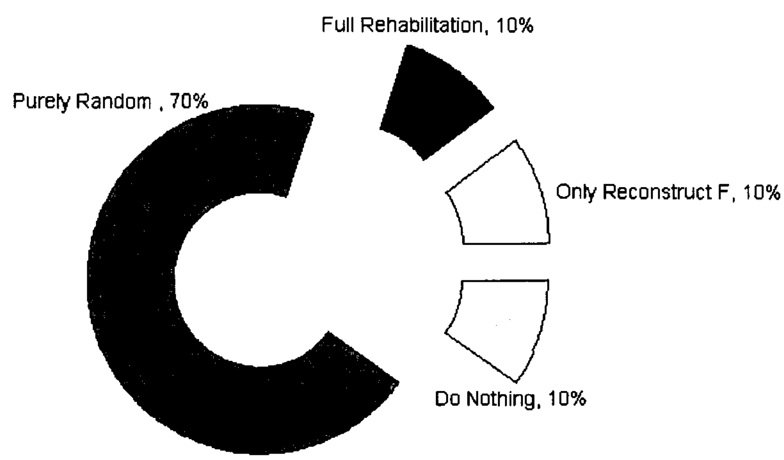


Figure 6-13 Initial Population Initialization Probability and Schemas

6.5.2 *Apply Rehabilitation Strategy "Actions"*

For each chromosome in the population, the suggested rehabilitation strategies are applied to the infrastructure model, and the resulted performance levels for each asset along with the infrastructure model are evaluated, (including condition index, percentage in conditions D and F, percentage in conditions F), and the total strategy cost is evaluated. These values will be referenced later on in the fitness evaluation. Section 2.5.2 provides an example of the application of rehabilitation actions.

6.5.3 *Fitness Evaluation*

Based on the optimization objective the fitness values are evaluated as described in section 6.3.3.

6.5.4 *Chromosomes Arrangement*

Once the fitness values are evaluated, the chromosomes will be arranged based on their fitness value. The purpose behind this arrangement is to assign a weight or selection value using the "Roulette Wheel". The higher the fitness values the higher the chance for that chromosome to be one of the parents during the reproduction phase.

6.5.5 *Elitism*

The concept behind elitism is to keep the best solution of chromosome unharmed during the reproduction phase; this is achieved by copying the top 5 or 10 percent of the current generation to the new generation without any crossover or mutation.

In this research, 5% of the generation's top chromosomes were transferred to the new generation.

6.5.6 Crossover and Mutation

Crossover and mutation were presented in section 6.3.4, this research followed that description.

6.5.7 Stopping Criteria

The optimization will be stopped if any of the following actions is activated:

1. User interruption: if the user wants the optimization to stop.
2. Reaching the defined number of generations: number of generations in this research was 1000.

6.5.8 Update Model

After the optimization is completed, the best chromosome is taken as the optimum or near-optimum solution. All of the suggested action will be executed and a new cycle of optimization will be initialized, if the planning horizon is not completed.

6.6 Model Validation

In order to validate the model results a case study was adopted from the state-of-the art identified in the literature, and solved using the model. The results were then compared. This case study goes back to 1979 and was introduced first by Karan et al (1981), and then by Kikukawa and Haas in (1984).

This case study was adopted from projects that cover a major part of the highway system in Prince Edward Island. About 116 kilometres of the network was examined, broken into 25 heterogeneous sections. Kikukawa et al (1984) used this data to make a comparison study between two methodologies assessing the network's needs. The first method is linear optimization (multi-year priority programming model by Karan (1981)) and the second one is a ranking method (rational factorial rating method by Fernando (1983)).

The next section will present the case study input, basic assumptions, and the results of the analysis.

6.6.1 Model Input

The model input data is taken from the project level, in which each section represents a project. The objective is to determine the appropriate rehabilitation strategy and best point at which to apply the strategy in that section. The case study includes 25 sections of different lengths ranging between 900m up to 13350m. The data adopted from Kikukawa et al. (1984) and shown in Table 6-1.

For each section, the length in kilometre and the current Pavement Quality Index (PQI) (scale 0-10) or serviceability index were provided. The following assumptions were used in the original analysis:

1. A minimum acceptable PQI level of 5.0 was used in the analysis.
2. A programming period of 5 years was selected.

Table 6-1 Sectional Data Summary (adopted from Kikukawa 1984)

Section	Length (km)	PQI
50	11.60	7.50
51	13.35	7.80
52	7.90	5.80
53	4.65	5.70
54	5.40	4.80
55	4.80	3.80
56	11.50	6.10
57	5.45	5.00
58	2.15	5.80
59	1.65	6.90
60	4.75	7.30
61	3.25	6.90
62	3.30	5.30
63	2.10	2.90
64	3.05	5.00
65	1.00	4.00
66	5.85	7.80
67	2.00	4.80
68	6.50	5.40
69	4.75	5.10
71	6.20	5.20
701	1.00	3.00
702	0.90	1.90
703	1.30	2.40
704	1.45	3.10

3. Deterioration modelling was carried out using Markov chain model approach in which the nonlinearity was simplified as a linear relationship. In this research, the deterioration curve was established and the relationship between PQI and time will be used for deterioration prediction. See Figure 6-14.

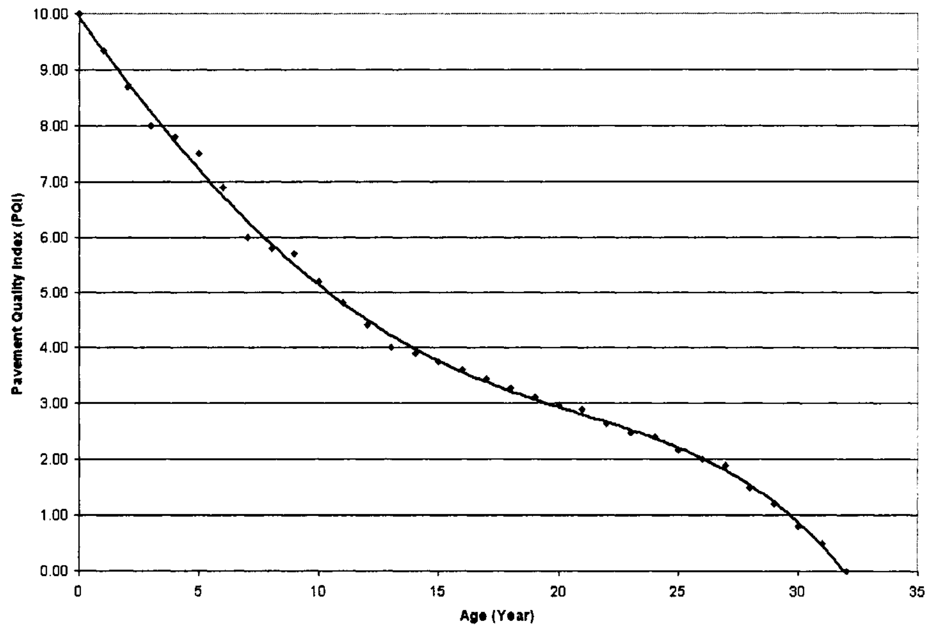


Figure 6-14 Deterioration Curve (PQI with Age)

Figure 6-14 was produced by arranging the PQI information from Table 6-1 and assuming that the Highway would live for 32 years. The curve was produced by fitting a polynomial curve to the 4th degree. The relationship is given in Equation 6-16 in which $R^2 = 0.998$.

$$PQI(Age) = -2.0E-5 * Age^4 + 0.0006 * Age^3 + 0.0062 * Age^2 - 0.5894 * Age + 9.9314 \quad \text{Equation 6-16}$$

4. The following rehabilitation actions were used in the analysis:

   1. Thick overlay: An 89 mm ($3\frac{1}{2}$ inches) thick asphalt concrete overlay placed on top of the existing pavement at a cost of $7.65/m^2. This cost is based on the analysis time and will be respected on this research.

   2. Reconstruction: A completely new pavement with a structural design of 152mm (6 inches) asphalt concrete surface and 245 mm to 305 mm (10 to 12 inches) base at cost of $22.50/m^2.

5. Three levels of the expected annual rehabilitation budget, $2,000,000, $1,000,000 and $500,000, were considered in the study. They were assumed to be constant over the five-year programming period.

6.6.2 Comparison of Results

The following assumptions were made because of a lack of information (these assumptions may affect the results):

1. The deterioration curve was established based on a typical highway life duration of 30 to 35 years, and the associated pavement's quality index was evaluated based on regression analysis

2. The cost of rehabilitation strategies includes the direct agency cost and the user benefit cost, which resulted in different costs for each of the assumed levels. The proposed model does not account for those costs.

3. The original analysis evaluated the network average pavement quality index without weighting the section length. The results were given the same weight for all the sections; whereas, the proposed model incorporates the asset length weight in the evaluation of the average pavement quality index.

6.6.2.1 Inventory Performance and Asset Distribution

The input data was transferred into the intermediate-level, in which one asset with a certain number of condition states equals the asset age. This asset is developed so that each state contains the total length of the associated sections with the same age. This distribution is depicted in Table 6-2. The network initial distribution of assets is shown in Figure 6-15.

Table 6-2 Input Date Assets distribution

Year	Condition	PQI	Length	Total	PQI*Length
1		10.00	0.00		0.00
2	A	9.34	0.00		0.00
3		8.68	0.00		0.00
4		8.00	0.00	0.00	0.00
5		7.80	19.20		149.76
6	B	7.50	16.35		122.63
7		6.90	4.90		33.81
8		6.00	11.50	51.95	69.00
9		5.80	10.05		58.29
10		5.70	4.65		26.51
11	C	5.20	16.00		83.20
12		4.80	20.65		99.12
13		4.40	0.00		0.00
14		4.00	1.00	52.35	4.00
15		3.90	0.00		0.00
16		3.76	4.80		18.05
17		3.60	0.00		0.00
18		3.44	0.00		0.00
19		3.28	0.00		0.00
20		3.12	1.45		4.52
21	D	2.96	1.00		2.96
22		2.90	2.10		6.09
23		2.64	0.00		0.00
24		2.48	0.00		0.00
25		2.40	1.30		3.12
26		2.16	0.00		0.00
27		2.00	0.00	10.65	0.00
28		1.60	0.00		0.00
29		1.20	0.00		0.00
30	F	0.80	0.90		0.72
31		0.40	0.00		0.00
32		0.20	0.00		0.00
33		0.00	0.00	0.90	0.00
			Total	115.85	681.77
				Average PQI	5.88

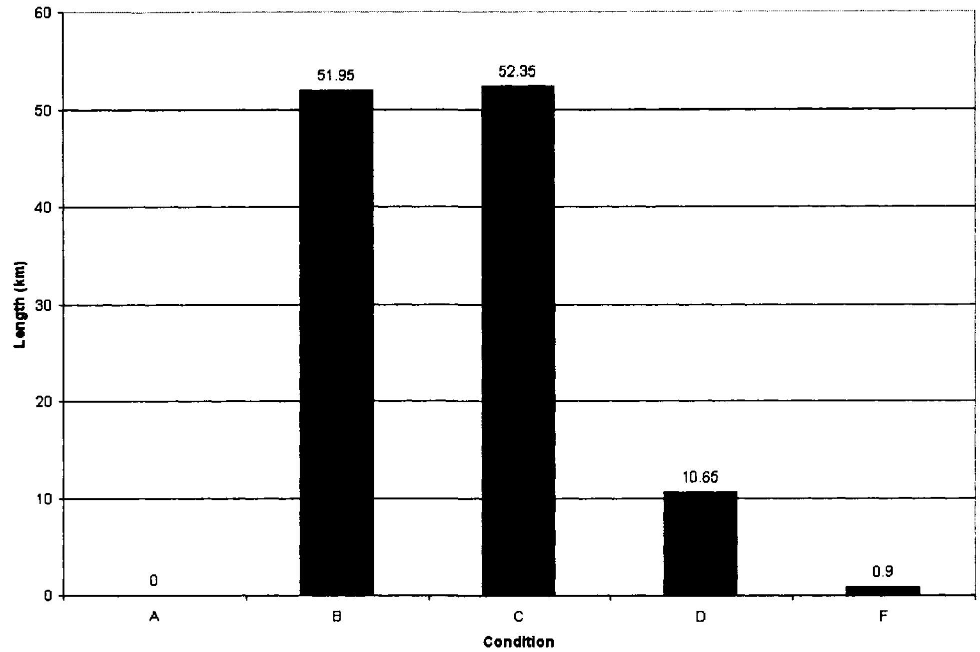


Figure 6-15 Network Assets Distribution

6.6.2.2 Multi-Year Priority Programming Model by Karan

Linear optimization was used in this analysis, with the number of decision variables and constraints listed as 375 and 401, respectively. The optimization used a software package called LP1 (created by Cyberware Computer System Ltd.). The results for each budget level are given in Table 6-4.

Based on the results shown in Table 6-4 the cost for reconstruction and overlay was computed and shown in Table 6-3.

Table 6-3 Rehabilitation Strategy Cost

Budget/Year ($ Million)	Budget over 5 years	Reconstruction (km)	Overlay (km)	Reconstruction Million/km	Overlay Million/km
0.5	2.5	10.55	17.90	$ 0.15	$ 0.05
1	5	19.10	9.35	$ 0.22	$ 0.08
2	10	28.45	0.00	$ 0.35	$ 0.12

Table 6-4 Pavement Rehabilitation needs

Budget Level	Year 1		Year 2		Year 3		Year 4		Year 5		Total Length	
	R	O	R	O	R	O	R	O	R	O	R	O
0.5 Million	57				63	55		64	65	54		
					67			701				
								702				
								703				
								704			10.55	17.9
1 Million	57			63	55		54					
				64	67		704					
				65								
				701								
				702								
				703							19.1	9.35
2 Million	55		63		54							
	57		64		703							
			65									
			67									
			701									
			702									
			704								28.45	0

R: Reconstruction, O: Overlay

6.6.2.3 Intermediate-Level Modelling Budget Optimization Results

Karan's model generated the conclusion that the strategy involving $1 million/year budget will most likely keep the network PQI constant throughout the five-year period. This case will be used to validate the proposed model. All the input data were transferred in the model, as shown in Table 6-2. The optimization was then conducted to minimize the cost, and to keep the PQI at the initial condition (PQI>= 5.88). Also, the critical assets were given constraints as in the following %F= 0% and %F+D <= 10%.

Rehabilitation actions in the model were assumed to be as in Table 6-5.

Table 6-5 Rehabilitation Actions

Rehab Cost $Million/km		
Action ID	Action	Cost
1	B→A	N/A
2	C→A	0.22
3	C→B	0.08
4	D→A	0.22
5	D→B	0.08
6	D→C	N/A
7	F→A	0.22
8	F→B	N/A
9	F→C	N/A
10	F→D	N/A

6.6.2.3.1 Budget Optimization Results for an Unconstrained Budget

The optimization model results, as shown in Table 6-7 and Table 6-8, show that an average of $1.12 Million/year is required to keep the network level at the same level of performance. The total length of reconstruction and overlay compared to Karan is shown in Table 6-6.

Table 6-6 Rehabilitation Strategies Comparison

Model	Reconstruction (km)	Overlay (km)	Total number of affected sections
Karan	19.10	9.35	11
Proposed Model	2.39	63.51	16

Table 6-7 Proposed Budget Allocation Output-Unconstrained Budget- for Network Level

	Rehabilitation investments						
	C ---> B		D ---> A		F ---> A		Recommended
Year Number	Length (km)	Cost	Length (km)	Cost	Length (km)	Cost	Budget (Thousands)
Now	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1	12.15	$972	0.00	$0	0.05	$11	$984
2	12.89	$1,031	0.30	$66	0.12	$26	$1,123
3	14.56	$1,165	0.24	$53	0.63	$139	$1,356
4	16.17	$1,294	0.31	$69	0.09	$20	$1,383
5	7.74	$619	0.60	$131	0.04	$10	$760

Table 6-8 Asset Conditions Results-Unconstrained Budget- for Network Level

	Asset Conditions							
	Asset Length Distribution							
Year Number	Length A	Length B	Length C	Length D	Length F	PQI	%(D+F)	%F
Now	0.00	51.95	52.35	10.65	0.90	5.89	10.0%	1.0%
1	0.05	52.60	51.70	10.65	0.85	5.89	9.9%	0.7%
2	0.47	60.59	43.71	10.35	0.73	5.89	9.6%	0.6%
3	1.34	58.80	45.50	9.35	0.86	5.98	8.8%	0.7%
4	1.75	55.78	48.52	9.04	0.77	5.90	6%	0%
5	2.33	51.42	52.93	8.44	0.72	5.90	6%	0%

Table 6-9 Unconstrained Budget Optimization Results for Project Level

Year 1		Year 2		Year 3		Year 4		Year 5	
Reconstruction	Overlay	Reconstruction	Overlay	Reconstruction	Overlay	Reconstruction	Overlay	Reconstruction	Overlay
P702	64	P702	R57	P702	R71	R702	R53	P703	P56
	54	P703	69	P703	62	P63	58	P63	
	67		P71		68		52		
	65				P53		P56		
	P57								

P: Indicated that a percentage of the section length to be considered

R: indicated that the reminder of the section to be completed

The relationship between the generation number and the optimum solution for the first year is shown in Figure 6-16. The values of PQI, %F+D and %F, versus the generation numbers are shown in Figures 6-17 and 6-18. This run had 5000 generations. The figures reflect only the zone where an improvement was noticed, and following that the solution was constant.

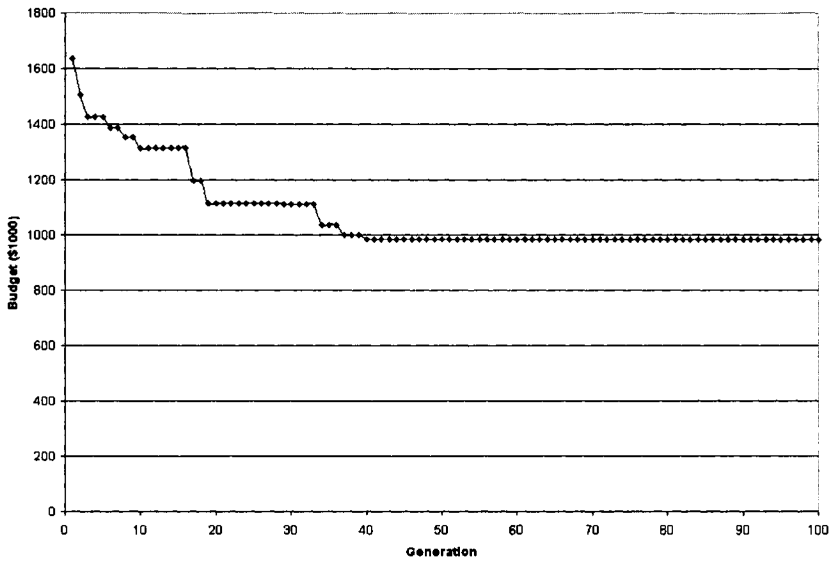


Figure 6-16 Budget versus Number of Generation for Unconstrained Budget

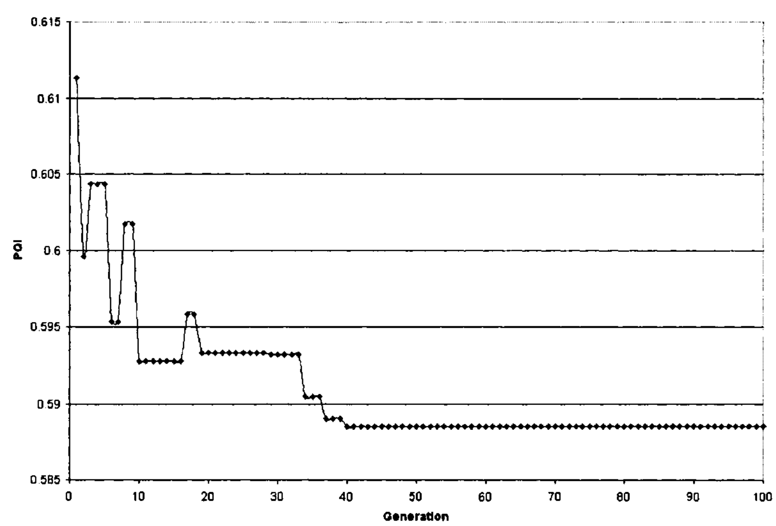


Figure 6-17 PQI versus Number of Generation for Unconstrained Budget

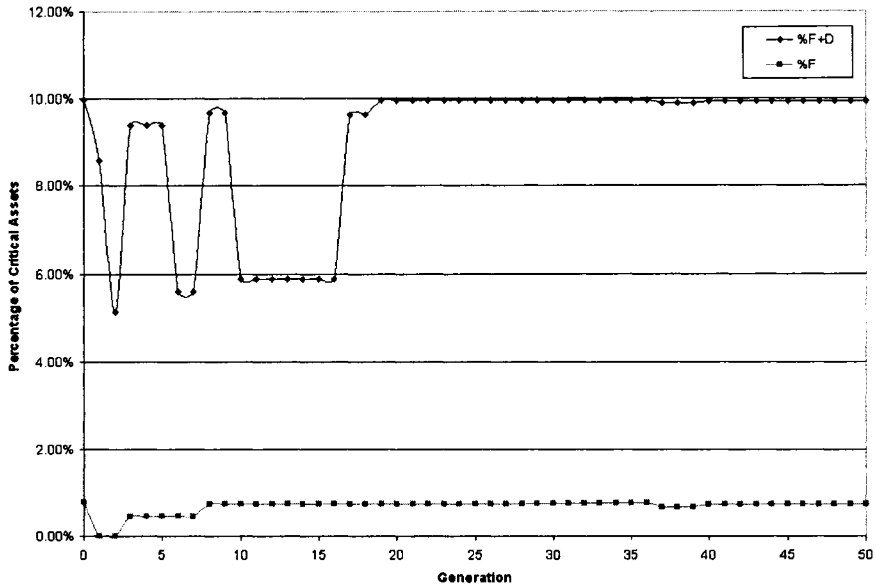


Figure 6-18 Percentages of Critical Assets PQI versus Number of Generation-Unconstrained Budget

6.6.2.3.2 Budget Optimization Results-Constrained Budget

The same model was optimized with a constrained budget of $1 million/year for a period of five years, the results show that a total of 49.22 km of overlay and 4.81 km of reconstruction are required over the period of five years, as shown in Table 6-10. The resulting performance and asset distribution is shown in Table 6-11.

Table 6-10 Proposed Budget Allocation Output-Constrained Budget-for Network Level

	Rehabilitation investments						
	C ---> B		D ---> A		F ---> A		
Year	Length (km)	Cost	Length (km)	Cost	Length (km)	Cost	Recommended Budget
Now	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1	10.16	$813	0	$0	0.85	$186	$ 999
2	10.80	$864	0.54	$119	0.08	$ 17	$ 1,000
3	11.91	$953	0.21	$ 47	0.00	$ -	$ 1,000
4	3.89	$311	3.13	$689	0.00	$ -	$ 1,000
5	12.46	$997	0	$0	0.00	$ -	$ 1,000
Total	49.22		3.88		0.93		$ 4,999

Table 6-11 Asset Conditions Results- Constrained Budget-for Network Level

Asset Conditions							
	Asset Length Distribution						
Length A	Length B	Length C	Length D	Length F	PQI	%(D+F)	%F
0.00	51.95	52.35	10.65	0.90	5.885	10%	1%
1.93	47.58	56.72	9.54	0.08	5.874	8%	0%
2.55	53.49	50.81	9.00	0.00	5.819	8%	0%
2.77	49.04	55.26	8.78	0.00	5.794	8%	0%
5.90	33.73	66.65	9.57	0.00	5.797	8%	0%
3.98	41.00	61.32	9.56	0.00	5.822	8%	0%

The optimization trends, including the relationship between the generation number and the allocated budget, PQI, and critical assets percentages, are shown in Figures 6-19, 6-20 and 6-21.

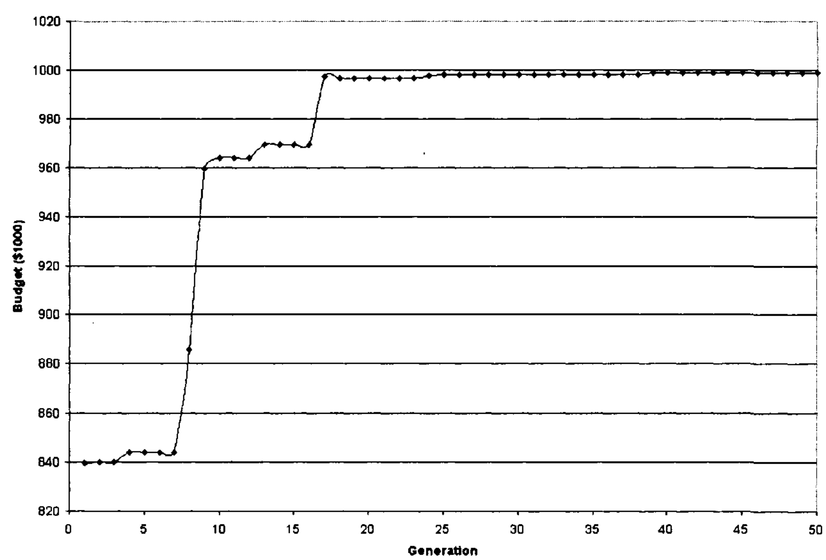


Figure 6-19 Budget versus Number of Generation- Constrained Budget

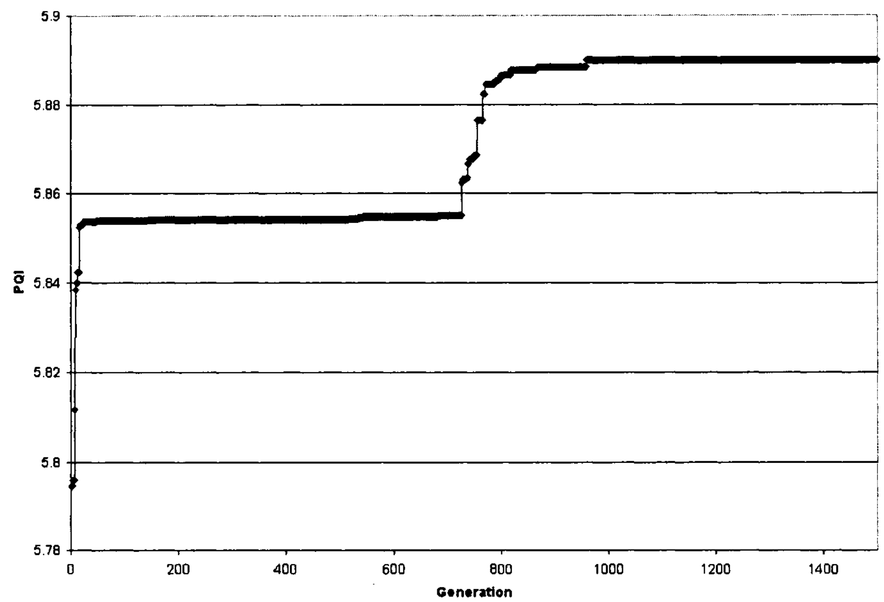


Figure 6-20 PQI versus Number of Generation- Constrained Budget

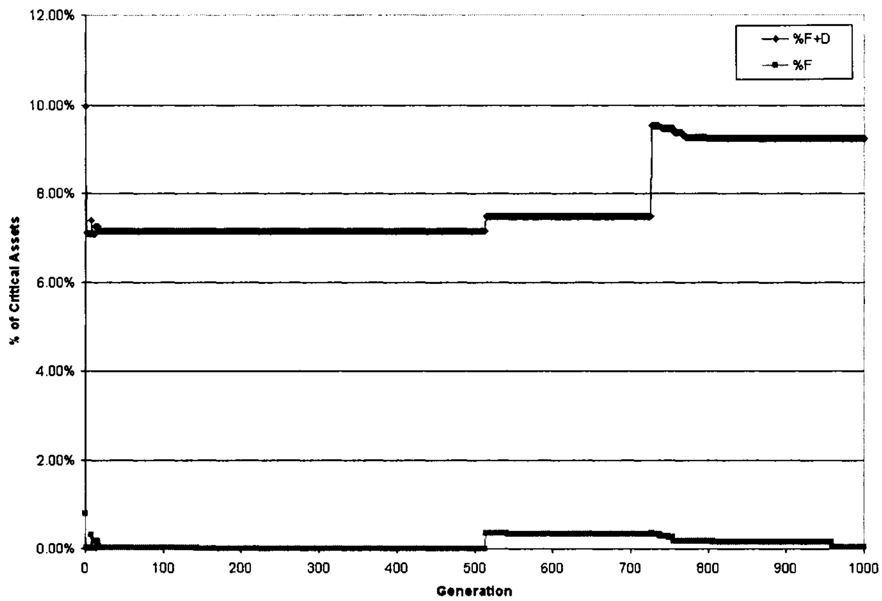


Figure 6-21 Percentages of Critical Assets PQI versus Number of Generation- Constrained Budget

By comparing the results of two runs the trend of investing more into overlay versus the reconstruction is found to be the same in both, and pavement quality index almost the same as well.

There are approximations of the deterioration behaviour (PQI vs. Age) and the difference in which the average PQI is evaluated, with those assumptions the comparison between the model results and Karan model shows strong agreement in terms of the required budget to keep the assets at the same condition, the difference between the results is mainly the adopted strategy which is due to the assumptions made in the model to select a solution with higher impact (e.g. if two solution have the same results and one of them impact 12 km and the other 20 km, the model will select the second solution.). This serves to validate the proposed model. The other important issue to consider when proposing an optimization method is the convergence of the model.

6.6.3 Assessing the Optimization Convergence

A genetic algorithm converges when most of the population is identical or, in other words, when the diversity is minimal (Louis et. al 1992). The issue of assessing the convergence of GA optimization has been discussed by many researchers. Kumar et al (2002) presented an overview of the methodologies used in assessing the convergence, including Pareto-front and rank-histogram. In this research, the Pareto-front approach along with rank histogram was used to the optimization convergence. Kumar et al presented the formulation of the multi-objective and the pareto optimal set.

Mathematically, a general multi-objective optimization problem containing a number of objectives intended to maximize/minimize, along with optional constraints to ensure satisfaction of achievable goal vectors can be written as:

Minimize/Maximize Objective $f_m(X)$, $m = 1,2,\ldots,M$

Subject of Constraint $g_k(X) \leq c_k$, $k = 1,2,\ldots,K$

Where $X = \{x_n : n = 1,2,\ldots,N\}$ is an N-tuple vector of variables

And $F = \{f_m : m = 1,2,\ldots,M\}$ is an M-tuple vector of objectives

In a maximization problem of m objectives, an individual objective vector F_i is partially less than another individual objective vector F_j , $(F_i \prec F_j)$ if:

$$(F_i \prec F_j) = (\forall_m)(f_{mi} \le f_{mj}) \wedge (\exists_m)(f_{mi} \prec f_{mj})$$

Then F_j is said to dominate F_i. If an individual is not dominated by any other individual, it is said to be non-dominated. The notation of Pareto-optimality was introduced in order to assign equal probabilities of regeneration each of the individuals (chromosomes) in the population.

Pareto Optimal Set: A set $A \subseteq Y$ (where Y denotes the entire decision space) is called a Pareto Optimal set if:

$\forall\, a \in A$: there does not exist $x \in Y : a \le x$.

6.6.3.1 Pareto-Front

According to the pareto-front approach many solutions are generated which satisfy Pareto Optimality Criterion (Optimization criteria). The set of all Pareto optimal solutions forms a surface known as a Pareto front. When dealing with two variables the surface can be generated by collecting all the solutions from the various generations.

To illustrate the Pareto front, that same example of unconstrained budget and the objective of keeping the performance level at the initial condition and %F=0 is referenced. Figure 6-22 shows the Pareto-front curve with respect to PQI, and Figure 6-23 shows the Pareto-front with respect to %F+D.

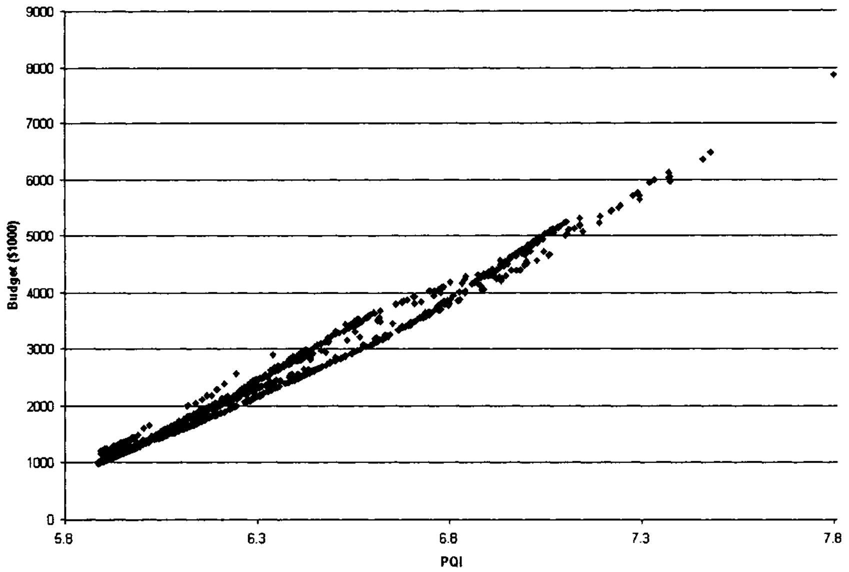


Figure 6-22 Pareto Front Generated for PQI

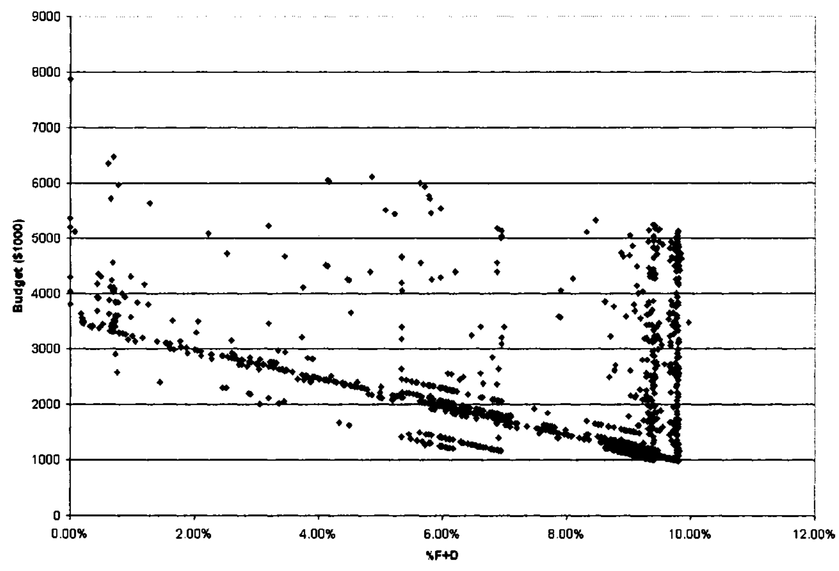


Figure 6-23 Pareto Front Generated for %F+D

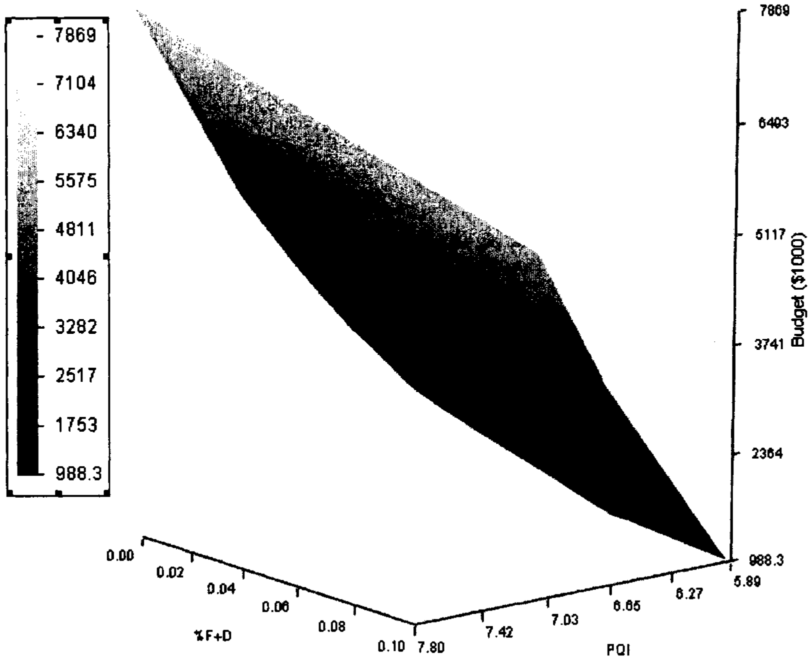


Figure 6-24 Pareto Front Surface

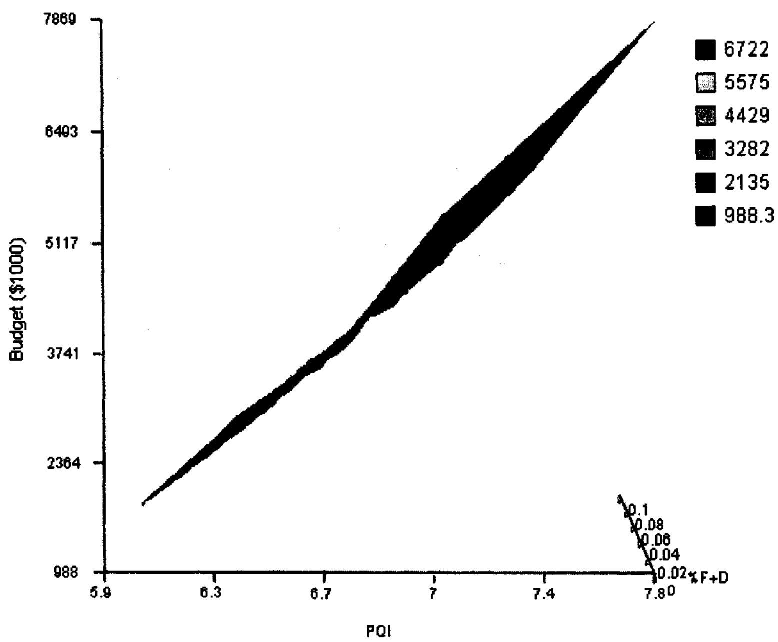


Figure 6-25 Pareto Front Generated for PQI from the Surface View

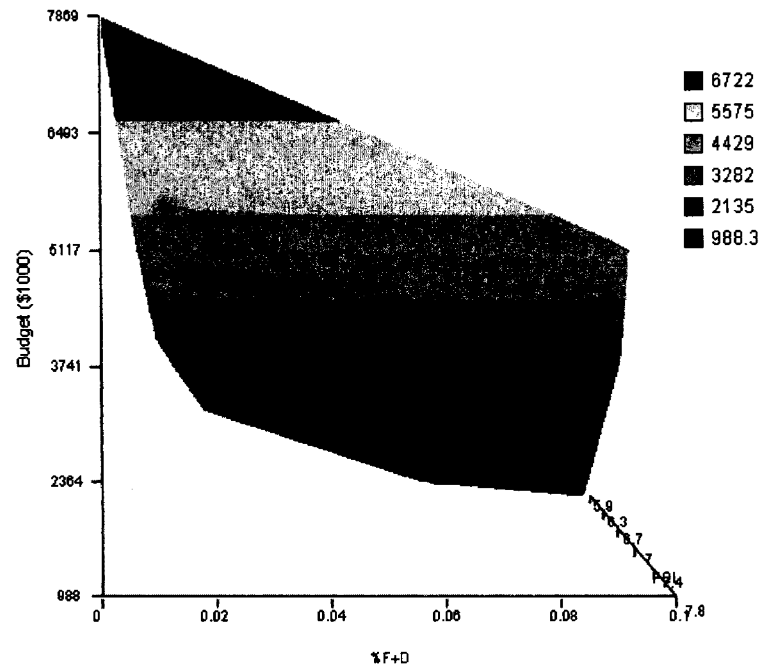


Figure 6-26 Pareto Front Generated for %F+D from the Surface View

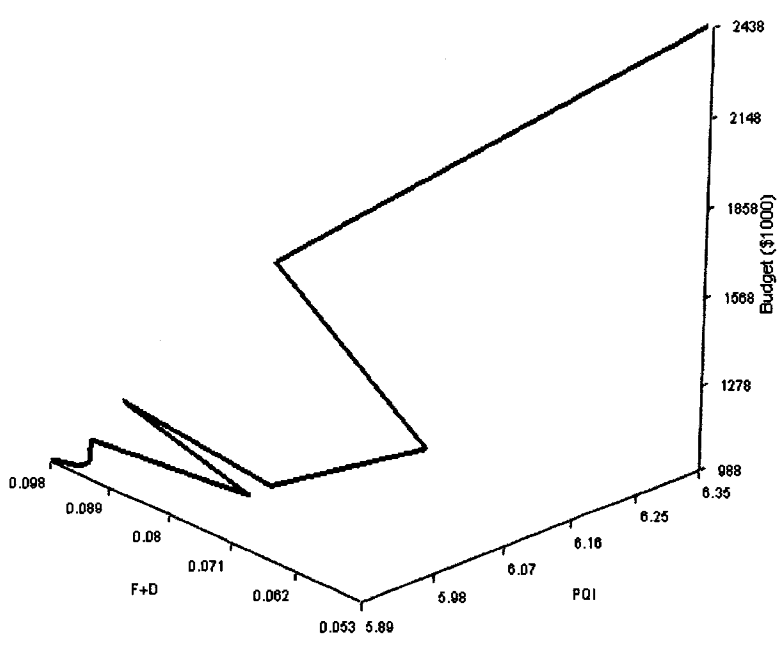


Figure 6-27 Optimum Budget Search Path

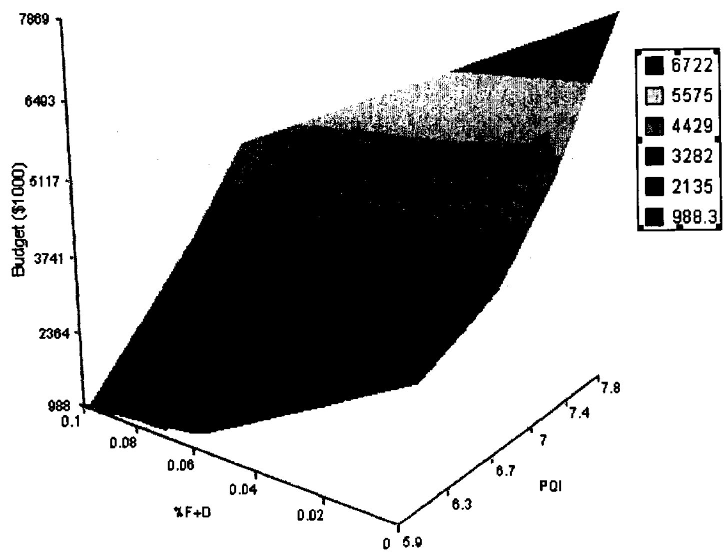


Figure 6-28 Optimum Budget Search Path Over Pareto Surface

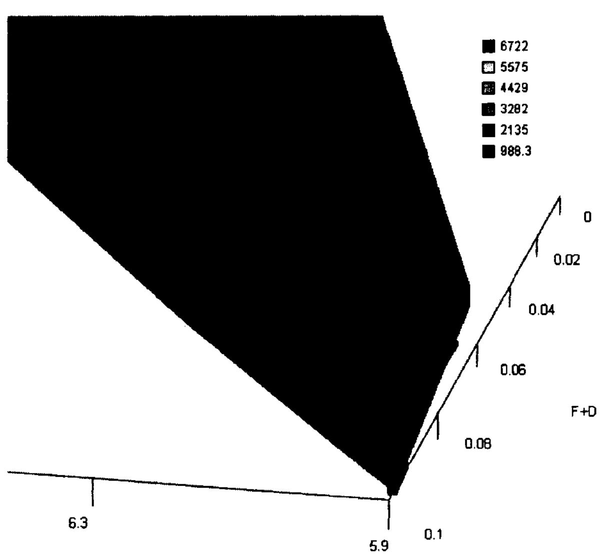


Figure 6-29 Optimum Budget Search Path Over Pareto Surface

The Pareto surface is shown in Figures 6-24 through 6-29 and was established by running the optimization for 100 generations. Each generation includes 200 chromosome which resulted in a total of (26523) acceptable solutions. In addition, to that the optimum search path which the algorithm utilized during the search for the optimum budget is plotted in Figures 6-27 and 6-29.

The optimum solution is allocated on the bottom tip of the surface. As a conclusion we can say that the algorithm converged to the optimum solution, as there are no further improvements on the solution.

The next section will introduce the Rank Histogram methodology that was applied on the solution to test for convergence, the results of which show that the algorithm has converged.

6.6.3.2 Rank-Histogram

The Rank Histogram methodology is applied by combining two consecutive population at time $t-1$ and time t, Pop_{t-1} and Pop_t, to form $(Pop_t \cup Pop_{t-1})$,then taking each Rank in turn to generate a histogram for the fraction of the members from Pop_t in $(Pop_t \cup Pop_{t-1})$ for the same Rank (Kumar, et al. 1997).

If the optimization has progressed to a perfect convergence this *rank ratio histogram* will have a single non-zero entry of 0.5. This means that all of the chromosomes in both generations have the same rank. In Figure 6-30-a the population consists of both dominated and non-dominated chromosomes and is in an unconverted state. Figure 6-30-b shows a rank ratio histogram for a converged population state.

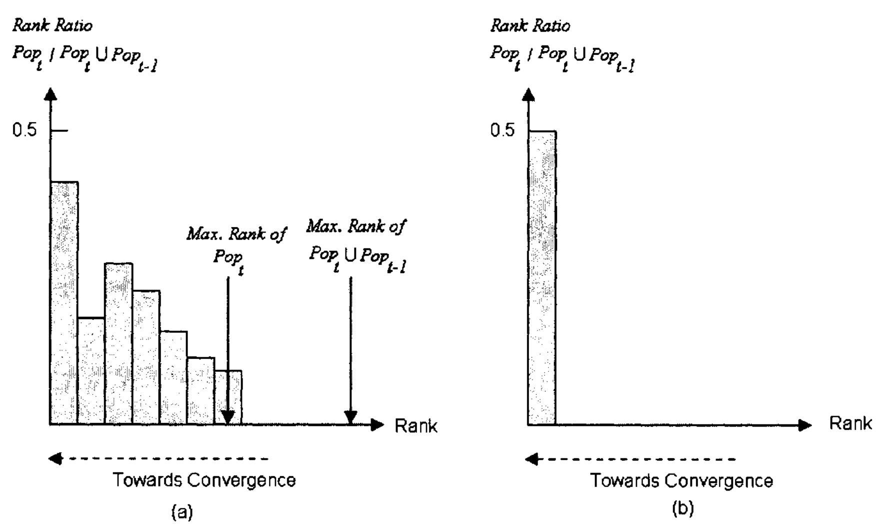


Figure 6-30 Rank Ratio Histogram of a Population (Adopted from Kumar et al. 1997)

The optimization was conducted for 5000 generations and the rank histograms were established for the following generations: 50, 100, 500, 1000, 3000, and 5000. As shown in the figures below, the algorithm converged to the optimum solution, Rank #1 (the best solution), increasing through the optimization from 0.28 (generation 50) to 0.485 (generation 5000).

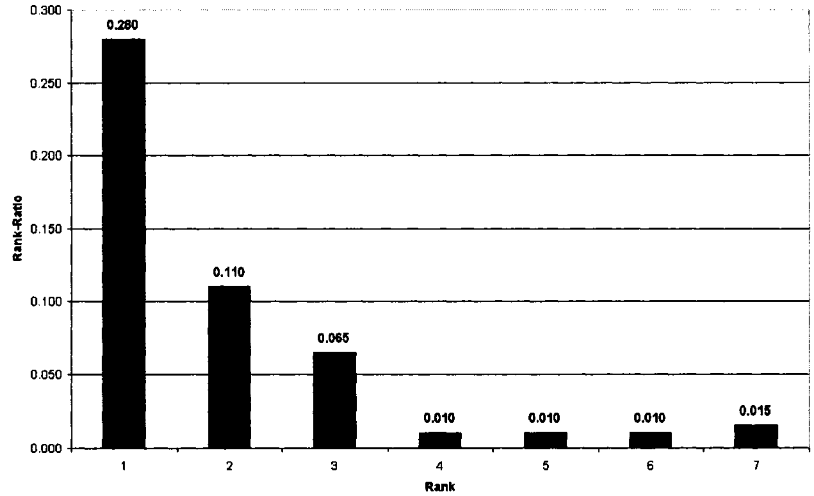


Figure 6-31 Rank Ratio Histogram for Generation # 50

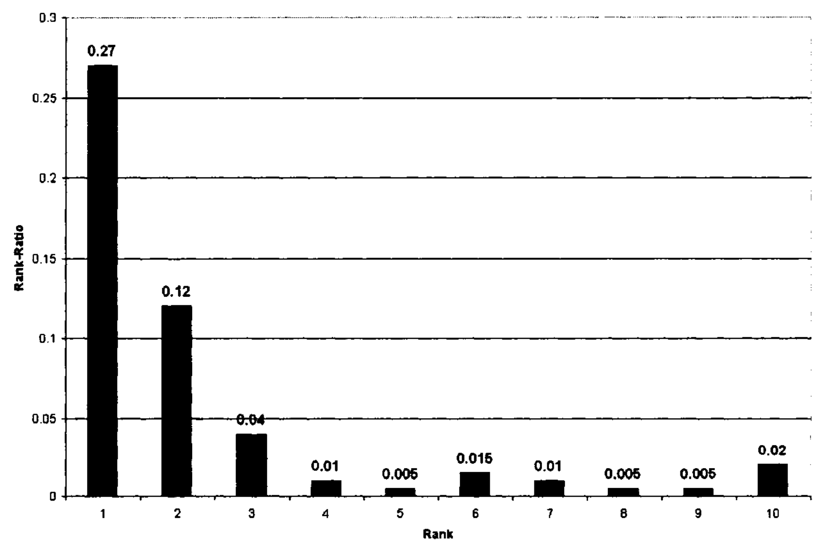


Figure 6-32 Rank Ratio Histogram for Generation # 100

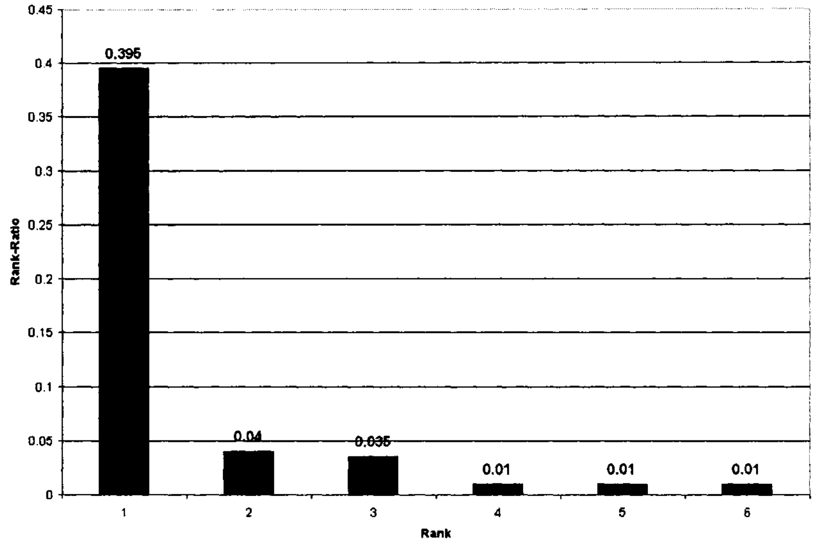


Figure 6-33 Rank Ratio Histogram for Generation # 500

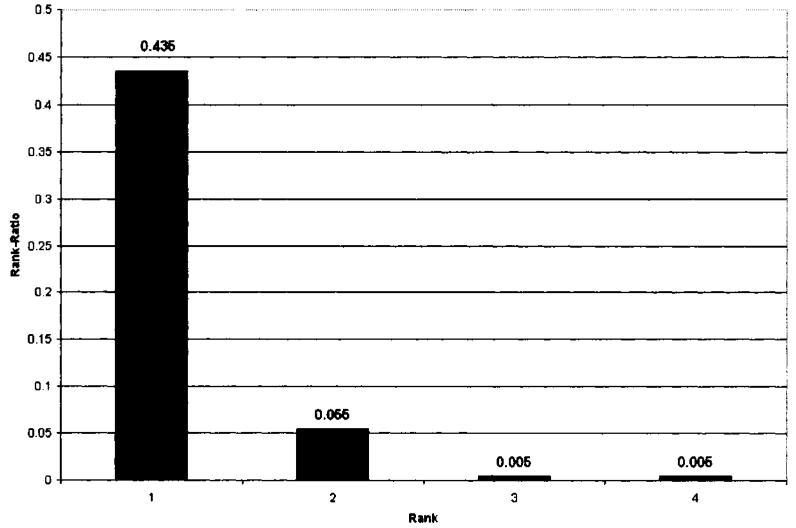


Figure 6-34 Rank Ratio Histogram for Generation # 1000

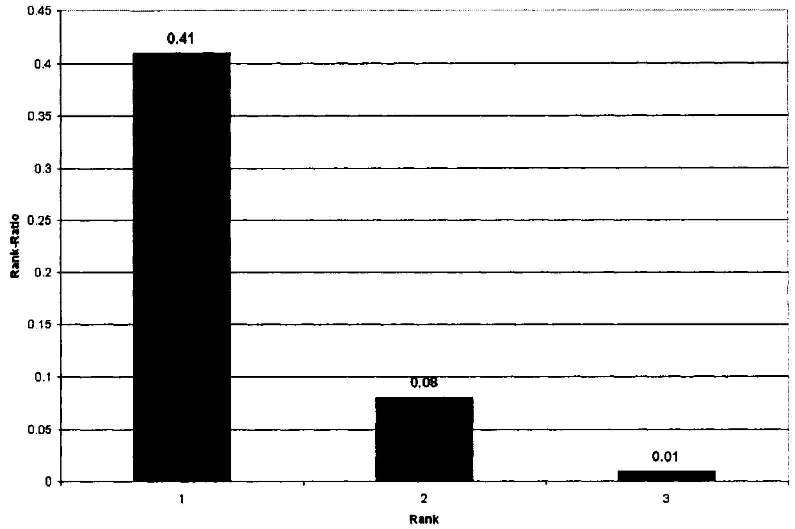


Figure 6-35 Rank Ratio Histogram for Generation # 3000

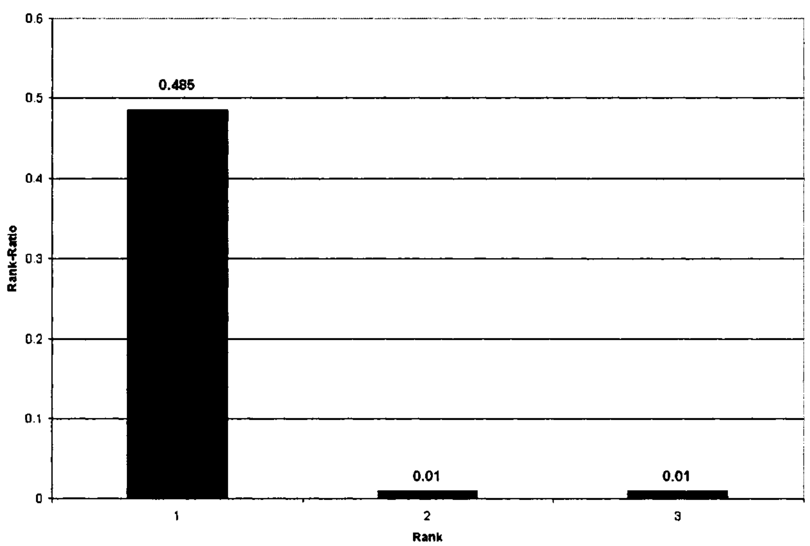


Figure 6-36 Rank Ratio Histogram for Generation # 5000

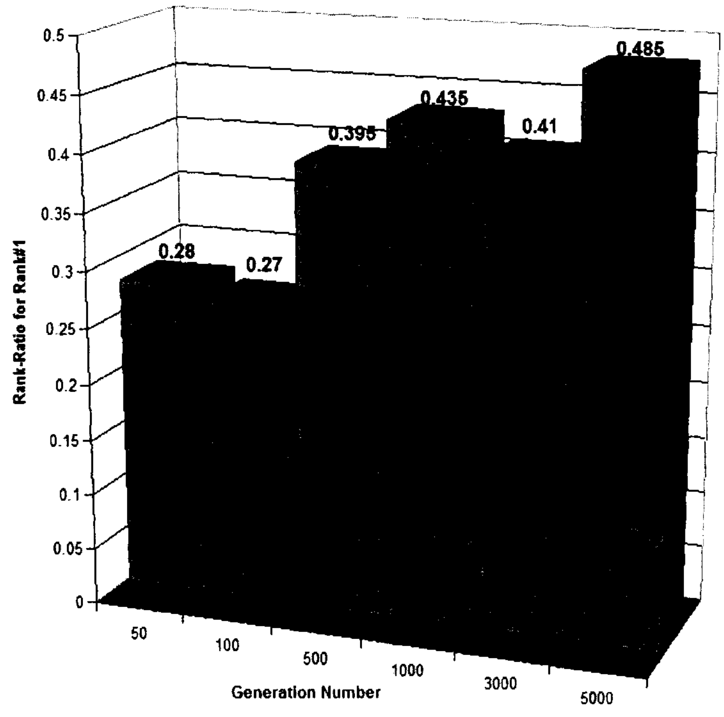


Figure 6-37 Rank-Ratio in Rank #1 versus Generation Number

6.7 Summary

This chapter presented the infrastructure intermediate-level budget allocation optimization for cases involving both constrained and unconstrained budgets, and the implementation utilizing Genetic Algorithm was explained. The adopted model results were validated by solving optimization problem adopted from the literature and comparing the results. The results showed strong agreements and served to conclude the validation of this model.

The assessment of the optimization convergence was presented by testing the convergence using two methods: the Pareto-Front Surface method and the Rank-Histogram method; both methods suggested that the model converged to an optimum or near optimum solution.

7. Case Study for Existing & New Infrastructure Budget Allocation

7.1 Introduction

This chapter will demonstrate the application of the proposed model in two types of assets: existing assets and new assets. For the existing assets, a model was adopted from a report prepared for the City of Edmonton (2003) "Toward a life cycle investment strategy for Edmonton $500 million infrastructure asset: its sidewalks" (Haas et. al. 2003). The purpose of that report was to develop a strategy that would preserve the City's sidewalk investment, so the data were transferred to the model and the optimization was conducted.

The second type are new assets, which do not exist at the moment but will be part of the infrastructure in the future. There is a great opportunity to build a sustainable infrastructure fund program to provide these assets with their needs, once materialized. The proposed model accepts the addition of new assets during the execution which would give the opportunity to model these assets and define their needs.

This chapter will present a concept for developing applicable best practice guidelines for infrastructure maintenance and rehabilitation investment. There have been attempts to develop a framework or process (e.g. Canada Infraguide) whose objective and scope is to maintain a sustainable infrastructure, but there is no indication of "how to do it". The development of such guidelines would begin by investigating the assets nature and variation, as there are number of characteristics that distinguish an asset as a unique type including deterioration behaviour, applicable maintenance and rehabilitation strategies, and the associated cost of the maintenance and rehabilitation strategies.

There are some questions that need to be answered when developing a practical set of guidelines, for example, which is best to follow: a pure reconstruction program or rehabilitation program? Or, would it be best to follow a mixed program that combines both reconstruction and rehabilitation? And, if it is a mixed program, what is the ratio between reconstruction and rehabilitation? And, during an asset life, what is the percentage of the asset value required for maintaining the asset at an acceptable level of performance? What is the relationship between the investment percentage and the minimum level of performance? These questions are legitimate and this chapter will attempt to answer some of them.

7.2 Existing Infrastructure

The existing infrastructure is unique for each owner and that is due to the difference in the assets history, including age, previous rehabilitation and reconstruction, and surrounding environment, construction defects, and extreme unforeseen events (such as floods, earthquakes, hurricanes etc.) conditions which all play a very important role in determining the assets distribution over different conditions and the assets predicted deterioration behaviour.

The case study input was adopted from a published report that analyzed the sidewalks on the City of Edmonton (Haas et. al 2003), and it is important to note that the numbers listed in this section are not intended for any application, and that the ratio between rehabilitation and reconstruction is not recommended to be used, as many of those numbers are not applicable any more.

The first step was to validate that the model generates the same results reported for the base case scenario of "do nothing". The results showed that there is good match between the two models, so the model was used in the analysis.

The next section will discuss the model input data, and the results of the optimization.

7.2.1 Model Input Data

The model input data includes the level of service measurement, the asset inventory and current (2002) level of service, deterioration curve (behaviour), applicable rehabilitation strategies, and the cost of rehabilitation strategies.

7.2.1.1 Level of Service Measurements

The City of Edmonton uses 5 levels of service scale as shown in Table 7-1.

Table 7-1 Condition Rating

Level of Service	State	Condition Rating
A	Very Good	4.5-5.0
B	Good	3.9-4.4
C	Fair	3.2-3.8
D	Poor	2.1-3.1
F	Critical	1.0-2.0

7.2.1.2 City of Edmonton Sidewalks Inventory (2002)

The total length of the listed inventory is about 3,800 km distributed over different types of sidewalks, as shown in Table 7-2.

Table 7-2 City of Edmonton Sidewalk Network Inventory 2002

	Sidewalk Type									
LOS	Concrete Boulevard (m)	Concrete Curbline (m)	Concrete Alternating (m)	Asphalt Boulevard (m)	Asphalt Curbline (m)	Asphalt Alternating (m)	Unistone (m)	Wooden (m)	Concrete Monowalk (m)	Total Length (m)
A	229,298	349,529	61,815	16,931	3,945	655	12,592	693	393,516	1,068,974
B	313,196	430,592	48,770	36,711	2,052	-	-	-	332,843	1,164,164
C	291,563	428,898	30,895	69,101	2,232	1,537	-	-	253,854	1,078,080
D	190,801	230,527	7,884	55,862	1,932	964	-	-	58,792	546,762
F	12,305	14,390	-	9,872	1,054	-	-	-	2,274	39,895
Total	1,037,163	1,453,936	149,364	188,477	11,215	3,156	12,592	693	1,041,279	3,897,875

7.2.1.3 Deterioration Behaviour

The sidewalk assumed to have linear deterioration behaviour with a total life of around 50 years, and the same deterioration was used for all the sidewalk types which were assumed to be one asset type.

7.2.1.4 Rehabilitation Strategies

For this analysis, two rehabilitation strategies were considered: reconstruction at \$150/m (F or D→ A) and trip hazard at \$55/m (D→B).

7.2.2 Model Validation

This validation was conducted to make sure that the developed model would give a result comparable to the one listed in the report. For this purpose only, the developed model was used for the base case scenario "do nothing" in which no rehabilitation would be conducted for 20 years, the results of which show that both models produced the same initial condition index of 3.93, and the condition after 20 years (2022) is 3.10. The assets distribution is shown in Figure 7-1 and Figure 7-2.

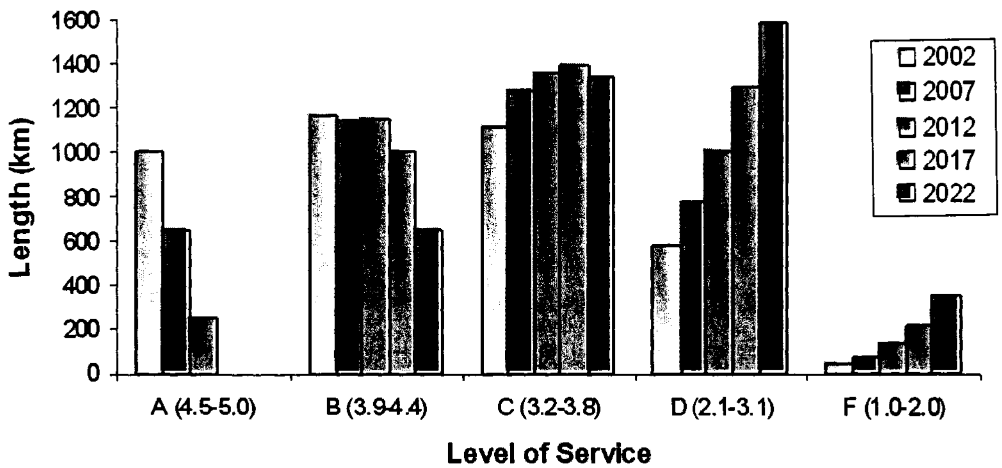


Figure 7-1 Distribution of LOS for no Replacement Budget (Haas et al. 2003)

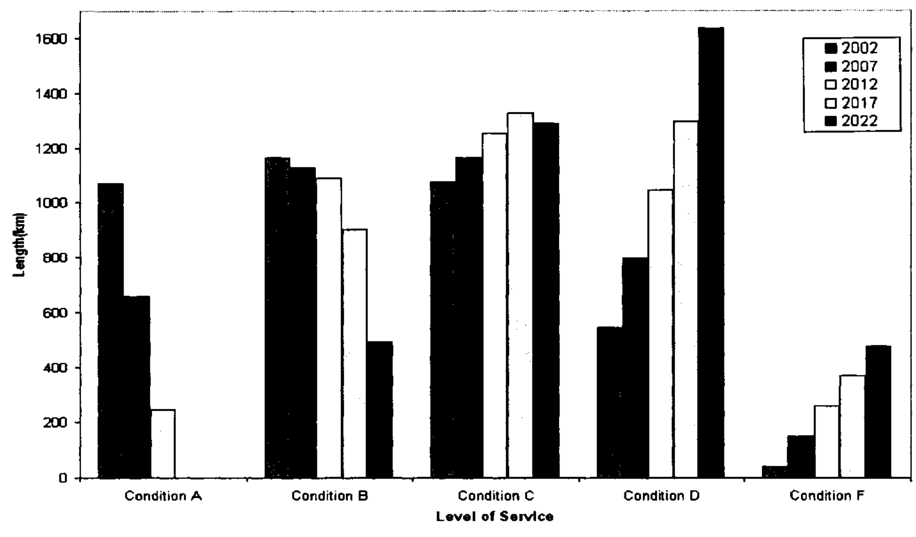


Figure 7-2 Distribution of LOS for no Replacement Budget (Model Results)

The results shown above suggest that the model produces the same results as reported by Haas et al, and the next section will present a comparison between the results of the model and the results of the studied scenarios.

7.2.3 Optimization of Budget Allocation:

The methodology followed by Haas et al was to develop a set of rehabilitation strategies and compare them and then select the best alternative to be followed. One important issue that was noted was that the rehabilitation strategy was fixed to a $500,000/year which equivalent to 9.1 km/year, and the search was done for a reconstruction strategy. The proposed model does not limit the length of rehabilitation or the length of reconstruction; they are decided by the model.

The report discussed four scenarios including "do nothing" as well as three variations of ramping up a number of kilometers of reconstruction. The third option of which resulted in maintaining the condition index as of 2002 selected to be the case of comparison.

Option number three is to replace 10 km in year 1, 20 km in year 2 "ramped up to 70 km in year 7 and continuing thereafter, in addition to that, an ongoing rehabilitation equivalent to $0.5 million/year will take place. For this option, the total present value (based on 4% discount rate) for the 20 year period is 121.07 million dollars.

Table 7-3 Option #3 Total Present Value (Haas et al. 2003)

Year	Budget ($million) Rehabilitation ($Million)	Reconstruction ($Million)	Total Budget ($Million)	Present Value ($Million)
1	0.5	1.5	2.00	1.92
2	0.5	3.0	3.50	3.24
3	0.5	4.5	5.00	4.44
4	0.5	6.0	6.50	5.56
5	0.5	7.5	8.00	6.58
6	0.5	9.0	9.50	7.51
7	0.5	10.5	11.00	8.36
8	0.5	10.5	11.00	8.04
9	0.5	10.5	11.00	7.73
10	0.5	10.5	11.00	7.43
11	0.5	10.5	11.00	7.15
12	0.5	10.5	11.00	6.87
13	0.5	10.5	11.00	6.61
14	0.5	10.5	11.00	6.35
15	0.5	10.5	11.00	6.11
16	0.5	10.5	11.00	5.87
17	0.5	10.5	11.00	5.65
18	0.5	10.5	11.00	5.43
19	0.5	10.5	11.00	5.22
20	0.5	10.5	11.00	5.02
			Total Present Value	121.07

Net present value evaluated by using Equation 7-1:

$$NPV = \sum_{n=1}^{20} \frac{Cost_n}{(1+i)^n} \qquad \text{Equation 7-1}$$

i = Discount rate (4%), n = year number

The optimization was conducted and the results are shown in Table 7-4, 7-5, and 7-6. Table 7-4 shows the net present value for the required budget with a total of $82.6 million over the 20 year planning horizon, while Table 7-5 shows the selected rehabilitation strategy and its associated cost in each year, and in Table 7-6 the expected asset distribution and performance levels are listed for each year.

The result shows that most of the selected rehabilitation actions were to do minor rehabilitation and not reconstruction.

Table 7-4 Optimization Net Present Value

Year	Budget	Present Value
1	5.70	5.485
2	4.15	3.837
3	4.44	3.946
4	4.47	3.818
5	4.78	3.928
6	5.16	4.082
7	5.69	4.322
8	6.83	4.992
9	6.08	4.270
10	6.21	4.192
11	7.27	4.720
12	6.40	3.995
13	6.54	3.930
14	6.69	3.862
15	6.88	3.820
16	7.03	3.756
17	7.23	3.713
18	7.85	3.875
19	7.54	3.579
20	9.73	4.441
	Total	82.6

Table 7-5 Optimization Results

	Rehabilitation investments										
	C ---> A		C ---> B		D ---> A		D ---> B		F ---> A		
Year	Length (km)	Cost	Length (km)	Cost	Length (km)	Cost	Length (km)	Cost	Length (km)	Cost	Recommended Budget
2002	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2003	0	$ -	0	$ -	0	$ -	42.9	$2,359,500	22.3	$3,345,000	$ 5,704,500
2004	0	$ -	0	$ -	0	$ -	71.1	$3,910,500	1.6	$ 240,000	$ 4,150,500
2005	0	$ -	0	$ -	0	$ -	72.8	$4,004,000	2.9	$ 435,000	$ 4,439,000
2006	0	$ -	0	$ -	0	$ -	81.2	$4,466,000	0	$ -	$ 4,466,000
2007	0	$ -	0	$ -	0	$ -	86.9	$4,779,500	0	$ -	$ 4,779,500
2008	0	$ -	0	$ -	0	$ -	93.9	$5,164,500	0	$ -	$ 5,164,500
2009	0	$ -	0	$ -	0	$ -	103.4	$5,687,000	0	$ -	$ 5,687,000
2010	0	$ -	0	$ -	3.1	$ 465,000	80.3	$4,416,500	13	$1,950,000	$ 6,831,500
2011	0	$ -	0	$ -	0	$ -	110.5	$6,077,500	0	$ -	$ 6,077,500
2012	0	$ -	0	$ -	0.3	$ 45,000	112	$6,160,000	0	$ -	$ 6,205,000
2013	0	$ -	0	$ -	13.2	$1,980,000	96.1	$5,285,500	0	$ -	$ 7,265,500
2014	0	$ -	0	$ -	0	$ -	116.3	$6,396,500	0	$ -	$ 6,396,500
2015	0	$ -	0	$ -	0.5	$ 75,000	117.6	$6,468,000	0	$ -	$ 6,543,000
2016	0	$ -	0	$ -	0	$ -	121.6	$6,688,000	0	$ -	$ 6,688,000
2017	0	$ -	0	$ -	0	$ -	125.1	$6,880,500	0	$ -	$ 6,880,500
2018	0	$ -	0	$ -	0	$ -	127.9	$7,034,500	0	$ -	$ 7,034,500
2019	0	$ -	0	$ -	0	$ -	131.5	$7,232,500	0	$ -	$ 7,232,500
2020	0	$ -	0	$ -	6.1	$ 915,000	126.1	$6,935,500	0	$ -	$ 7,850,500
2021	0	$ -	0	$ -	0	$ -	137.1	$7,540,500	0	$ -	$ 7,540,500
2022	2.6	$390,000	9.5	$522,500	26.3	$3,945,000	88.6	$4,873,000	0	$ -	$ 9,730,500
										Average	$ 6,333,350

Table 7-6 Sidewalks Expected Conditions

Sidewalks Conditions								
		Asset Length Distribution						
Year	Length A	Length B	Length C	Length D	Length F	CI (5)	%(D+F)	%F
2002	1068.86	1164.15	1077.90	546.75	39.90	3.93	15%	1%
2003	1008.94	1199.72	1095.59	575.71	17.60	3.93	15%	0%
2004	928.32	1263.49	1113.28	576.47	16.00	3.93	15%	0%
2005	849.00	1328.96	1130.97	575.53	13.10	3.93	15%	0%
2006	766.78	1402.83	1148.66	566.19	13.10	3.93	15%	0%
2007	684.56	1482.40	1166.35	551.15	13.10	3.93	14%	0%
2008	602.34	1568.97	1184.04	529.11	13.10	3.93	14%	0%
2009	520.12	1665.04	1201.73	497.57	13.10	3.93	13%	0%
2010	454.00	1738.01	1219.42	486.03	0.10	3.93	12%	0%
2011	371.78	1841.18	1237.11	447.39	0.10	3.93	11%	0%
2012	289.86	1945.85	1254.80	406.95	0.10	3.93	10%	0%
2013	220.84	2034.62	1272.49	369.51	0.10	3.93	9%	0%
2014	138.62	2143.59	1290.18	325.07	0.10	3.93	8%	0%
2015	56.90	2253.86	1307.87	278.83	0.10	3.93	7%	0%
2016	34.60	2272.64	1361.13	229.09	0.10	3.93	6%	0%
2017	33.00	2246.02	1442.59	175.85	0.10	3.93	5%	0%
2018	30.10	2221.80	1508.06	137.50	0.10	3.93	4%	0%
2019	30.10	2189.88	1581.93	95.55	0.10	3.93	2%	0%
2020	36.20	2146.86	1661.50	52.90	0.10	3.93	1%	0%
2021	36.20	2107.84	1748.07	5.35	0.10	3.93	0%	0%
2022	65.10	2020.32	1812.04	0.00	0.10	3.93	0%	0%

7.2.4 Sensitivity Analysis:

Sensitivity analysis in the context of optimization of budget allocation is attempting to define the relationship between the optimum budget and performance level measures. Usually when dealing with budget allocation optimization a specified minimum performance level measure is set as a constraint, but now the question is: what is the implication of changing the performance levels? And what is the relationship form, is it linear or could it be described as a curve.

Sensitivity analysis could be completed by changing one of the performance levels and deriving the required spending over a certain period of time, and then plotting those results. For the same sidewalk network a sensitivity analysis was conducted to define the relationship between the average investments over a 20 year period with Condition Index. %(F+D) and %F, as seen in Figure 7-3, 7-4, and 7-5.

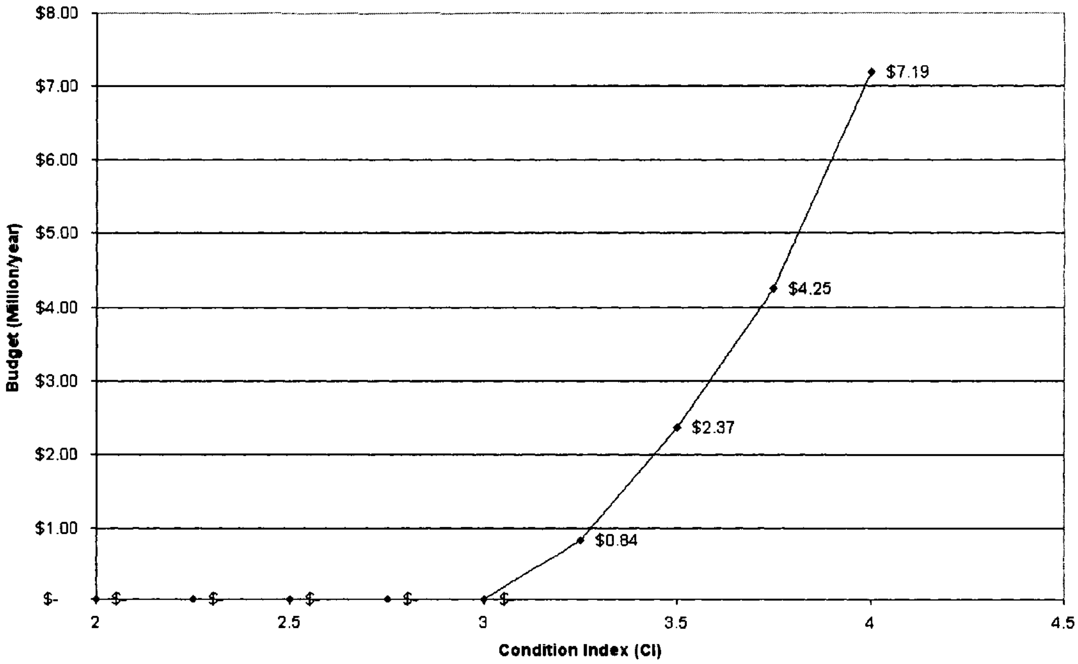


Figure 7-3 Condition Index vs. Level of Investment (Million/year) over 20 years Planning Horizon

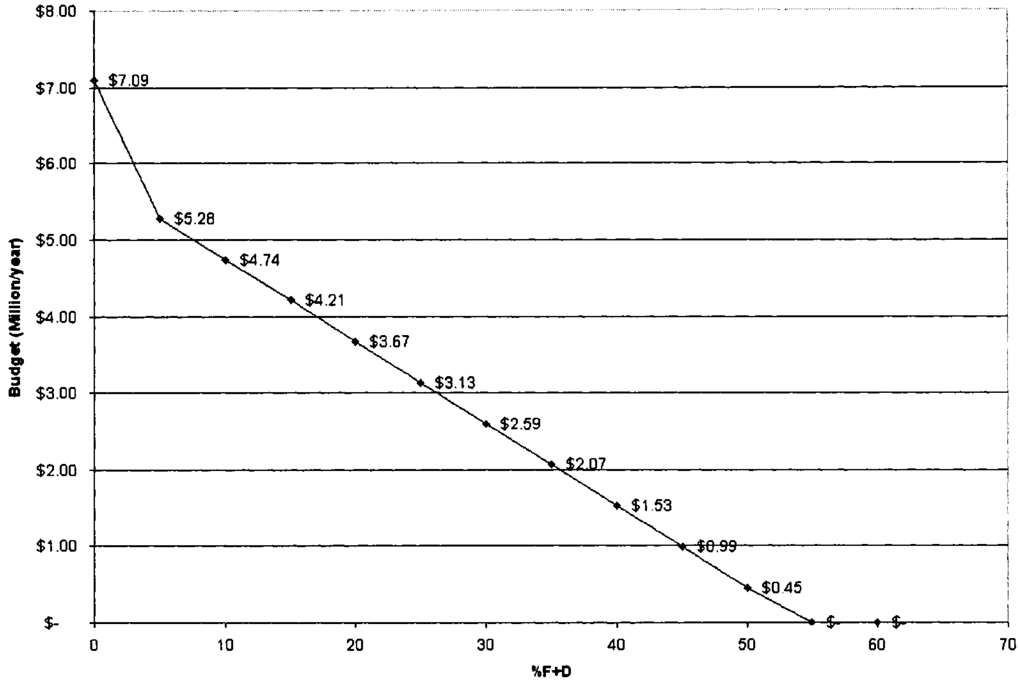


Figure 7-4 %F+D vs. Level of investment (Million/year) over 20 years Planning Horizon

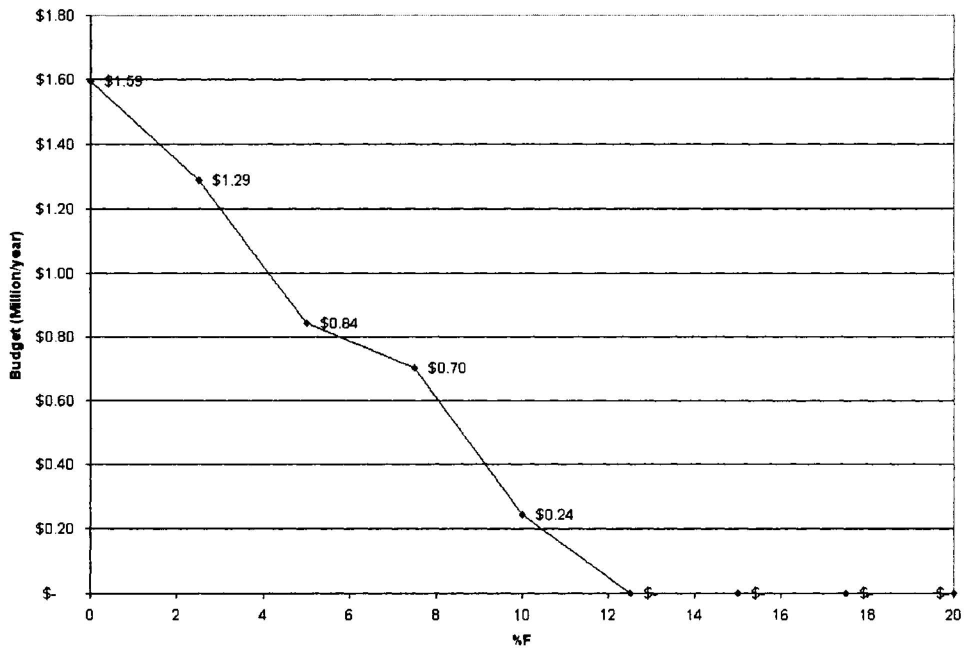


Figure 7-5 %F vs. Level of Investment (Million/year) over 20 years Planning Horizon

7.3 New Assets

In this section, the optimization of new asset will be derived for typical asset and the percentage of rehabilitation and reconstruction will be evaluated for different cost ratio between reconstruction and rehabilitation.

Five levels of condition will be used (A, B, C, D, and F), with two applicable rehabilitation actions: reconstruction (which will take the asset from any condition to condition A) and rehabilitation (which will take the asset from D: C→B condition).

Two types of assets will be considered in this section: the first is a typical asset with a short life duration that lives for about 30 years with the following life duration in each condition: A: 3 years, B: 6 years, C: 9 years, D: 12 years and then F condition. The second type of asset is one with long life duration and a total expected life duration of 120 (years A:11, B:22, C:25, D:38, and then F condition).

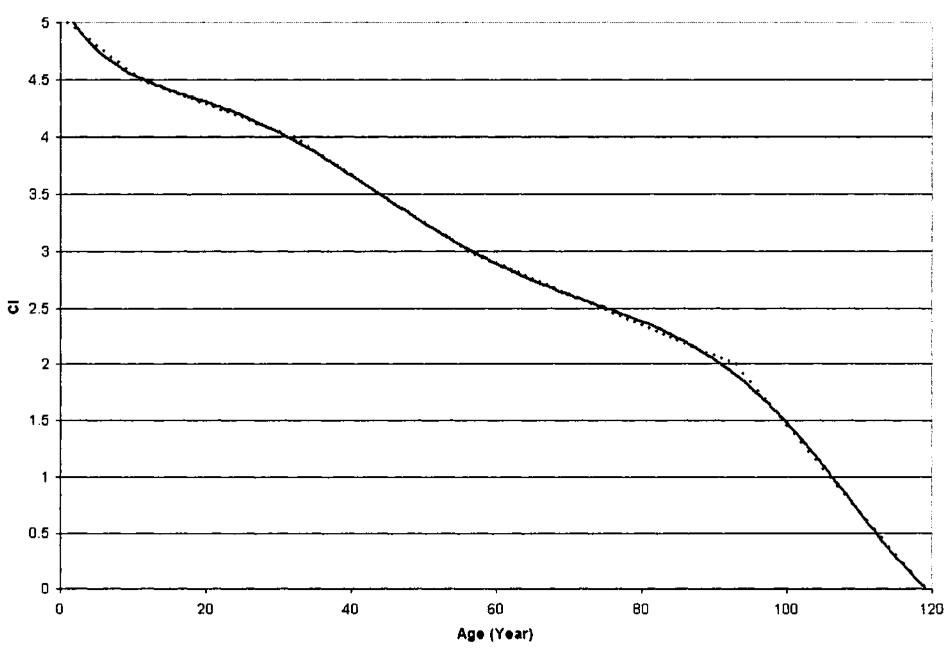


Figure 7-6 Typical Asset with Long life Duration Deterioration Curve

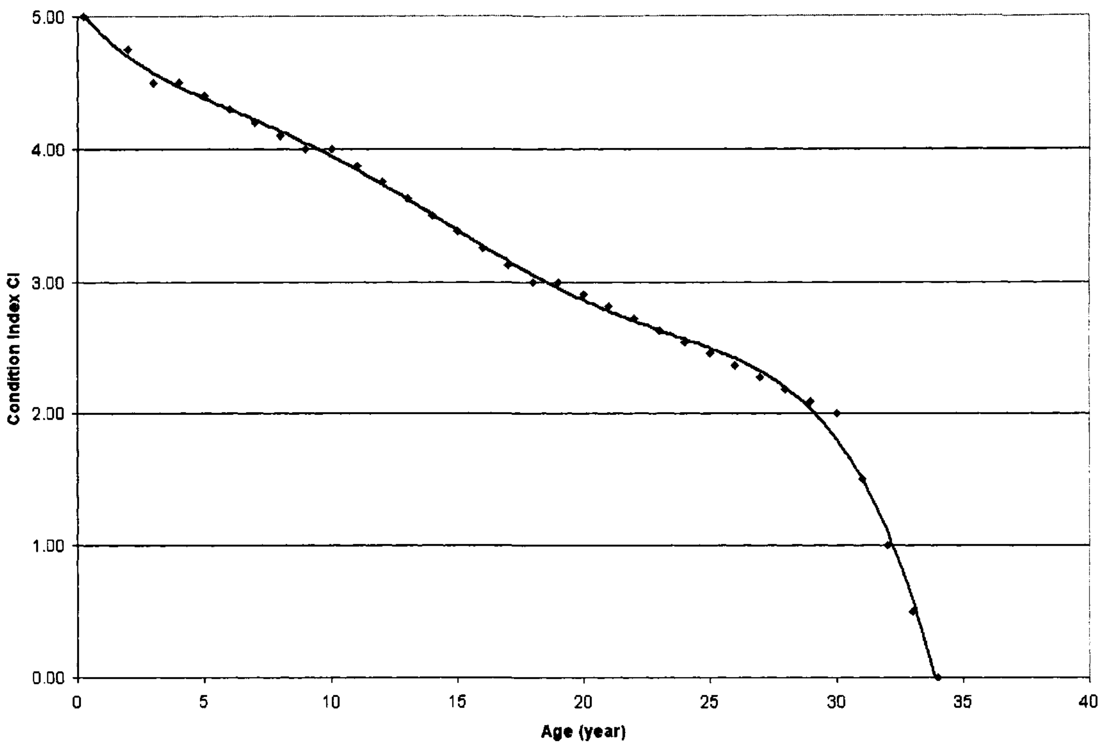


Figure 7-7 Typical Asset with Short life Duration Deterioration Curve

The new assets will start entering the model at year number 1, with a constant rate of 10 units per year until the model reaches the asset life duration. The model will be executed for 2 life cycles, and the level of performance will be changed to see how sensitive the results will be.

7.3.1 Typical Long Life Duration Asset Results

The model was run for 200 years with an unlimited budget and a constrained minimum condition index of 3.5/5.0, with the cost ratio between rehabilitation and reconstruction assumed to be 0.1, 0.3, 0.5, 0.7, and 1.0. The results of this model are shown in Table 7-7.

Table 7-7 Long life duration Asset Total Strategy Length to Keep $CI \geq 3.5$

	Cost Ratio				
Strategy	0.10	0.30	0.50	0.70	1.00
Rehabilitation (km)	1372.67	1098.80	719.37	420.83	0.00
Reconstruction (km)	74.68	327.38	635.03	853.38	1187.00
Total (km)	1447.35	1426.18	1354.40	1274.21	1187.00

As shown in Figure 7-8 regardless of the cost ratio in all cases the total length that has been rehabilitated or replaced is more than the total length, and as the cost ratio increases the length of replacement increases while at the same time the length of rehabilitation decreases. It seems that there is a point at which the length of rehabilitation is equal to the length of replacement for this particular asset with the given assumptions.

Figure 7-9 shows the expected yearly average spending represented as a percentage of the asset total value. This percentage was calculated based on the duration in which rehabilitation and replacement is applied. The percentage increases as the cost ratio increases, and it reaches a maximum value of 1.12% each year.

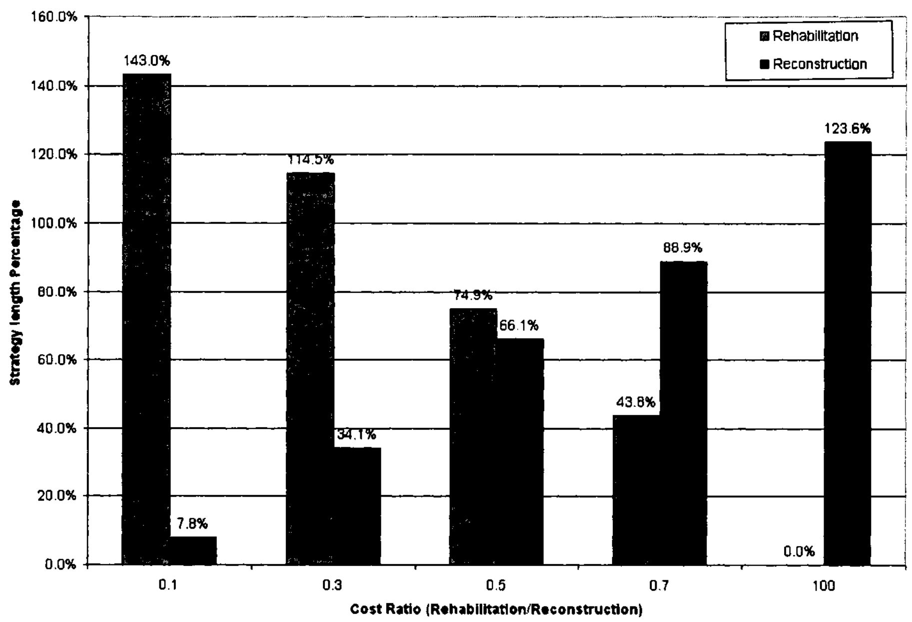


Figure 7-8 Typical Long Life Duration Asset Total Strategy length as a percentage of the Total Asset Inventory for each cost ratio to keep the Asset $CI \geq 3.5$

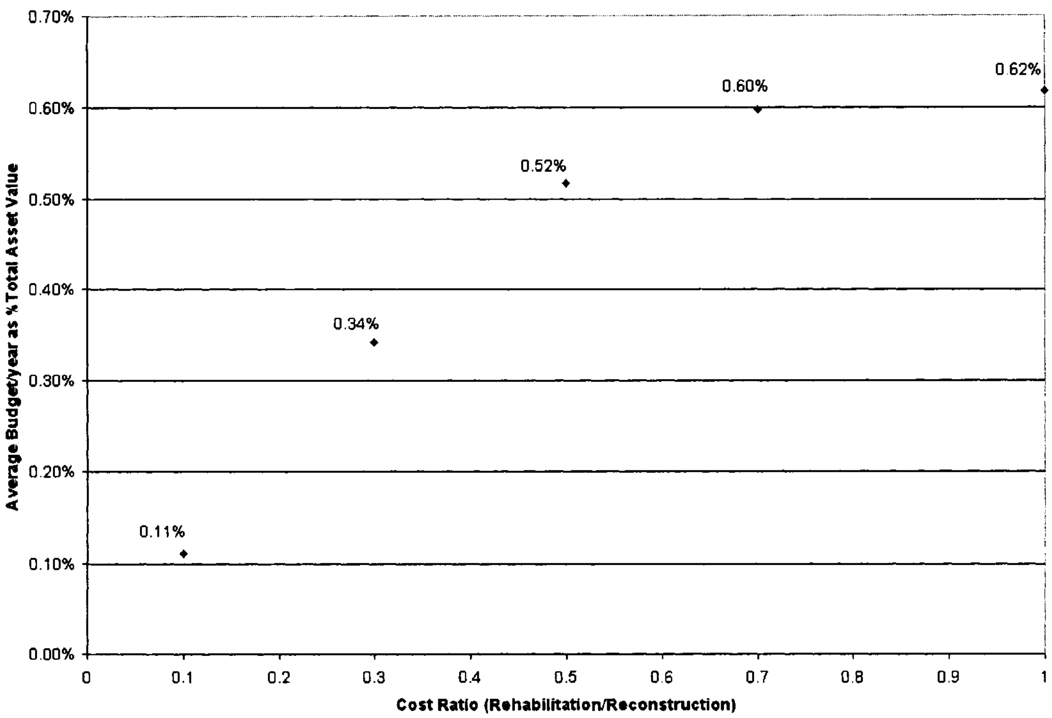


Figure 7-9 Typical Long Life Duration Asset Yearly Average Required Budget as a Percentage of the Total Asset Value to keep the Asset $CI \geq 3.5$

7.3.2 Typical Short Life Duration Asset Results

An unconstrained-budget allocation optimization for a 90-year span was conducted for the short-life duration asset for the different cost ratio, and the results of the optimization are shown in Table 7-8.

Table 7-8 Short life duration Asset Total Strategy Length to Keep $CI \geq 3.5$

	Cost Ratio				
Strategy	0.10	0.30	0.50	0.70	1.00
Rehabilitation (km)	846.02	791.95	714.52	429.35	0.00
Reconstruction (km)	20.81	67.13	134.48	368.98	701.80
Total (km)	866.82	859.08	849.00	798.34	701.80

Figure 7-10 shows the required length for each strategy as a percentage of the total asset inventory. The total percentage length is higher than what was noticed in the asset with long life duration, and in this case the rehabilitation is dominant over the reconstruction strategy.

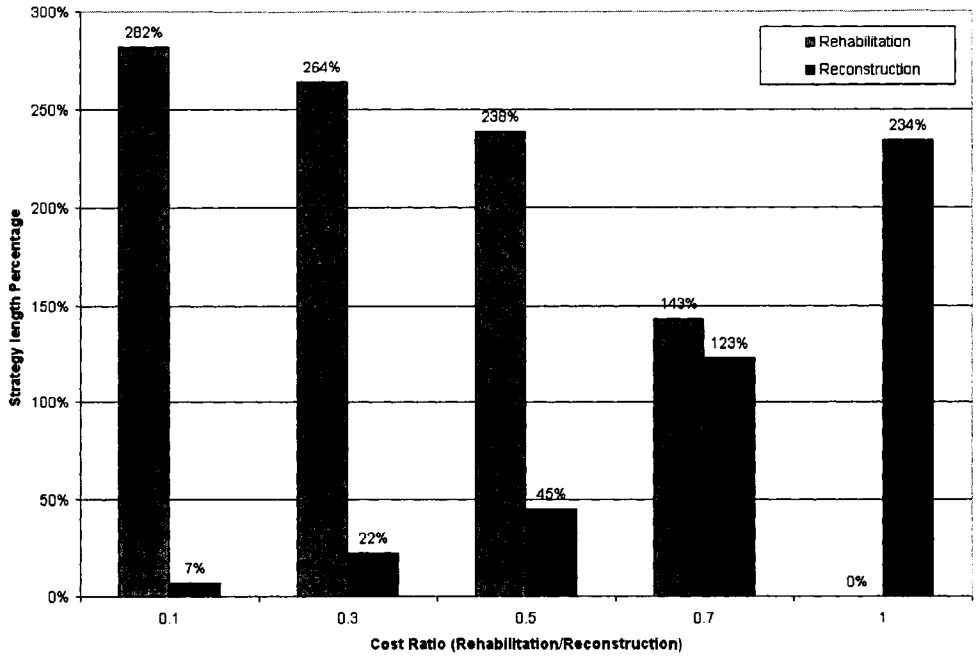


Figure 7-10 Short Life Duration Asset Total Strategy Length as a Percentage of the Total Asset Inventory for Each Cost Ratio (keep the asset $CI \geq 3.5$)

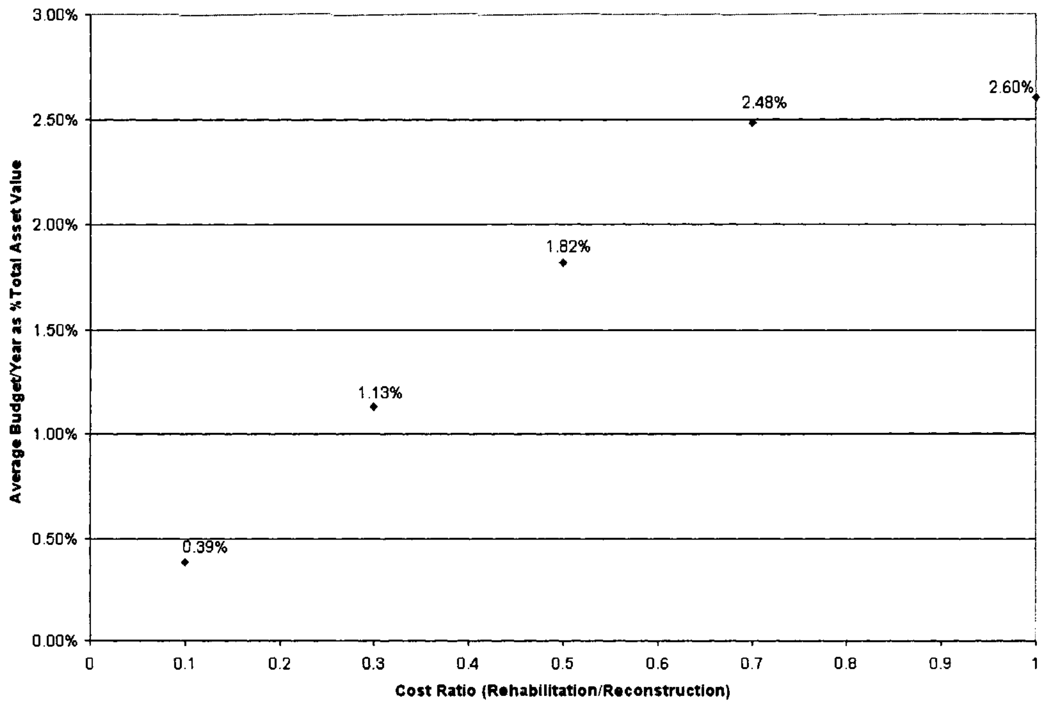


Figure 7-11 Short Life Duration Asset Yearly Average Budget as a Percentage of the Total Asset Value to keep the Asset $CI \geq 3.5$

The average yearly budget was found to range from 0.56% to 3.71% depending on the cost ratio; this value is also higher than that of the long life duration asset, as shown in Figure 7-11.

7.4 Summary

This chapter illustrated the application of the model in dealing with existing infrastructure in order to optimize budget allocation, and as described earlier the model can optimize either constrained budget allocation or unconstrained budget allocation depending on the problem in hand.

The challenge of predicting budget allocation with respect to new assets was solved by means of a variable rehabilitation/reconstruction cost ratio and, for different asset life duration, the purpose of that example is to introduce a methodology which could be used to establish optimal practice guidelines for infrastructure budget allocation. The example showed that there are direct relationships between the optimum solution and the asset life duration, as well as between the cost ratio and the different rehabilitation strategies and their improvements.

The example was developed and names were avoided in order to make it clear that this is not a solution for a specific asset and was only cited for illustration purposes. To develop such guidelines the owner must establish the desired performance level, define assets types and the associated deterioration behavior, rehabilitation strategies and associated improvement. These relationships can then be developed to aid the owner in planning for the future and predicting the required investment.

8. Conclusion

In this chapter the details of the research discussed in the previous chapters are summarized, research contributions are discussed, and recommendations for future research are presented.

8.1 Summary of Work

There is a need to bridge the gap between the network-level and project-level in modelling infrastructure. Usually, the infrastructure manager would be more interested in the network-level and not in the individual entities or elements, which are the interest of the project-level. Solving the budget allocation task, if done on the project-level, would result in large budget requirements resulting in a non-acceptable funding policy at the network-level. By adopting the network-level budget allocation strategy, the project-level would be disconnected and might result in a different allocation than the anticipated allocation at the network-level.

The proposed intermediate-level would satisfy both levels by producing optimum and practical budget allocations. The proposed framework was developed, and the results show that it could be used for both levels in a practical manner.

This research presented a robust optimization methodology using Genetic Algorithms (GA) which can be used for both the network-level and project-level. This methodology could also be applied to the existing and new assets, features which are not available in other systems.

The model components and mechanics, including the performance measures, deterioration, rehabilitation, and budget allocation, were introduced in conjunction with the formulation of budget allocation multi-optimization. This formulation was introduced for both constrained and unconstrained budget allocations.

The budget optimization utilizing GA was explained, and the adopted model results were validated by solving the optimization problem adopted from the literature state-of-the art. The results of the validation were compared, and as they were very close, the model was concluded to be validated. The assessment of the optimization convergence was presented by a testing of the convergence using two methods: the Pareto-Front Surface method and the Rank-Histogram method. Both of these methods suggested that the model converged to an optimum solution or near-optimum solution.

An existing infrastructure model for the sidewalks in the City of Edmonton was adopted from a published report, and the results of the budget allocation on the network-level showed good results. The new assets budget allocation prediction was solved with a variable rehabilitation to reconstruction cost ratio. As well, for varying asset life durations, the idea of the example was to introduce a methodology which could be used to establish best-practice guidelines for infrastructure budget allocation. The example showed that there are direct relationships between the optimum solution and the asset life duration, as well as the cost ratio between different rehabilitation strategies and the improvement the bring about.

The developed best-practice guidelines for new assets suggested that there is a solution for different types of assets with a different set of rehabilitation strategies cost ratio. This solution would be best if implemented when suggested, given that the expected deterioration behavior is accurate. This idea is similar to applying a heuristic set of rules or an expert opinion, but if the assets are not new and there is a backlog to be taken care of, then the heuristic set of rules of the best-practice guidelines might not be the best way to answer the assets needs.

8.2 Research Contributions

The accomplishment of the research objectives, the development of the infrastructure intermediate-level modelling, and the formulation and implementation of the budget allocation optimization using GA are all significant contributions to the state-of-the-art in establishing a robust and practical decision support system for linear infrastructure budget allocation. The major contributions from this research are:

1. Introducing the infrastructure intermediate-level modelling which can satisfy all levels of management, and is able to produce results that are practical.
2. The exploration of utilizing GA in optimizing the budget allocation with variable scenarios of budget constraints, as well as the presentation of the mathematical formulation and implementation.
3. The presentation of how to establish a set of infrastructure investment best-practice guidelines by optimizing new assets with variable characteristics. In this research, typical assets were used for illustration purposes and once an organization decided to develop those guidelines, actual information needs to be collected and introduced into the model.
4. This research shows the flexibility of applying GA in optimizing budget allocation problems and also the methods in which convergence could be verified. The model also used GA? to solve a real case for existing assets, the results of which compared well with those reported.
5. In terms of industry contribution, the set of components and algorithms developed in this research could be used in developing budget allocation decision support systems to help the decision makers in making the right decisions in a timely manner.
6. This research opens the doors for other researchers to solve other, larger optimization problems by changing the level of details to a higher level and adopting the intermediate-level concept.

8.3 Recommendation for Future Research

During the implementation and development of this research the following were noted and identified as potential research areas and topics for the future which could compliment this research:

1. Investigate the application of the intermediate-level for composite assets, such as buildings and bridges. This research considers only linear assets in which the failure of one unit or section will have no impact on other elements in the system.

2. Investigating the interaction between different assets in the infrastructure hierarchy. During this research we noted that the cost of replacement of one asset might include additional costs to replace other adjacent assets during construction. For example, the cost of reconstruction of a sewer pipe might include about 50% of the cost to replace the pavement. If those two assets were linked together in the model, it could be cost saving for the owner by synchronizing the rehabilitation actions of the project-level.

3. Developing an actual infrastructure best-practice guide by collecting real data for asset deterioration, rehabilitation strategies and their associated cost. Continue this by implementing the optimized and required budget for those assets to be used for future planning and development of a sustainable infrastructure investment plan.

4. Investigate the impact of using heuristic or expert charts in the prioritization of assets budget allocation at the project-level. This could be done by implementing the rules and simulating the assets over a period of time, optimizing the budget allocation using the intermediate-level model, and comparing the resulting assets conditions and total investment over the duration of the analysis.

5. Introduce uncertainty of asset deterioration and the cost of rehabilitation to the model. The uncertainties impact and causes need to be identified and quantified. It is highly important to quantify the impact of uncertainty on budget allocation and adjust the allocation accordingly.

6. As shown from the relationship between the percentage of rehabilitation and reconstruction to the cost ratio between rehabilitation and reconstruction, searching for cheaper rehabilitation methods might afford a large impact on reducing the overall required budget to maintain the assets within an acceptable level.

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