University of Alberta

Asset Levels of Service-based Decision Support System for Municipal Infrastructure Investment

by

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Dedication

This thesis is dedicated to my wife and parents for their love and support.

Abstract

The single biggest challenge facing municipalities today is a shortage of funds and labor for upgrading and expanding aging infrastructure. This continued lack of funding impairs the municipalities' ability to maintain desired levels of service. Over the last decade, many Canadian municipalities have faced pressures of increasing complexity in infrastructure asset management decision-making which can be partly attributed to cost escalation, increasing service demand and interdependencies between networks.

The goal of this research is to develop the framework for Asset Levels of Service (ALOS)-based decision support systems for municipal infrastructure network investment. The proposed framework is based on the fact that ALOS should be one of the main criteria for municipal infrastructure maintenance, repair and rehabilitation (MR&R). Since ALOS is based on qualitative and quantitative parameters, the use of ALOS in municipal infrastructure MR&R decisions will result in improved funding allocation. Secondary parameters used for municipal infrastructure investment decision making in the proposed framework are the physical deterioration of assets, future growth and the impact on the dependent infrastructure network. The proposed framework focuses on funding allocation for the MR&R of municipal networks. The framework is applicable to municipal infrastructure networks, excluding the other assets such as buildings, parks, etc.

Application of the proposed framework is demonstrated by its implementation in the case of urban roads. Implementation is carried out in four phases. Phase I involves the quantification of ALOS for urban roads. Quantification of ALOS for urban roads has

various challenges such as multiple users and interdependencies of levels of services between various users. An Analytical Hierarchy Process (AHP) has been used to quantify ALOS. Phase II involves the determination of a multiattribute utility function for investment decision. Calculated multiattribute utility of investment decision is used in the multiobjective optimization model in Phase III. In Phase IV, the proposed methodology is incorporated into a computer application called OPTIsys (OPTImum Infrastructure SYStems). OPTIsys will facilitate MR&R decision making based on fully integrated considerations of ALOS, future demand and network interdependencies.

Stakeholders benefiting from OPTIsys include the general public, asset-managers, infrastructure departments and municipal councils. OPTIsys will enable infrastructure departments to maintain the operational capability of the network in compliance with the targeted levels of service. Overall, municipalities will be able to reduce the infrastructure deficit while maximizing economic returns.

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Nomenclature

A= Relative priorities (or importance) of the attributes.

c= Vector of the attributes to be prioritized.

w = Weight (or importance) vector.

v= Consistency vector.

$\lambda_{\max}$ = Maximum or Principal Eigenvalue.

U_i = Utility of the i^{th} alternative for $i=1,2,\ldots,n$.

$u(x_{ij})$ = Utility of the i^{th} alternative with respect to the j^{th} attribute for $i=1,2,\ldots,n$; $j=1,2,\ldots,m$.

l_i = Length of the segment (i) for $i= 1,2,\ldots,n$.

los_{ji} = LOS for the user (j) corresponding to the segment (i) for $j= 1,2,\ldots,m$ and $i= 1,2,\ldots,n$.

$VLOS_{i,}$ = VLOS for i^{th} segment for $i= 1,2,\ldots,n$.

$PLOS_{i,}$ = PLOS for i^{th} segment for $i= 1,2,\ldots,n$.

$BLOS_i$= BLOS for i^{th} segment for $i= 1,2,\ldots,n$.

u(ALOS)= Utility of increased ALOS of the road section due to an investment decision.

u(NGR)= Utility change of a road section due to the projected future neighbourhood growth rate of an area where the road section is located.

u(IRI)= Utility of an increased International Roughness Index of the road section due an investment decision.

$u(EMS)$= Utility of an increased Emergency Medical Services rating of the road section due to an investment decision.

v_p = Passenger car equivalent flow rate for peak 15 minute period.

$f_{d/np}$= Adjustment factor for the combined effect of the percentage of directional. distribution of traffic and the percentage of passing zone.

f_{np} = Adjustment for the percentage of no passing zone.

f_p = On-street parking effect coefficient (=0.20).

f_b = Buffer area barrier coefficient (=5.37 for trees spaced 20 feet on center).

f_{sw} = Sidewalk presence coefficient (= 6 – 0.3Ws).

W_{ol} = Width of the outside lane.

W_l = Width of the shoulder or bicycle lane.

W_b = Buffer width (distance between the edge of the pavement and the sidewalk in feet).

W_s = Width of the sidewalk.

W_e = Average effective width of the outside through lane.

FFS = Free flow speed.

$\%\ SOP$ = Percent of segment with on-street parking.

L = Total number of directional through lanes.

ATS = Average running speed of motorized vehicle traffic (mi/hr).

SP_t = Effective speed factor.

HV = Percentage of heavy vehicles.

PR_5 = Federal Highway Agency's five-point surface condition rating.

x = Vector of road sections (or candidates) which are to be considered for resource allocation.

$\boldsymbol{\alpha}$ = Vector of values 0 or 1, depending whether the project is selected $(\alpha = 1)$ or rejected $(\alpha = 0)$.

P = Vector of treatments which can be applied to vector **x** of the road sections (or candidates).

Z = Vector of objective functions.

MAU-ID$_{ipt}$ = the multiattribute utility of applying the MR&R treatment (*p*) to the candidate (x_i) in a given time period (*t*) for *i=1,2,…,n; p=1,2,…,P; t=1,2,…,T.*

$a_{ipt'}$ = the cost incurred on candidate (x_i) (or road section) due to the selection of treatment (*p*) in year *t'* for *i=1,2,…,n; p=1,2,…,q; and t'=1,2,…,T'.*

$\alpha_{ipt'}$ = 0 or 1 for every treatment (*p)* applied to the candidate (x_i) in a given time period (*t'*), depending whether the candidate is selected or not for treatment (*p*) in year *t'* for *i=1,2,…,n; p=1,2,…,q; and t'=1,2,…,T'.*

$B_{t'}$ = the amount of budget available in the year *t'* for *t'=1,2,…,T'.*

U_c = aggregate utility of chromosome (*c)* for *c= 1, 2,…,C*

Chapter 1: Introduction

1.1 Motivation

The importance of infrastructure management has been recognized at the national level by the Prime Minister's Caucus Task Force on Urban Issues (2002), which has identified infrastructure as the most significant issue facing Canadian cities. Infrastructure deficit has emerged as one of the major challenges for Canadian municipalities. Infrastructure deficit can be defined as the difference between what is actually spent and what is needed to be spent in infrastructure assets to meet certain service standards (Mintz et al. 2006). Although asset management systems have been in existence for decades (Golabi et al. 1982; Thompson 1987), the infrastructure deficit for individual municipalities generally is continuing to increase. Due to limited resources, with respect to funding and labor, for example, municipalities are unable to reinvest in the rehabilitation of assets. Such actions have compounding consequences on the problem of infrastructure deficit.

Delays in Maintenance, Repair and Rehabilitation (MR&R) of infrastructure networks further increase the expenses due to cost escalation. For example, by the fall of 2006, Alberta's Finance Minister had conceded approximately $3 billion-worth of inflation-driven overruns on Alberta's five-year capital budget of $18.5 billion (Sadawa 2007). In the City of Edmonton, the non-residential construction price index increased 6.9% in 2005 with a projected increase of 10% in 2006 and a further 9.4% in 2007 (City of Edmonton 2006e).

Municipalities are also experiencing increasing infrastructural demands due to population growth. For example, Edmonton's metropolitan area is estimated to have received a net figure of 18,500 migrants in 2006, which is more than double the past annual average, and the trend is expected to persist for the next five years (City of Edmonton 2006e). This growth impacts the capacity and the quality of the services provided by the municipal infrastructure and should be a consideration for funding allocation in municipal infrastructure systems.

Traditionally, infrastructure decision making is undertaken by means of a Cost-Benefit Analysis (CBA) (Georgi 1973; Loucks et al. 1981; Taylor et al. 1992). CBA calculates the equivalent money value of costs and benefits related to a decision. This approach is still widely accepted (Hsieh and Liu 2004). The vulnerability of this approach becomes obvious when non-tangible benefits need to be measured and quantified in terms of a dollar value. Some shortcomings of this approach were solved by the introduction of a multiobjective decision making technique (Koopmans 1951; Kuhn and Tucker 1951; Teng 1992; Teng and Tzeng 1996; Tseng and Lu 1990).

Today's infrastructure networks create new and complex patterns of interaction amongst each other and the natural systems they affect (Allenby 2004). The degree of maintenance and rehabilitation of one network will affect the performance of its dependent networks. A decision support system must consider these inter-dependencies while selecting MR&R investment alternatives.

Levels of Service (LOS) is an index that measures the quality of service provided by an infrastructure asset to an user. LOS assists in decision making and investment planning related to the development, operation, maintenance, rehabilitation, planning and replacement of municipal infrastructure (Infrastructure Canada 2003). Asset Levels of

Service (ALOS) is the integration of LOS for all the users of an asset. In the case of urban roads, for example, ALOS is the aggregation of LOS provided by the road to automobile users, pedestrians and cyclists. Since ALOS measures the qualitative and quantitative sufficiency of an infrastructure system, a decision support system for municipal infrastructure resource (funding) allocation based on ALOS is currently needed.

1.2 Research Goal

This research aims to develop an ALOS-based framework for optimal funding allocation in the MR&R of infrastructure networks which can account for the utility of increased ALOS, network interdependencies and future growth in user demand. The application of the framework is limited to municipal infrastructure networks such as transportation, water supply and sanitation networks. Other infrastructure assets, such as buildings and parks, are not covered by the developed framework. The effectiveness of the framework is demonstrated through its implementation in the case of urban roads.

1.3 Research Objectives

The research goal is accomplished by achieving the following research objectives:

1. Provide a framework to quantify the ALOS for infrastructure networks;
2. Formulate and solve a multiobjective decision model for optimal resource (funding) allocation in MR&R alternatives based on the utility of increased ALOS, future demand and interdependencies within the networks; and

3. Develop a web-based computer application to implement the proposed research methodology.

1.4 Report Organization

Chapter 2 has been organized to give a clear and concise description of the proposed research methodology.

Chapter 3 outlines the academic literature pertaining to the research project. It gives an overview of the current state of infrastructure in Canada and in the City of Edmonton as well as City of Edmonton's infrastructure investment practices. This chapter provides an overview of the current research trends in infrastructure decision support systems. A brief discussion about the Analytical Hierarchy Process (AHP), Multiattribute Utility Theory (MAUT), multiobjective optimization theory, deterioration and costing models and Genetic Algorithms (GA) has been provided to explain the concept and theory behind these tools and techniques.

Chapter 4 to 8 illustrates the implementation of the research methodology with the working example. Chapter 4 illustrates the quantification of ALOS for urban roads. Chapter 5 illustrates the assessment of a Multiattribute Utility Function (MAUF) for the investment decision.

Chapter 6 explains the development of a multiobjective resource (funding) allocation model for MR&R treatments. The model has been integrated in the OPTImum Infrastructure SYStems computer application (OPTIsys) along with other mathematical models.

Chapter 7 outlines the algorithms and logics behind the development the OPTIsys computer application. OPTIsys is a web-based application which implements the proposed methodology. This chapter also provides a numerical example to show the application of OPTIsys in funding allocation problems.

Chapter 8 provides research conclusions along with future research possibilities.

Chapter 2: Research Methodology

The proposed research methodology executes the research objectives delineated in Chapter 1. The research methodology provides an ALOS-based framework for the optimal resource (funding) allocation in the MR&R of infrastructure networks which account for the utility of increased ALOS, network interdependencies, and future growth.

The methodology was implemented on an urban road network through the development of a web-based computer application, OPTIsys, which can be used for MR&R decision making. The proposed methodology has been divided into the following four major phases for implementation purposes:

- *Phase I:* Quantification of Asset Levels of Service (ALOS)
- *Phase II:* Determination of Multiattribute Utility Function for investment decisions
- *Phase III:* Multiobjective Decision Model Formulation and Optimization
- *Phase IV:* Web-based Computer Application Development (OPTIsys)

2.1 Phase I: Quantification of Asset Levels of Service (ALOS)

ALOS is an index representing the integrated LOS for all users of an asset of an infrastructure system. For example, in the case of urban roads, ALOS represents the cumulative expected LOS of vehicle users, bicyclists and pedestrians. LOS is represented as an index which measures the quality of service provided by an infrastructure asset (InfraGuide 2002). Determination of LOS is based on a number of factors such as qualitative measurements, legislative requirements (minimum standards) associated with an asset, financial constraints and delivery mechanisms. It is easy to measure individual LOS for a given user of an asset. The challenge lies in measuring ALOS, the combined LOS for all users of an asset, which can be used in the decision-making process. The following challenges are addressed in the determination of ALOS:

1. LOS for various users are interdependent. To quantify ALOS accurately, these interdependencies must be accounted for in the model;
2. There are limited scientifically accepted techniques for combining LOS for multiple users; and
3. Performance measures used to calculate LOS are quantitative. This necessitates the incorporation of qualitative performance measures in the assessment of ALOS.

Figure 1 shows the primary steps for quantifying ALOS. The ALOS quantification process begins with the study and analysis of existing LOS-determination models for the selected infrastructure network (Step 1). The objective is to identify suitable LOS-determination models which can be adopted into a Canadian municipal network context with minimal changes. Step 2 of this research phase is to identify the system parameters that affect LOS in the infrastructure network (in this case, in urban road networks). Expert and user input are obtained and coupled with data from the literature review to identify qualitative factors affecting ALOS (such as safety). In step 3, Analytical Hierarchy Process (AHP) is used to quantify the impact of the identified factors on ALOS. AHP is a decision-analysis method that assists in making decisions that involve a number of interrelated and contending factors. The outcome of this research phase yields a single-index ALOS which accounts for the aggregated LOS for various users of the network. The framework incorporates identified qualitative variables that are not accounted for in the capacity-based LOS models. The quantified ALOS is incorporated into OPTIsys by means of a multiobjective resource (funding) allocation model.

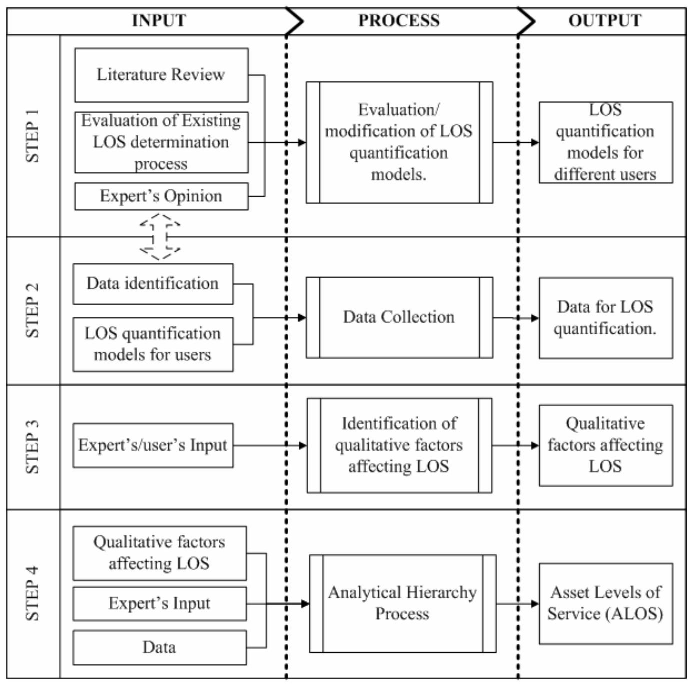

Figure 1: Phase I: Primary steps for Asset Levels of Service (ALOS) quantification.

2.2 Phase II: Determination of a Multiattribute Utility Function for Investment Decisions

Each MR&R decision impacts ALOS and the assets which are dependent upon it. In decision making, the utility change of increased ALOS is a more relevant measure than the absolute change in ALOS. Also, the usefulness of a decision may vary depending upon the existing condition of the asset. For example, overlay on road surfaces will have more value if applied to roads with a poor roughness index as opposed to roads with a good roughness index. *Phase II* involves the application of a Multiattribute Utility Theory (MAUT) to quantify the multiattribute utility of investment decision.

Step 1 of this phase involves the identification of attributes contributing to the multiattribute utility of investment decision (Figure 2). Typical attributes included in this research to quantify the multiattribute utility change due to application of MR&R treatments are: (1) increase in ALOS; (2) the physical deterioration of an asset after treatment; (3) future demands on an asset; and (4) the improvement of dependent infrastructures (in this case, emergency medical services). An utility function is derived for all the attributes affecting the impact factors listed above. Based on the needs of the municipalities, other impact factors can be identified and included in the Multiattribute Utility Function (MAUF).

Step 2 involves the use of AHP to decide the relative importance of each utility function while considering the impact of interdependencies between the attributes. In Step 3 of this research phase, all the single attribute utility functions are combined using the appropriate aggregate function to yield a MAUF. This function quantifies the utility of a particular MR&R decision. Figure 3 shows the primary steps for determining a MAUF for ALOS.

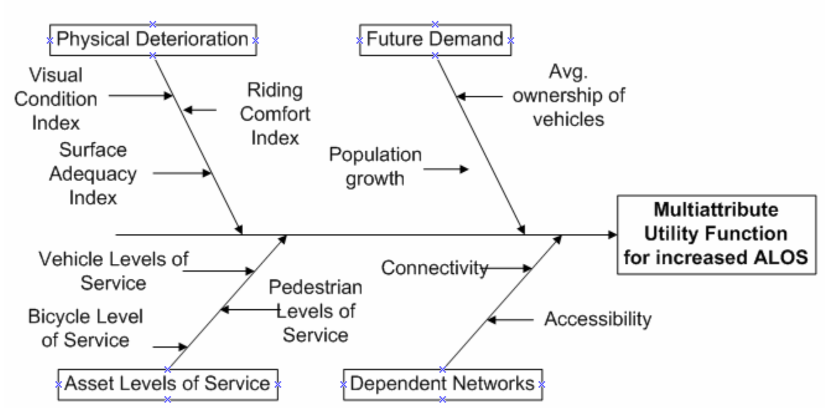

Figure 2: Interdependencies and factors impacting utility change of ALOS.

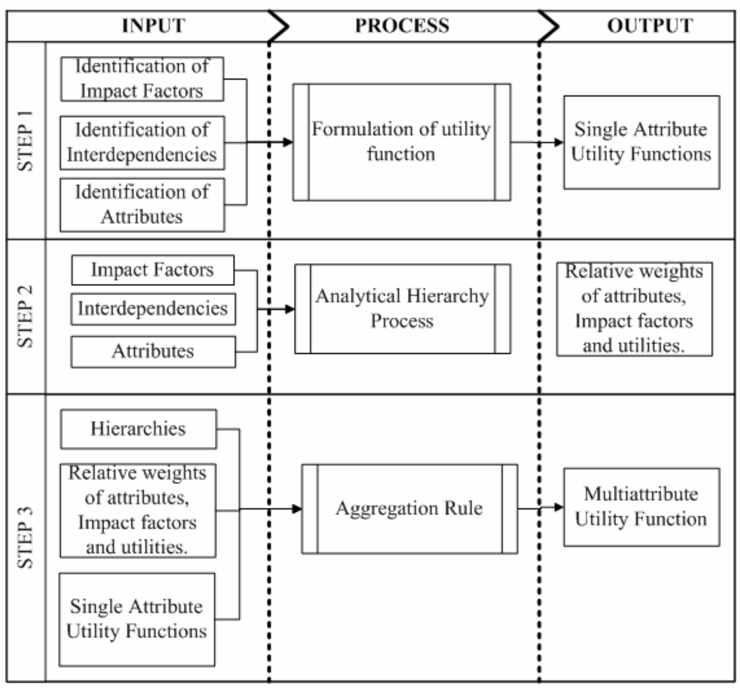

Figure 3: Phase II: Primary steps for determination of a Multiattribute Utility Function.

2.3 Phase III: Multiobjective Decision Model Formulation and Optimization

Decision making for infrastructure MR&R resource (funding) allocation is multiobjective in nature. Decisions are based on multiple and often contending objectives. This phase involves the development of a multiobjective resource (funding) allocation model and optimization technique for resource allocation.

Step 1 of this research phase involves the identification of objective functions, criterion and constraints on which MR&R funding allocation is to be based. The following objective functions have been included in the optimization model: (1) the maximization of the utility of investment decision; and (2) the maximization of budget utilization. All the identified objectives and constraints are incorporated into the multiobjective resource (funding) allocation model, which is solved by Genetic Algorithms (GA).

Step 2 involves the use of AHP to determine the relative importance of the objective functions. GA have been used to solve the multiobjective resource (funding) allocation model. GA belong to the group of evolutionary computation techniques which are based on the principle of natural evolution and selection. Step 3 of this research phase involves the development of the algorithms and the logistics to solve the multiobjective optimization model. These algorithms formulated the basis for the development of the web-based application, OPTIsys, developed in the final research phase. Figure 4 shows the proposed framework for P*hase III*.

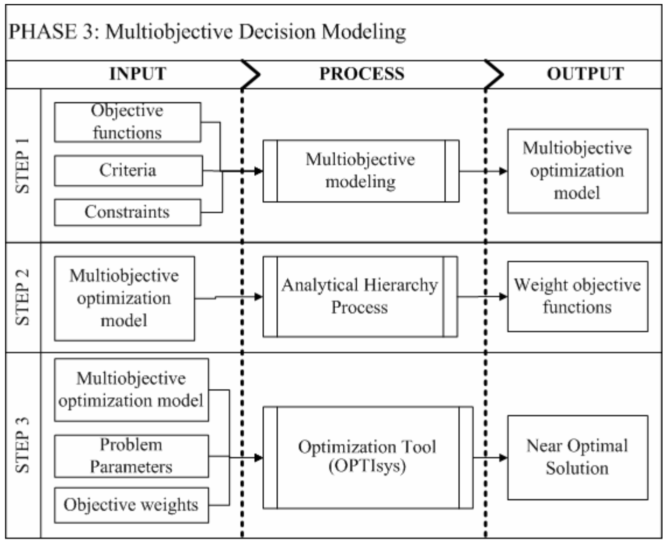

Figure 4: Phase III: Primary steps in the development of a multiobjective decision model and optimization module for funding allocation in infrastructure networks.

2.4 Phase IV: Development of a Web-based Computer Application: OPTIsys

This phase involves the development of a computer application named OPTIsys. OPTIsys is the optimal funding allocation program for the MR&R of urban roads based on ALOS. OPTIsys integrates all the mathematical models developed in research *Phases I* through *III* and implements the research methodology into the World Wide Web environment. OPTIsys allows the user to make MR&R decisions in an interactive way. OPTIsys is a web-based application developed by using *J#* and *Apache Tomcat*. *Tomcat* implements Java Sevlets and Java Server Pages and provides an HTTP web server environment for Java code to run. A central asset information repository, Asset Database, is developed in *MS Access*.

Input needed for the OPTIsys to run is shown in Figure 5. The first set of input for OPTIsys is obtained from the Asset Database. OPTIsys has a built-in module to add and edit roads in the central database. This module allows the storing of the roads' physical and functional attributes along with traffic data. In the second set of input, the OPTIsys user is asked to provide budgetary information, the analysis horizon and the various parameters for the GA. Once all the input is provided, OPTIsys runs the optimization module which is based on the models developed in the previous research phases. The results are displayed in the form of a webpage. The user also has the option to receive the results in *MS Excel* spreadsheets and text files (XML) for further analysis. XML files make it possible to share the optimization results with other applications.

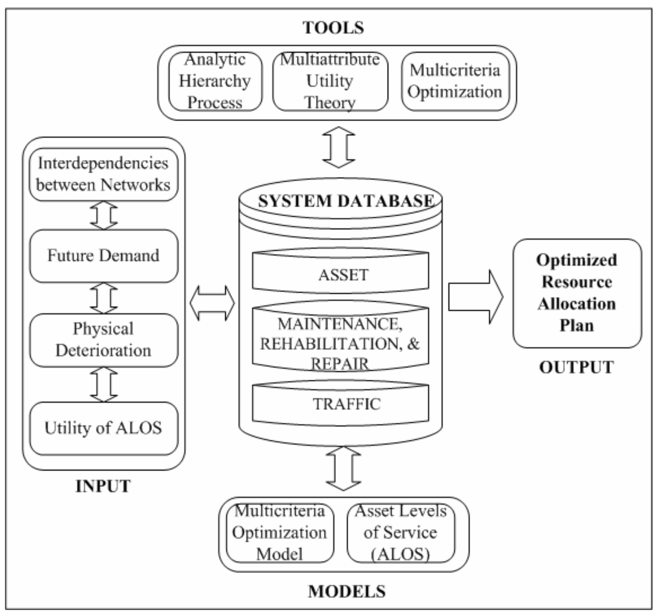

Figure 5: Architecture of OPTIsys: Application for urban road networks.

Chapter 3: Literature Review

3.1 Municipal Infrastructure

In any municipality, typical infrastructure assets are found in transportation networks (e.g., roads, bridges, walkways and transit), protection services (e.g., fire, police, emergency medical services, facilities and equipment), community services (e.g., parks, recreation, cultural and community services and amenities), general government services (civic buildings, information technology and fleet) and utility networks (e.g., water supply, sanitary sewerage, storm drainage, flood control and solid waste management). As defined by the City of Edmonton (2006b), infrastructure inventory includes "the physical assets developed and used by a municipality to supports its community's social and economic activities." In terms of taxonomy, municipal infrastructure systems can be categorized as (Poisson 2002):

Basic Urban Infrastructure: Tangible infrastructure networks such as transportation (e.g., urban roads, bridges, interchanges and transit systems), municipal sanitation (e.g., water supply, sanitary and storm water sewerage and solid waste services), protective services (e.g., fire, police and emergency medical services) and other facilities (such as street lighting, etc.).

High-Tech Infrastructure: Communication networks such as cellular and satellite telecommunications, the Internet, etc.

Amenities: Public parks, developed green/open spaces, museums, theatres, convention centers and leisure, recreational, cultural and community facilities.

Educational and Health Infrastructure: Educational facilities, libraries, research facilities, hospitals and health centers.

3.1.1 State of Public Infrastructure in Canada

Infrastructure deficit is a growing concern for the Canadian government and Canadian municipalities. It is defined as the difference between the existing and the needed infrastructure (Kitchen 2003). Kitchen (2003) summarized various studies measuring the infrastructure deficit in Canada and suggested that no study accurately gauged the infrastructure deficit in Canada. There are no established benchmarks to measure the desired levels of the infrastructure service. Similarly, studies based on the measurement of existing capital stock may be inadequate due to data limitations. Since the actual maintenance costs are not available, one cannot estimate the exact infrastructure deficit (Kitchen 2003). The problem of quantifying the deficit is further complicated by the lack of reliable information on the "status, location, capacity, performance, condition and operating costs of existing infrastructure" (Infrastructure Canada 2003).

The Federation of Canadian Municipalities has measured infrastructure deficit based on estimating the cost to rehabilitate current municipal infrastructure to an acceptable level of repair, although the term "acceptable level" was not clearly defined (Federation of Canadian Municipalities 1996). Based on responses from the municipalities, the estimated infrastructure deficit totaled $24 billion or $1,484 per capita. Hence, the projected infrastructure deficit for all of Canada amounted to $44 billion. TD Bank Financial Group (2002) published a report suggesting that the municipal infrastructure gap in Canada is $44 billion, and that it is increasing by $2 billion annually. However, the report does not mention the infrastructure assets included in the study and sources of data. Another report from TD Bank Financial Group (2004) estimated Canada's infrastructure gap to be between $50 billion and $125 billion. A report published by the Canadian Society of Civil Engineers (2002) estimated a total municipal infrastructure shortfall of $57 billion for Canada. Statistics Canada (2003) estimated the desired annual maintenance cost between $16 and $64 billion, assuming that 1-4%of the total value of its capital assets goes for maintenance.

Infrastructure in Canada is aging rapidly. Nearly 30% of Canada's total public infrastructure is over 80 years old (Canadian Society of Civil Engineers 2002). It is even argued that most of the public infrastructure in the country has passed 80% of its useful life (Canadian Society of Civil Engineers 2002). All of this implies the need for better maintenance expenditures since older infrastructure is more costly to maintain. Limited funding and labour resources often prompt municipalities to defer the maintenance of some infrastructure assets. The sustained deference of maintenance brings even more fiscal pressure on local governments (Mirza 2003). A lack of understanding, proper management tools, communication, support or a sustainable approach to infrastructure management has clearly contributed to the problem (City of Hamilton 2001).

In 2002, the Canadian infrastructure inventory was worth $ 227.5 billion, nearly 48% of which belonged to municipalities, as listed in Table 1. Table 2 shows the categorization of investments in municipal, provincial and federal public infrastructure. In 2000, municipalities in Canada invested $79 billion in public infrastructure.

Table 1: Public infrastructure inventory in Canada in 2000 (Harchaoui 2003).

	Total	Federal		Provincial		Municipal	
Year	$Billion	$Billion	%	$Billion	%	$Billion	%
1961	13.6	5.3	39.1	4.8	35.0	3.5	25.9
1973	39.0	10.2	26.1	16.5	42.3	12.3	31.6
1979	83.5	17.7	21.2	37.4	44.8	28.4	33.9
1988	153.1	29.6	19.3	63.7	41.6	59.8	39.1
2000	219.1	38.0	17.3	78.2	35.7	102.9	47.0
2002	227.5	40.1	17.6	77.9	34.3	109.5	48.1

Table 2: Public infrastructure investments in Canada in 2000 (Harchaoui 2003).

Infrastructure Category	Municipal Public Infrastructure	Provincial Public Infrastructure	Federal Public Infrastructure
	$Billion	$Billion	$Billion
Highways and roads	35.5	44.7	2.1
Sewage treatment	9.6	6.2	0.8
Sanitary sewers	13.7	2.5	1.3
Bridges	3.5	3.1	0.3
Outdoor recreational	3.2	0.9	0.3
Waste disposal facilities	1.5	1.1	NA
Other	12	6.6	6.4
Total	79	65.1	11.2

3.1.2 State of Municipal Infrastructure: A Case Study of Edmonton

The City of Edmonton's asset inventory replacement value was $20.2 billion in 2005 (Figure 6). The average life expectancy of the City of Edmonton's infrastructure assets is about 50 years, as shown in Figure 7, and the current average age of the City's infrastructure assets exceeds the 30-year mark (City of Edmonton 2006d). The City of Edmonton evaluated its asset inventory on the basis of three criteria: physical condition, demand/capacity and functionality (Figure 8). The assessment results reveal that:

- 13% ($2.6 billion) of assets are in poor or very poor physical condition;

- 17% ($3.3 billion) of assets are in poor or very poor demand/capacity; and
- 7% ($1.4 billion) of the assets have poor or very poor functionality.

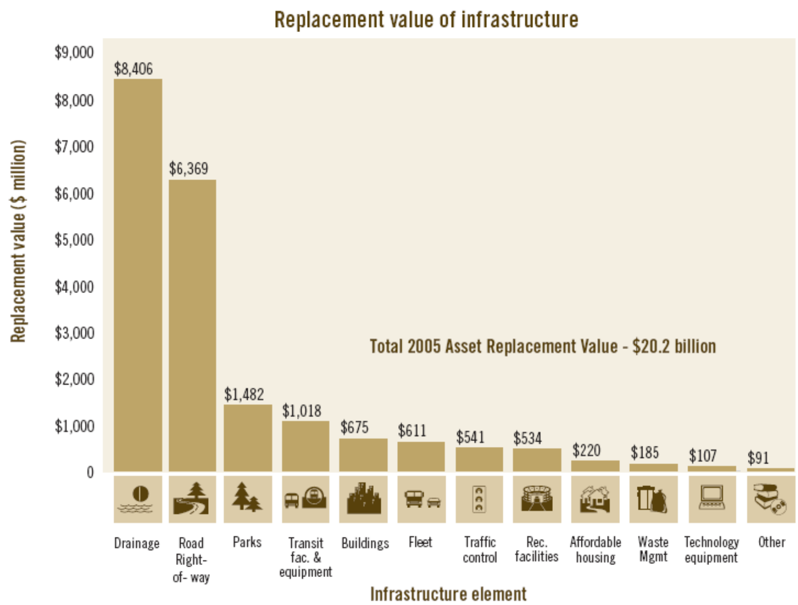

Figure 6: Replacement value of City of Edmonton infrastructure assets (City of Edmonton 2006b).

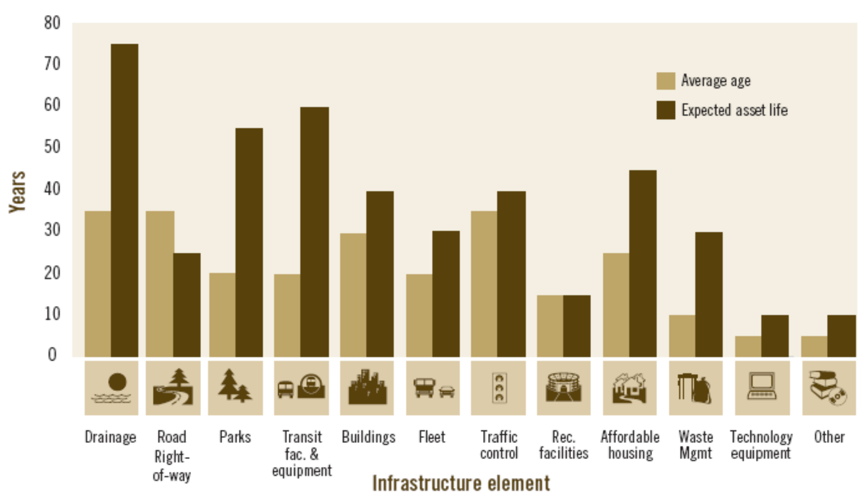

Figure 7: Average age and expected life of City of Edmonton infrastructure assets (City of Edmonton 2006d).

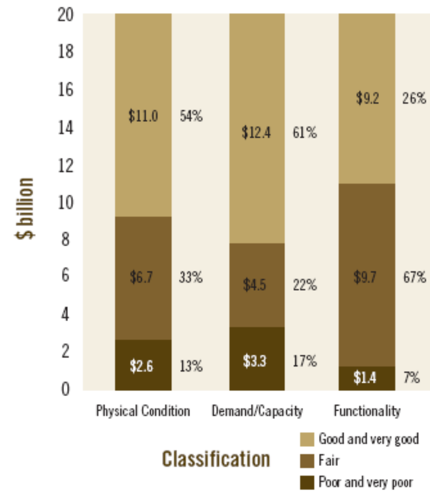

Figure 8: Condition of City of Edmonton infrastructure assets (City of Edmonton 2006d).

The City's 2006-2015 long-range financial plan estimates that the City requires $8.6 billion over 10 years for capital and rehabilitation projects (City of Edmonton 2006a). The funded portion of the long-range financial plan is close to $4.8 billion, leaving a gap of approximately $3.8 billion (City of Edmonton 2006a). Of the $3.8 billion infrastructure gap, nearly $1.7 billion (44%) is required to rehabilitate existing infrastructure; $2.1 billion (55%) is needed to fund capital projects; and the remaining $30 million (1%) is needed for other projects (City of Edmonton 2006a). Due to this shortfall in funds, some of the capital and rehabilitation projects may be delayed. The longer the delay, the more expensive these projects become.

3.1.3 Municipal Funding Allocation Practices: A Case Study of Edmonton

In the beginning of 1998, Edmonton City Council adopted a formal infrastructure strategy outlining the City's vision, goals and guiding principles for the revitalization of Edmonton's infrastructure (City of Edmonton 2006c). The vision is to have "Sustainable infrastructure, maintained through sound financial policies and asset management practices, which will contribute to the vibrancy of the City's economy; the vitality of its neighbourhoods; safety of its citizens; protection of the environment; and its capacity to accommodate growth" (City of Edmonton 2006c). The strategy identifies and addresses the various issues related to Edmonton's infrastructure, especially the growing infrastructure gap, rationale for renewal and the impact of the City's infrastructure on the quality of life. To effectively implement the infrastructure strategy, City Council created the Office of Infrastructure in 2000 with a mandate to develop and implement tools and processes to help address the projected infrastructure gap. The Office is also responsible for maintaining a comprehensive inventory of infrastructure assets, for developing and implementing strategies to reduce the infrastructure gap and for coordinating funding from different sources. An Infrastructure Technical Advisory Committee (ITAC) has also been constituted, comprised of key stakeholders in the infrastructure management process. A Capital Infrastructure Committee (CIC), consisting of managers from key civic departments, provides general guidance about the implementation of an infrastructure strategy.

Decision making for municipal road infrastructure investment is carried out at two operational levels: network and project. Network-level decision making involves the development of a priority programme to schedule rehabilitation and maintenance within budgetary limits. Project-level decision making involves engineering and design costs, construction costs and design decisions.

In the complete hierarchy of the decision-making process (see Figure 9), City Council rests at the top. It allocates the budget between the various departments such as Transportation, Asset Management and Public Works and Community Services. At this level, departments compete with each other for available funds, and each department must justify its budgetary demands. The next decision-making level is concerned with the allocation of funds to the various sectors within a department. For example, the budget for the Transportation Department will be allocated toward various assets such as roads, public transit, traffic operations and transportation planning. The Roads Budget is used for MR&R projects, capital projects and administration expenses. There can also be some constraints on budget allocation. The provincial fuel tax rebate, for instance, is only applicable for arterial roads and transit system investments.

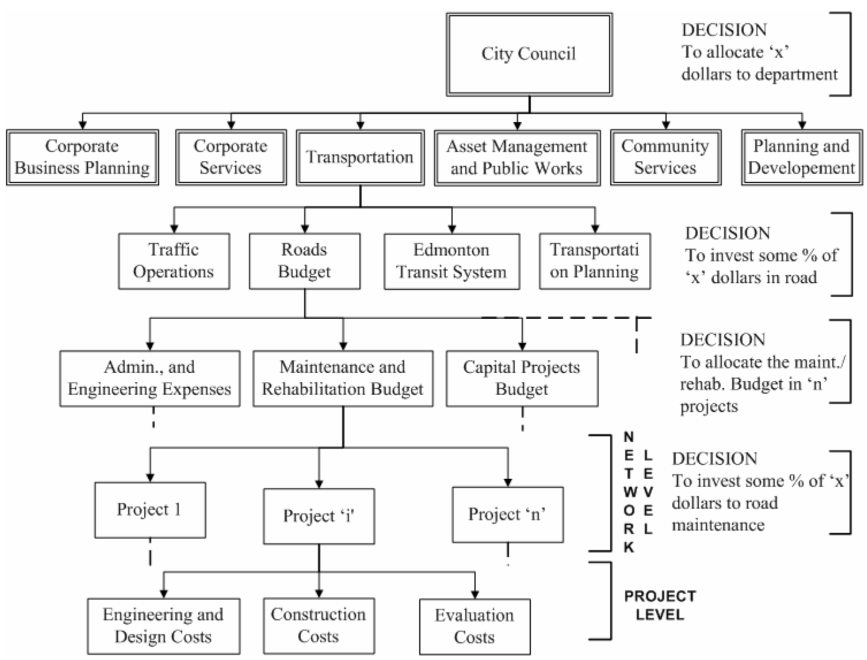

Figure 9: Example of infrastructure investments decision-making hierarchies.

The City of Edmonton uses the Municipal Pavement Management Application (MPMA) for MR&R decision making regarding road networks. MPMA is used for asset database management, analysis of assets for MR&R operations and resource allocation for MR&R alternatives. In addition to MPMA, the City also uses Geographical Information System (GIS) software, *GeoMedia* by Intergraph, to visualize the network in 2D.

The data stored in the MPMA can be categorized as MR&R, structural, traffic and peripheral data. The MPMA keeps track of all the MR&R data of an asset. This typically includes the type of MR&R treatment applied, the date of treatment and the Pavement Quality Index (PQI) before and after treatment. The structural data of an asset includes the riding comfort index, visual condition index and structural adequacy index. The MPMA combines all the aforementioned indices into an overall PQI between a range of 0 and 10, 10 being the best. The PQI is the primary indicator used by the City to determine LOS associated with a particular section. PQI values of 5.0 and 4.5 are the minimum acceptable values for primary and secondary roads, respectively. Traffic data stored in the MPMA include annual average daily traffic, the equivalent single-axle load and the number of buses passing through the section as well as the number of trucks. Peripheral data give details about the peripheral assets along a road section, including manholes, storm water disposal points, sidewalks and bicycle lanes.

The MPMA consists of an analysis module which allows the decision maker (DM) to choose a set of alternatives based on certain constraints and rules. The DM utilizes the decision tree interface to set these rules. The analysis module allows the DM to define the set of potential candidates for MR&R treatments. For each defined MR&R treatment, the following optional attributes can be recorded: pavement type before and after the MR&R treatment, unit cost of treatment and increase in riding comfort index and visual condition index. The analysis module also allows the DM to set the maintenance cost of MR&R treatments, which is a function of age, condition and type of wearing-surface.

Once the set of prospective candidates for MR&R treatment is determined, the DM uses the optimization module to select a feasible set of candidates to which MR&R treatment should be administered. The MPMA's objective is to maximize the average PQI of the network within a given budget. The prediction of an asset's PQI deterioration is based on a generic deterioration model coded in the MPMA. If enough historical data exists, the future condition of the asset can be predicted using regression analysis.

3.2 Municipal Infrastructure Management Systems

Infrastructure management systems have been in existence for the last 35 years. In the case of transportation networks, these systems broadly address the management of asset safety (on pavements, highways, etc.); public transit assets, inter-modal facilities and functions; and the monitoring of traffic data (Markow 1995). Typical examples of infrastructure management systems include highway survey systems, pavement design and analysis systems, optimization of rout alignment systems and maintenance management systems. This literature review explores the Decision Support Systems (DSS) related to the MR&R of road networks.

DSS were previously stand-alone applications (e.g., pavement management system, bridge management system, maintenance management system, etc.) with limited data exchange capabilities (Markow 1995). The perception of DSS changed in the 1980s with the introduction of desktop computers. This led to the development of new tools to aid decision making in the MR&R of road networks. Past research in the infrastructure investment area can be broadly categorized into three areas: 1. Development of an investment model and programming methods to solve the model (Taylor and Keown 1983); 2. Economic evaluation of infrastructure investments (Forkenbrock and Foster 1990); and 3. General resource allocation problems (Prosperi 1980).

In contemporary research, Hsieh and Liu (1997) introduced a multistage heuristic approach to solve infrastructure investment decision problems for public agencies responsible for routine infrastructure investment decisions. Wang and Liu (1997) introduced the fuzzy set based pavement network optimization system to minimize the annual pavement preservation cost over the planning period. Kleiner (2001) introduced a decision framework to assist municipal engineers and planners to optimize decisions regarding the renewal of large infrastructure assets such as water transmission pipes, trunk sewers or other assets with high costs of failure, inspection and condition assessment using a semi-Markov process for deterioration modeling. Pablo (2004) introduced the MR&R decision-making framework for infrastructure facilities without a deterioration model. Dewan and Smith (2005) used the value of an asset, calculated through a specific evaluation method, to justify and support asset management decisions. Kobayashi et al. (2008) proposed an integrated pavement management accounting system as a method for controlling the lifecycle costs of road pavement. Bernhardt and McNeil (2008) presented agent-based modeling as a paradigm to improve infrastructure decision making.

3.3 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) is a decision-analysis method aimed to assist in decision making involving a number of interrelated and competing factors. The AHP reduces a system to a sequence of pair-wise comparisons of the identified components (or attributes or alternatives). Since a hierarchy is an abstraction of the system, the AHP combines deductive and systems approaches. The AHP has been widely used in this way to quantify intangible factors. Central to the approach is the reality that people are inconsistent in their decisions, but decisions must be made despite these inconsistencies (Saaty 1980). The departure from consistency is measured on a ratio scale, which is estimated based on a maximum eigenvalue approach (Saaty 1980). Skibniewski and Chao (1992) used the AHP to evaluate advanced construction technology and to quantify the resulting intangible benefits and risks involved in implementing such technologies using traditional economic analysis techniques. Seydel and Olson (1990) applied the AHP to quantify the DM's preferences in a bidding process where multiple criteria must be considered. The AHP is also used to prioritize resources in the transit market (Khasnabis 1994), in multi-sector urban infrastructure projects (Ziara et al. 2002), in urban road construction (Ando 2004) and in sewerage rehabilitation (Yang et al. 2005).

This section presents the mathematical concepts underlying the AHP as adapted from Saaty (1980). Details of the AHP can be found in relevant literature (Gass 1985; Harker and Vargas 1987; Saaty 1980). The AHP can be implemented in five broad steps. *Step 1* involves the decomposition of the system into various hierarchies. The top level of the hierarchy is the primary objective, while the various dimensions of the problem form the lower strata. One must be careful to observe whether the elements of a given hierarchy carry relatively equal relevance to the problem. If factors carry more or less impact, they should be grouped together appropriately in a new hierarchy. If the AHP is used to determine the relative importance of the various attributes, the lowest stratus of the hierarchy should be composed of the set of attributes with lowest priority.

Step 2 involves the pair-wise comparison of elements to determine their relative importance. A pair of elements in a given hierarchy is compared with all the elements of the immediate higher hierarchy. The results of the comparison are recorded in a separate "decision matrix" (see Eq. (3.1) matrix **A**). Saaty (1980) offers a numerical scale to quantify the verbal comparisons (e.g., low, strong, very strong, etc.). Table 3 gives the numeric scale, as proposed by Saaty (1980), comparing two elements (P & Q) of one hierarchy to an element (R) of a higher hierarchy. For example, if the impact of the element P on element R is "absolutely more important" than element Q, then the significance of P over R is represented by the numeric scale as a "9."

Table 3: Priority scale used for pair-wise comparison of elements (Saaty 1980).

Relative Importance	Scale
P and Q are equally important	1
P is weakly more important than Q	3
P is strongly more important than Q	5
P is very strongly more important than Q	7
P is absolutely more important than Q	9
The numbers 2,4,6,8 and their reciprocals are used to facilitate compromise between slightly differing judgments.	

Step 3 involves the calculation of eigenvectors for the decision matrices. According to Saaty (1980), the eigenvector of the decision matrix represents the priority vector of the compared elements. Simply, the eigenvector represents the relative importance of

each element with respect to the elements located one level higher in the hierarchy. Saaty (1980) gives several approximation methods to calculate the eigenvector of the decision matrix, of which, the averaging of normalized columns is the most accurate (see Eq. (3.2)). *Step 4* entails the determination of the overall importance of each attribute. This is achieved by multiplying local priority vectors by the relative importance of the elements immediately above them. This step is skipped if there are less than three hierarchies in the structure. *Step 5* involves the calculation of a Consistency Ratio (CR) which controls the consistency of the pair-wise comparisons. A CR of 0.10 or less is considered acceptable (Saaty 1980).

Let **c**= (C_1, C_2,….,C_n) be the vector of the attributes to be prioritized. Let matrix **A**= (a_{ij}) represent the relative priorities (or importance) of the pairs (C_i, C_j) for the given decision (also known as pair-wise comparison), such that:

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ & & & \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \qquad \text{... (3.1)}$$

where $a_{ij} = 1/a_{ji}$ is the element located in the i^{th} *row* and the j^{th} column for all $i, j = 1, 2 . . . . . n$. Let **w** = (w_1, w_2 . . . . , w_n) be the weight (or importance) vector assigned to **c**. Using the average of normalized columns method, the weight vector is obtained, such that:

$$w_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\left(\sum_{k=1}^{n} a_{kj}\right)} \qquad \text{for } i, k = 1,2,\ldots n. \qquad \text{... (3.2)}$$

The eigenvector is obtained by dividing the weight vector (**w**) with the consistency vector (**v**), where **v** is given by **A*w**.

The eigenvalue ($\lambda_{\max}$) is obtained by taking the average of all the elements of the eigenvector. A Consistency Index (CI) representing the deviation from consistency is calculated, satisfying Eq. (3.3) (Saaty 1980):

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1} \qquad \text{... (3.3)}$$

Where:

n = number of elements in the matrix row

The Consistency Ratio, CR, is based on the division of the CI by a constant, known as a Random Index (RI).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \qquad \text{... (3.4)}$$

Table 4 gives the value of RI corresponding to number of elements in the matrix row of **A** (Saaty 1980).

Table 4: Random Index (RI) for the decision matrix in AHP (Saaty 1980).

Number of elements in the matrix row (n)	1	2	3	4	5	6	7	8
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4

The following is a simple example to demonstrate the application of the AHP. Consider a situation where ALOS is affected by the number of users, by neighbourhood safety and by neighbourhood aesthetics. The aim is to find the relative importance of these factors in the determination of ALOS. The attributes are organized in a hierarchy (*Step 1*), as shown in Figure 10.

Figure 10: Sample AHP application: Hierarchical breakdown of the problem.

Each pair of elements in a given hierarchy is compared with all the elements of the higher hierarchy (i.e., ALOS). For example, in a pairing of number of users and neighbourhood safety, both elements contribute to or impact the value of ALOS. The level of impact or contribution will vary according to context. Let us assume that for a given context the number of users using an asset has a "strongly more important" impact on (the value of) ALOS than the neighbourhood safety. The expression "strongly more important" corresponds to an index value of "5" on the scale suggested by Saaty (1980) (Table 3). Similarly, the pair-wise comparison of other alternatives (*Step 2*) is carried out and listed in the "decision matrix" (**A**). *Step 3* involves the calculation of eigenvectors for the decision matrices, which represent the relative importance of each element with respect to the elements located one level higher in the hierarchy (i.e., ALOS). The weight vector (**w**) is calculated using Eq. (3.2). the consistency vector (**v**) is calculated by vector multiplication **A*w** (Figure 11). The eigenvector is calculated by dividing the weight vector (**w**) by the consistency vector (**v**) (Figure 12).

	Decision Matrix		
	NU	NS	NA
NU	1	5	9
NS	0.2	1	5
NA	0.11	0.2	1

*

	Weight Vector
NU	0.723054492
NS	0.21572201
NA	0.061223498

=

	Consistency Vector
NU	2.352676022
NS	0.666450398
NA	0.184707288

Figure 11: Sample AHP application: Calculation of consistency vector.

	Weight Vector
NU	0.723054492
NS	0.21572201
NA	0.061223498

/

	Consistency Vector
NU	2.352676022
NS	0.666450398
NA	0.184707288

=

	Eigenvector
NU	3.2538
NS	3.0893
NA	3.0169

Figure 12: Sample AHP application: Calculation of eigenvector.

Since the problem has only two hierarchies, *Step 4* is not applicable. *Step 5* involves measuring the consistency of the process by measuring the CI and CR using Eq. (3.3) and (3.4). The calculated CR for this problem is 0.1, which is within permissible limits. Hence, the weight vector (**w**) gives the relative importance of attributes in the calculation of ALOS.

3.4 Multiattribute Utility Theory

Utility can be described as alternative way of measuring the attractiveness of a decision. Decision making is one of the foundations of utility theory. Utility theory assumes that the DM's preferences will govern the selection. In other words, given two alternatives, one is either strictly preferred to the other or the two are seen as preferentially equivalent (choice indifferent). A study of preference relation has established that, given the utility of any two alternatives, the alternative with the greater utility will be preferred. Even if the DM does not prefer one alternative over the other, the absence of strict preference should not imply indifference. Sometimes a preference structure is absent because the DM does not want to, or does not know how to, compare the alternatives.

The first assumption in the Multiattribute Utility Theory (MAUT) is the transitivity of the preference structure. The preference relation is assumed to be transitive (i.e., If $A \succ B$ and $B \succ D$, then $A \succ D$.). $A \succ B$ represents the preference of A over B, which can be read as "A is preferred to B." The second major assumption is the utility maximization assumption, according to which, given the preference of *A* over *B*, *A* has a higher utility than *B*. The third assumption is the decomposition hypothesis related to the MAUT, according to which, the utility of a multiattribute alternative is an aggregate of the individual utility components.

Let *X* be a set of finite alternatives $x_1, x_2, ..., x_n$. Let $x_2 \succ x_1$ represent the preference of x_2 over x_1, which can be read as "x_2 is preferred to x_1." Let $u(x_1), u(x_2), ..., u(x_n)$ be the utilities assigned to $x_1, x_2, ..., x_n$ in *X*. Let $a_1, a_2, ...a_j, ...a_m$ be the attributes on which the given alternative x_i is to be evaluated. Hence, $u(x_{ij})$ represents the utility of the i^{th} alternative with respect to the j^{th} attribute. The aim of the MAUT is to avoid the complex direct assessment of $u(x_{i1}, x_{i2}, ...x_{ij}, ...x_{im}) \forall i$ by decomposing the problem into a series of single-attribute utility functions such that:

$$u(x_{i1}, x_{i2}, ...x_{ij}, ...x_{im}) = f[u(x_{i1}), u(x_{i2}), ...u(x_{ij}), ...u(x_{im})] \forall i \qquad ... (3.5)$$

Where: *f* is the decomposition function.

The utility of a multiattribute alternative (or treatment) is an aggregate of the individual utility components. Several aggregation rules, or utility decomposition models, for multiattribute utility functions have been developed. These utility decomposition models include additive models, weighted additive models, multiplicative or log-additive models, quassi-additive models, quasi-pyramid models, etc. Edwards (1977) asserts that the weighted average linear method will yield extremely close approximation to complicated non-linear functions while being easier to use and understand. Zeleney (1982) suggests that the additive and multiplicative decomposition models are the only practical options for decisions involving more than four attributes. In practice, single-attribute utilities are combined with their respective weights (or importance) to form the MAUF given by Eq. (3.6) (Edwards 1977).

$$U_i = \sum_{j=1}^{m} w_j u(x_{ij}); \ \forall i = 1, \ldots, n. \qquad \ldots (3.6)$$

Where:

U_i is the utility of the i^{th} alternative

w_j is the relative weight (or importance) of the j^{th} attribute

$u(x_{ij})$ is the utility of the i^{th} alternative with respect to the j^{th} attribute

The MAUT has been employed widely in various research fields. Camasso and Dick (1993) used the MAUT as a priority setting tool in human services planning. Memtsas (2003) applied a simple multiattribute rating technique to assign conservation values to nature reserves. Hung et al. (2006) used a combination of multiattribute and multiobjective decision-making methods to provide qualitative and quantitative solutions to environmental management problems. Pan and Rahman (2006) integrated the MAUT with the AHP to evaluate electric generation expansion strategies, where the AHP facilitates the process of eliciting single-attribute utility functions and weighing parameters.

In construction, Elmisalami and Jaselskis (2006) used the MAUT to facilitate decision making regarding the evaluation of IT systems based on technical, economic and risk parameters. Gharaibeh et al. (2006) applied the MAUT to allocate funds across transportation asset classes. Kulakarni et al. (2004) developed a multiattribute need function that quantifies relative concerns of a highway agency and the traveling public regarding various physical and operational deficiencies for a given segment of highway. Shapira and Goldenberg (2005) presented a selection model based on the AHP and MAUT which specifically provides solutions to these two problems. Chan et al. (2006) used the AHP and MAUT to formulate a dispute resolution selection prototype. Michaud and Apostolakis (2006) offered a scenario-based methodology to rank the elements of a water-supply network according to their respective preferences to the owner. Kulkarni et al. (1993) used the multiattribute penalty function to evaluate alternative alignments for a proposed highway project in California. Finally, Hyari and El-Rayes (2006) used the MAUT to facilitate the selection and execution of the best alternative from a set of prospective plans for a given project.

3.5 Multiobjective Optimization

In many areas, decisions are being made subjectively, using criteria which are not compatible with an organization's objectives (National Asset Management Steering Group 2004). In infrastructure management, optimized decision making can be carried out using Cost Benefit Analysis (CBA) and multi-criteria decision analysis. CBA is a traditionally used method, but is criticized partly because of complications related to the monetary quantification of intangible costs and benefits (National Asset Management Steering Group 2004). For effective analysis and decision making, new types of information, specifically with respect to finance and demographics, need to be considered on a real-time basis. CBA limits the flexibility of the addition and/or elimination of this new information and objectives. Limited interaction with the DM is another limitation of CBA-based decision making.

In contrast, multiobjective problem solving allows for an organization to develop an optimization process based explicitly on its objectives and criteria. In past decades, the consideration of multiple objectives in decision making has grown substantially which resulted in the emergence of the field of multiobjective decision making (Haimes 2004). The multiobjective optimization problem has two distinct stages: stage 1 involves the generation of feasible alternatives, and stage 2 involves the selection of an alternative based on the DM's perspective.

Various attempts have been made to classify multiobjective optimization techniques. One of the most popular methods, proposed by Cohon and Marks (1975), classified multiobjective optimization techniques into three categories. The first category included the techniques based on prior articulation of preferences. Techniques included in this category include the global criterion method (Osyczka 1985), goal programming (Charnes and Cooper 1961; Ijiri 1965), the lexicographic method (Rao 1984; Sarma et al. 1993), min-max optimization (Rao 1986; Tseng and Lu 1990), the MAUT, surrogate worth trade-off (Haimes and Hall 1974) and ELECTRE (Roy 1971). The second category includes techniques based on posteriori articulation of preferences, including the linear combination of weights (Zadeh 1963) and the ε-Constraint Method (Osyczka 1985). The third category includes techniques which rely on progressive articulation of preferences, including the probabilistic trade-off development method (Goicoechea et al. 1976), and the STEP method (Cohon and Marks 1975; Ignizio 1982).

As stated by Osyczka (1985), multiobjective optimization (also called multicriteria optimization or vector optimization) finds decision variables which satisfy the constraints and optimizes a vector function composed of objective functions. Any decision problem has related decision variables, constraints, attributes, objective functions and criteria. Decision variables are numerical quantities which are given values during optimization. The decision variables vector can be denoted as $\mathbf{x} = x_1, x_2, \ldots, x_n$. Constraints are the restrictions imposed by the problem or the environment (e.g., budget constraints, labour constraints, time constraints, etc.). A solution for the problem must satisfy these constraints, which can be presented by mathematical inequalities or equalities. The number of equal constraints must be less than the number of decision variables: otherwise the problem is said to be over constrained, leaving no degrees of freedom for optimization.

The objective functions vector is denoted as $\mathbf{Z}(\mathbf{x}) = Z_1(\mathbf{x}), Z_2(\mathbf{x}), \ldots, Z_m(\mathbf{x})$. The optimization problem will involve the n-dimensional decision space and m-dimensional solution space. Every point in the decision space has a corresponding point in the solution space. For our research, the optimization problem deals with discrete sets of alternatives with deterministic outcomes and can be categorized as a discrete multiobjective decision analysis problem which can be written as:

$$\underset{\mathbf{x} \in \Omega}{Max} \{ Z_1(\mathbf{x}), Z_2(\mathbf{x}), \ldots, Z_m(\mathbf{x}) \} \quad \ldots (3.7)$$

Where

$$\mathbf{Z} : \Omega \rightarrow \mathbb{R}^m$$

$$\Omega = \{ \mathbf{x} \mid \mathbf{g}(\mathbf{x}) \geq 0, \mathbf{h}(\mathbf{x}) = 0 \}$$

Constraints **g(x)** and **h(x)** define the feasible region (Ω). Any point **x** in Ω defines a feasible solution. The vector function Z(x) maps the set Ω into the Euclidian space ($\mathbb{R}^m$) which represents all possible values of objective functions.

A feasible set of solutions is called non-inferior or Pareto-optimal if no other alternative that will improve one of the objectives (or criteria) without degrading the others exists. A decision (**x***) is said to be a Pareto-optimal solution (or non-inferior or non-dominant solution) to the problem if and only if another solution ($\mathbf{x}_1$) does not exist (so that $Z_i(\mathbf{x}_1) \geq Z_i(\mathbf{x}^*), j = 1, 2, \ldots, n,$ with strict inequality holding for at least one *j*). For example, solution $\mathbf{x}_1$ is dominated by solution **x***, if choosing **x*** will result in the improvement of at least one objective function and leaving all others unchanged. Pareto-optimal solutions are sets of solutions whose corresponding vectors are non-denominated with respect to all other vectors.

3.6 Genetic Algorithms

Many mathematical linear and non-linear programming methods exist to solve optimization problems. General search and optimization techniques can be classified into three categories: enumerative, deterministic and stochastic (Coello et al. 2002). Enumerative techniques evaluate every possible solution within the search space. However, the technique becomes infeasible for problems having large search spaces because of the computational demands. Deterministic search algorithms incorporate "previous experiences" in the search for optimal solutions. Examples of such algorithms include greedy algorithms, hill-climbing algorithms, calculus-based algorithms, etc. Greedy algorithms choose local optimums, assuming that optimum sub-solutions are always part of the global optimum solution (Husbands 1992). Hill-climbing algorithms find the optimal solution by searching in the direction of the steepest ascend (Russel and Norvig 1995), while calculus-based algorithms require continuity in the variable domain as a minimum prerequisite (Anton 1984).

Stochastic algorithms require a fitness function to evaluate the solutions. Examples of such algorithms include simulated annealing, Monte Carlo methods, evolutionary computations, etc. In the simulated annealing method, if a solution improves the current optimum, it is included in the solution set. Other unfit solutions are assigned a probability value of less than one. The probability decreases with the time. The method is based on the principle that if probability decreases slowly enough, the global optimum is found (Coello et al. 2002). Monte Carlo methods use random searches where any selected trial solution is independent of the previous solution. The current best solution is retained.

The notion of the Genetic Algorithms (GA) was first proposed by Holland (1975). GA belong to the group of evolutionary computation techniques which are based on the principle of natural evolution and selection. GA are designed to effectively search for the near optimal solution to complex problems (Richard 1994). The complexities of multiobjective optimization problems, such as large search spaces, noise, discontinuity in Pareto curves, etc., may render most of the traditional multiobjective optimization techniques useless (Coello et al. 2002). No single method has been found to be efficient for solving problems from different engineering fields (Adeli and Sarma 2006). The effectiveness of optimization techniques depend upon the choice of starting points. Currently, there are over 30 mathematical programming techniques for multiobjective optimization (Coello et al. 2002). Most of them are sensitive to the shape of the Pareto front (e.g., they do not work when the Pareto front is concave or when the front is disconnected). GA are not gradient-based methods (e.g., hill-climbing algorithms); hence, when the solution space has multiple peaks, the probability of being entrapped in a local minima is reduced. GA are a robust search technique based on the principles of natural selection (Goldberg 1989) and have been used extensively for optimization problems.

Fwa et al. (1994a, 1994b, 1997) and Chan et al. (2003) applied GA to optimize resource allocation for a transportation network. Hsieh and Liu (2004) used GA to determine investments for infrastructure under time and resource constraints. Kandil and El-Rayes (2006) made use of GA as an efficient and effective means to optimize resource utilization in large-scale construction projects. Elazouni and Metwally (2005) utilized GA to devise finance-based schedules that maximize project profits by minimizing financing and indirect costs. Senouci and Eldin (2004) explored the use of GA for resource scheduling in construction projects. Mawdesley (2002) applied GA to construction site layout problems. Hegazy (1999) used GA for resource allocation and levelling problems.

GA can be used directly for solving unconstrained optimization problems. When GA are used for solving constrained problems (as in this research), the constrained problem has to be transformed into an unconstrained problem. One way to do this is to generate the potential solutions without considering the constraints. If the solutions violate the constraints (i.e., if the solutions are infeasible), the solutions can either be discarded or they can be penalized by decreasing the "fitness." The penalty method is useful in cases where the problem is highly constrained. In other words, a constrained problem is transformed to an unconstrained problem by associating penalties with all constraint violations, and the penalties are incorporated in the fitness function. This research uses the penalty method to handle constraints while using GA.

Chapter 4: Quantification of Asset Levels of Service (ALOS)

This chapter illustrates the quantification of the Asset Levels of Service (ALOS) for a given urban road as a working example. In this chapter, the framework for the quantification of ALOS is described, followed by a numerical example to show the implementation of the ALOS quantification framework.

4.1 Asset Levels of Service (ALOS) Quantification: Framework

A given infrastructure system generally has multiple Levels of Service (LOS) for multiple users. To date, limited work has been done to combine these LOS to a single-indexed ALOS. In addition, existing methods to determine LOS are based on quantitative performance measures related to the capacity of the infrastructure system. These methods neglect other qualitative factors (such as neighbourhood safety, etc.). This section describes and illustrates the implementation of the ALOS quantification methodology. This quantified ALOS is used in OPTIsys for optimal resource allocation.

LOS is an index that measures the quality of service provided by an infrastructure network. LOS assist in decision making and investment planning related to the development, operation, maintenance, rehabilitation, planning and replacement of municipal infrastructure (Infrastructure Canada 2003). The LOS concept was introduced in the 1985 Highway Capacity Manual (HCM) (Transportation Research Board 1985). The HCM was well-received and was soon adopted in other infrastructure systems.

For highway systems, LOS determines the efficiency of a highway at less-than-capacity traffic volumes (Garber and Hoel 2002). LOS involves a quantitative stratification of the quality of service into six letter grades with "A" being the best and "F" the worst (Transportation Research Board 1985). Parameters used by the HCM to quantify LOS are related to the operational characteristics of the highway system (Transportation Research Board 1985). The LOS quantification process has been refined in subsequent editions of the HCM. For instance, the 2000 HCM (Transportation Research Board 2000) defines LOS for two-lane highways, multi-lane highways and freeways.

ALOS can be defined as the integration of LOS for all the users of an asset. In the case of urban roads, for example, a road can be shared by vehicular traffic, pedestrians and cyclists. Consequently, in the case of road networks, ALOS is the sum of vehicular, pedestrian and bicyclist LOS, represented by VLOS, PLOS and BLOS, respectively. For the quantification of ALOS, this study refers to the primary highway system structure proposed by the 2000 HCM (Transportation Research Board 2000). An *asset* is a continuous length of a road composed of various segments. A point marks the boundary between two segments. It can represent a signalized intersection, the boundary between two segments with differing LOS or a bicycle lane/sidewalk intersection. A segment is defined as a length of a road bound by two points and linked by analogous physical and traffic-pattern characteristics. For urban roads, the segment can extend from one intersection to another.

Consider an asset (or road) composed of a set of n segments, $\mathbf{S} = (S_1, S_2,\ldots,S_n)$. Let $\mathbf{L} = (l_1, l_2,.., l_n)$ be the corresponding lengths of the segments ($\mathbf{S}$) of the road. If the asset has m types of users, then vector $\mathbf{LOS} = (los_{11}, los_{12},\ldots, los_{ji},\ldots,los_{mn})$ represents the LOS for the m^{th} type of user of the n^{th} segment, where $j= 1,2,\ldots,m$ and $i= 1,2,\ldots,n$. Let $\mathbf{w}$ =

$w_1, w_2, \ldots, w_j, \ldots, w_m$ be the set of weights assigned to the vector **LOS**. ALOS for an asset will be given as follows:

$$ALOS = \sum_{j=1}^{m} w_j \left[\frac{\sum_{i=1}^{n} l_i (los_{ji})^2}{\sum_{i=1}^{n} l_i los_{ji}} \right] \qquad \ldots (4.1)$$

Where:

l_i = Length of the segment (i) for i= 1,2,…,n.

w_j= Relative weight/priority of levels of service for the user (j) for j= 1,2,…,m.

los_{ji} = LOS for the user (j) corresponding to the segment (i) for j= 1,2,…,m and i= 1,2,…,n.

The squaring of the LOS index in the numerator ensures that the impact of the LOS index is adequately accounted for while calculating ALOS. In the final step, the value of ALOS is obtained by normalization.

4.1.1 Vehicle Levels of Service (VLOS)

Vehicle levels of service (VLOS) represent LOS provided to automobile users. The 2000 HCM (Transportation Research Board 2000) has thus far been the main resource for VLOS calculation. The LOS quantification model used in this research is based on the 2000 HCM (Transportation Research Board 2000) with an exception where the alphabetical stratification is replaced by an indexed stratification (Table 5).

Table 5: Performance measures for the VLOS on a two-lane highway.

Levels of Service (LOS)	Average Travel Speed (ATS) mi/h	Percentage Time Spent Following Other Vehicles (PTSF)
1.5	55 or greater	No more than 35% of time
2.5	50 - 55	35%-50% of the time
3.5	45 - 50	50%-65% of the time
4.5	40 - 45	65%-80% of the time
5.5	40 or less	More than 80% of time
6.5	Variable	Congested (volume lower than capacity)

The 2000 HCM employs two measures to describe the service quality of a two-lane highway: percentage time spent following other vehicles (PTSF) and average travel speed (ATS). The calculation of these performance measures is as follows (Transportation Research Board 2000):

$$PTSF = 100\left[1 - e^{-0.000879 v_p}\right] + f_{d/np}$$

$$ATS = FFS - 0.00776 v_p - f_{np} \qquad \text{... (4.3)}$$

Where:

v_p = Passenger car equivalent flow rate for peak 15 minute period

$f_{d/np}$= Adjustment factor for the combined effect of the percentage of directional distribution of traffic and the percentage of passing zone.

FFS = Free flow speed

f_{np} = Adjustment for the percentage of no passing zone

If values of PTSF and ATS do not correspond to the same LOS, the lower value is used.

4.1.2 Pedestrian and Bicycle Levels of Service (PLOS & BLOS)

For pedestrian and bicycle LOS, the analytical models developed by the Florida State Department of Transportation (Florida State Department of Transportation 2002) are used. These models employ the multi-modal approach to account for interdependencies. The Florida State Department of Transportation LOS calculation models (Florida State Department of Transportation 2002) are based on common variables that impact VLOS, BLOS and PLOS. For example, BLOS and PLOS models use common variables, such as vehicular volume, vehicle running speed and number of lanes. The weighted coefficients for the variables are determined by stepwise regression modeling. T-statistics were used to determine the relative importance of the variables. LOS are measured by assigning a numerical score, which normally falls between 1.5 to 6.5. PLOS are given by Eq. (4.4) (Florida State Department of Transportation 2002):

$$PLOS = -1.2276\ln(W_{ol} + W_l + f_p + \%SOP + f_b W_b + f_{sw} W_s) \\ +0.0091(v_p / L) + 0.0004ATS^2 + 6.0468 \quad \text{... (4.4)}$$

Where:

W_{ol} = Width of the outside lane

W_l = Width of the shoulder or bicycle lane

f_p = On-street parking effect coefficient (=0.20)

$\% SOP$ = Percent of segment with on-street parking

f_b = Buffer area barrier coefficient (=5.37 for trees spaced 20 feet on center)

W_b = Buffer width (distance between the edge of the pavement and the sidewalk in feet)

f_{sw} = Sidewalk presence coefficient (= 6 – 0.3Ws)

W_s = Width of the sidewalk

v_p = Passenger car equivalent flow rate for peak 15 minute period

L = Total number of directional through lanes

ATS = Average running speed of motorized vehicle traffic (mi/hr)

BLOS are given by Eq. (4.5) (Florida State Department of Transportation 2002):

$$\begin{aligned} BLOS = 0.507\ln(v_p / L) + 0.199SP_t(1+10.38HV)^2 \\ + 7.066(1/PR_5)^2 - 0.005(W_e)^2 + 0.760 \end{aligned} \quad \text{... (4.5)}$$

Where:

v_p = Passenger car equivalent flow rate for peak 15 minute period

L = Total number of directional through lanes

SP_t = Effective speed factor

HV = Percentage of heavy vehicles

PR_5 = Federal Highway Agency's five-point surface condition rating

W_e = Average effective width of the outside through lane.

4.2 Asset Levels of Service (ALOS) Quantification: A Numerical Example

An example is presented below to determine the ALOS for a two-lane urban residential roadway. The example determines ALOS of a two-lane urban road adjoining a residential neighbourhood using the AHP. The road is shared by vehicular traffic, pedestrians and bicyclists. Consequently, ALOS is composed of VLOS, PLOS and BLOS. Data for each segment were calculated from the City of Edmonton. The asset/facility under study was composed of four segments (S_1, S_2, S_3, and S_4) and two intersections (I_1 and I_2). The VLOS for each segment was calculated by using Eqs. (4.2) and (4.3). PLOS and BLOS for the road were calculated by using Eqs. (4.4) and (4.5), respectively. Table 6 lists the calculated LOS for the road under study.

Table 6: Calculated LOS for different uses of the urban road under study.

Segment/ Intersection	Length (l_n)	VLOS	PLOS	BLOS
S_1	3.2 km	3.5	2.5	3.5
S_2	2 km	4.5	2.7	3.5
S_3	2.5 km	4.5	2.5	4.0
S_4	4 km	3.5	2.5	4.0
I_1	-	5.5	4.2	5.0
I_2	-	5.5	4.7	5.0

The prioritization vector, which provides the relative importance for LOS of various users, is calculated based on the AHP. The process begins by fragmenting the system into various hierarchies (*Step 1*). The literature review formulated the initial hierarchy for the system. The formulated hierarchy was presented to the asset manager to identify all the attributes (or factors) which should be included in determining ALOS; each attribute (of a hierarchy level) has relatively equal importance in that level of the hierarchy. Figure 13 illustrates the hierarchy of the attributes which contribute to the quantification of ALOS. The "determination of ALOS" is the top-level entry in the hierarchy. In determining the relative importance of LOS for various users, the number of users plays an important role. The qualitative attributes grouped in Level 2 of the hierarchy are the Number of Users using that facility, Neighbourhood Safety and Neighbourhood Aesthetics. Level 3 of the hierarchy lists the attributes that affect the attributes in Level 2. These attributes are based on neighbourhood transportation safety audits (District of Saanich 2003). All of the attributes in Levels 2 and 3 of the hierarchy affect VLOS, PLOS and BLOS, which constitute Level 4. The following is a list of factors in each level of the hierarchy:

Level 1: Asset Levels of Service

Level 2: Number of Users, Neighbourhood Safety and Neighbourhood Aesthetics

Level 3: Type of Road, Type of Neighbourhood, Traffic Lights), Signage, Sidewalk Conditions, Bicycle Lane Conditions, Cut-Through Traffic and Pedestrian Crossings

Level 4: Influence on VLOS, PLOS and BLOS

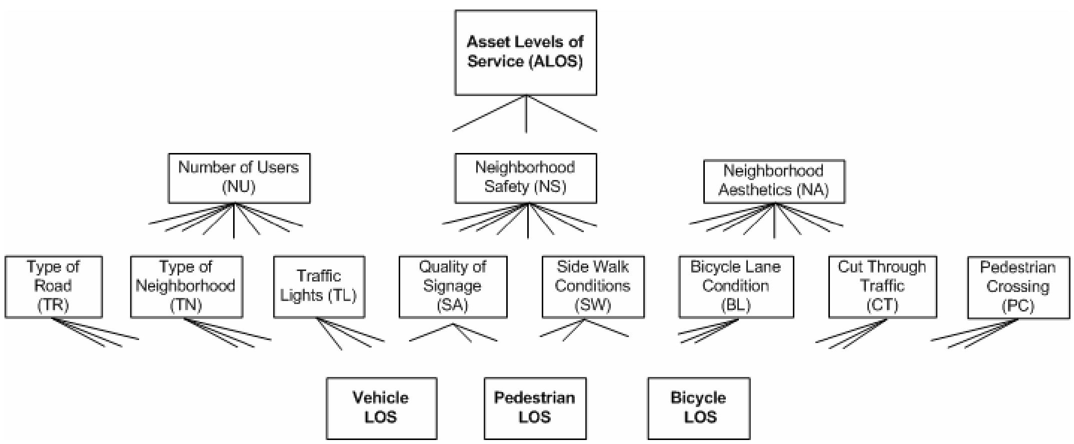

Figure 13: Hierarchy of various factors affecting ALOS of urban roads.

Step 2 involves the pair-wise comparison of elements to determine their relative importance. A pair of elements in a given hierarchy is compared with all the elements in the next higher hierarchy. The results of the comparison are recorded in a separate "decision matrix" for each level (Tables 7, 8 and 9). To determine the relative priorities of two attributes, the scale listed in Table 3 is used. For example, pair-wise comparison of Neighbourhood Safety and Neighbourhood Aesthetics with respect to ALOS shows that Neighbourhood Safety is much more important than Neighbourhood Aesthetics in determining ALOS.

Step 3 involves the calculation of eigenvectors for the decision matrices. Each column of the resultant matrices (Tables 7, 8 and 9) is normalized based on the sum of that column using Eq. (3.2). The maximum or principle eigenvalue (λ_{max}) is calculated from the eigenvector. The Consistency Ratio (CR) is calculated (Eq. (3.4)) based on the division of the Consistency Index (CI) (Eq. (3.3)) by a constant known as a Random Index (RI) (Table 4). A CR of 0.10 or less is considered acceptable (Saaty 1980). Tables 7, 8 and 9 list the pair-wise comparison of the factors in the hierarchy, illustrated in Figure 13, in a matrix form with a corresponding maximum or principal eigenvalue (λ_{max}), a CI and a CR.

Table 7: Decision matrix: Pair-wise comparison of Level 2 attributes.

	Asset Levels of Service (ALOS)		
	NU	NS	NA
NU	1	5	9
NS	1/5	1	5
NA	1/9	1/5	1

λ_{max} = 3.12004; CI = 0.06002; CR = 0.10348

Table 8: Decision matrix: Pair-wise comparison of Level 3 attributes.

	Number of Users (NU)							
	TR	TN	TL	SA	SW	BL	CT	PC
TR	1	3	9	9	8	8	4	8
TN	1/3	1	8	8	4	4	5	5
TL	1/9	1/8	1	1	1/5	1/4	1/6	3
SA	1/9	1/8	1	1	1/5	1/4	1/6	3
SW	1/8	1/4	5	5	1	3	1/3	3
BL	1/8	1/4	4	4	1/3	1	1/3	2
CT	1/4	1/5	6	6	3	3	1	4
PC	1/8	1/5	1/3	1/3	1/3	1/2	1/4	1

λ_{max} = 9.07228; CI = 0.15318; CR = 0.10864

	Neighbourhood Safety (NS)							
	TR	TN	TL	SA	SW	BL	CT	PC
TR	1	2	3	6	6	6	2	7
TN	1/2	1	2	6	4	4	1	5
TL	1/3	1/2	1	5	3	3	1	5
SA	1/6	1/6	1/5	1	3	3	1/6	1
SW	1/6	1/4	1/3	1/3	1	1	1/5	2
BL	1/6	1/4	1/3	1/3	1	1	1/5	2
CT	1/2	1	1	6	5	5	1	6
PC	1/7	1/5	1/5	1	1/2	1/2	1/6	1

λ_{max} = 8.51303; CI = 0.07329; CR = 0.05198

	Neighbourhood Aesthetics							
	TR	TN	TL	SA	SW	BL	CT	PC
TR	1	1/5	2	1/6	1/6	1/6	1	2
TN	5	1	1/3	1/5	1/5	1/5	3	7
TL	1/2	3	1	1/7	1/7	1/7	1/3	1
SA	6	5	7	1	1	1	5	8
SW	6	5	7	1	1	1	5	8
BL	6	5	7	1	1	1	5	8
CT	1	1/3	3	1/5	1/5	1/5	1	3
PC	1/2	1/7	1	1/8	1/8	1/8	1/3	1

λ_{max} = 9.17678; CI = 0.16811; CR = 0.11922

Table 9: Decision matrix: Pair-wise comparison of Level 4 attributes.

	Type of Road (TR)			Type of Neighbourhood (TN)		
	VLOS	PLOS	BLOS	VLOS	PLOS	BLOS
VLOS	1	7	5	1	1/5	1/3
PLOS	1/7	1	1/3	5	1	3
BLOS	1/5	3	1	3	1/3	1
λ_{max} = 3.0658; CI = 0.0329; CR = 0.0567				λ_{max} = 3.0387; CI = 0.0194; CR = 0.0334		

	Traffic Light (TL)			Signage (SA)		
	VLOS	PLOS	BLOS	VLOS	PLOS	BLOS
VLOS	1	5	5	1	3	3
PLOS	1/5	1	1	1/3	1	1
BLOS	1/5	1	1	1/3	1	1
λ_{max} = 3; CI = 0; CR = 0				λ_{max} = 3; CI = 0; CR = 0		

	Sidewalk condition (SW)			Bicycle lane condition (BL)		
	VLOS	PLOS	BLOS	VLOS	PLOS	BLOS
VLOS	1	1/9	1/2	1	1/3	1/9
PLOS	9	1	8	2	1	1/8
BLOS	2	1/8	1	9	8	1
λ_{max} = 3.0373; CI = 0.0187; CR = 0.0322				λ_{max} = 3.0373; CI = 0.0187; CR = 0.0322		

	Cut through Traffic (CT)			Pedestrian Crossing (PC)		
	VLOS	PLOS	BLOS	VLOS	PLOS	BLOS
VLOS	1	3	3	1	1/5	1/2
PLOS	1/3	1	1	5	1	5
BLOS	1/3	1	1	2	1/5	1
λ_{max} = 3; CI = 0; CR = 0				λ_{max} = 3.0542; CI = 0.0271; CR = 0.0467		

Matrix **P** (Eq. (4.6)) indicates the relative importance (or eigenvector) of factors which impact the outcome of ALOS. Matrix **Q** (Eq. (4.7)) lists the relative importance (or eigenvector) of the variables which impact the ALOS-determination factors. Matrix **R** (Eq. (4.8)) lists the relative importance (or eigenvector) of the variables of the VLOS, PLOS and BLOS.

$$
\mathbf{P} = \begin{array}{c} \\ \text{NU} \\ \text{NS} \\ \text{NA} \end{array} \begin{array}{c} \text{ALOS} \\ \begin{bmatrix} 0.723 \\ 0.216 \\ 0.061 \end{bmatrix} \end{array} \quad \text{... (4.6)}
$$

$$
\mathbf{Q} = \begin{array}{c} \\ \text{TR} \\ \text{TN} \\ \text{TL} \\ \text{SA} \\ \text{SW} \\ \text{BL} \\ \text{CT} \\ \text{PC} \end{array} \begin{array}{c} \begin{array}{ccc} \text{NU} & \text{NS} & \text{NA} \end{array} \\ \begin{bmatrix} 0.383 & 0.302 & 0.044 \\ 0.233 & 0.190 & 0.093 \\ 0.034 & 0.141 & 0.045 \\ 0.034 & 0.059 & 0.246 \\ 0.092 & 0.043 & 0.246 \\ 0.063 & 0.043 & 0.246 \\ 0.132 & 0.190 & 0.056 \\ 0.027 & 0.032 & 0.025 \end{bmatrix} \end{array} \quad \text{... (4.7)}
$$

$$
\mathbf{R} = \begin{array}{c} \\ \text{VLOS} \\ \text{PLOS} \\ \text{BLOS} \end{array} \begin{array}{c} \begin{array}{cccccccc} \text{TR} & \text{TN} & \text{TL} & \text{SA} & \text{SW} & \text{BL} & \text{CT} & \text{PC} \end{array} \\ \begin{bmatrix} 0.724 & 0.106 & 0.714 & 0.600 & 0.075 & 0.075 & 0.600 & 0.250 \\ 0.083 & 0.633 & 0.143 & 0.200 & 0.800 & 0.124 & 0.200 & 0.375 \\ 0.193 & 0.260 & 0.143 & 0.200 & 0.124 & 0.800 & 0.200 & 0.375 \end{bmatrix} \end{array} \quad \ldots \text{(4.8)}
$$

The relative priorities of VLOS, PLOS and BLOS in ALOS are represented as a matrix **T**= **w** = **R*Q*P** in Eq. (4.9):

$$
\mathbf{T} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = \begin{array}{c} \text{VLOS} \\ \text{PLOS} \\ \text{BLOS} \end{array} \begin{bmatrix} 0.449 \\ 0.304 \\ 0.247 \end{bmatrix} \quad \text{... (4.9)}
$$

Substituting **w**, from Eq. (4.9) into Eq. (4.1), ALOS of the given road can be calculated by using Eq. 4.10:

$$
ALOS_R = 0.449 \left[\frac{\sum_{i=1}^{6} l_i (VLOS_i)^2}{\sum_{i=1}^{6} l_i VLOS_i} \right] + 0.304 \left[\frac{\sum_{i=1}^{6} l_i (PLOS_i)^2}{\sum_{i=1}^{6} l_i PLOS_i} \right] + 0.247 \left[\frac{\sum_{i=1}^{6} l_i (BLOS_i)^2}{\sum_{i=1}^{6} l_i BLOS_i} \right] \quad \ldots \text{(4.10)}
$$

Where:

$ALOS_R$ = ALOS for a given roadway in a residential area

l_i = Length of the i^{th} segment for i= 1,2,…,n.

$VLOS_{i,}$ = VLOS for i^{th} segment for i= 1,2,…,n.

$PLOS_{i,}$ = PLOS for i^{th} segment for i= 1,2,…,n.

$BLOS_i$= BLOS for i^{th} segment for i= 1,2,…,n.

Substituting the length of segments, VLOS, PLOS and BLOS from Table 6 as well as $\boldsymbol{w}$ from Eq. (4.9), the calculated value of ALOS of the road under study is 3.80. The resultant priority vector (Eq. (4.9)) can be applied to other roads in residential areas with similar traffic characteristics. The vector has to be revised in cases where a substantial change in traffic or land use conditions has been identified.

One of the considerations underlying the development this framework is maintaining the simplicity and practicality of the application. ALOS given by Eq. 4.10 is not intended to substitute the operational analysis of the network or the actual decision making for the project-level MR&R. The calculated ALOS is used in the decision-making process through its incorporation into a MAUF (*Phase II*) and ultimately into the multiobjective optimization model for optimal funding allocation in MR&R alternatives for urban roads (OPTIsys).

Chapter 5: Assessment of Multiattribute Utility Function for Investment Decisions (MAU-ID)

This chapter provides the framework to quantify the multiattribute utility of investment decisions (MAU-ID). As explained before, the multiattribute utility change due to a particular investment decision (i.e. MR&R treatment) has been used as one of the criteria for funding allocation. During the course of research, it has been realized that the utility change of increased ALOS is a more relevant measure than the absolute change in ALOS for two reasons. First, the utility function allows the DM to set up the priority preferences of the alternatives. Second, the change of ALOS due to a particular MR&R treatment (or decision) may vary depending upon the existing condition of the asset. For example, the overlaying of road surfaces will have more utility or usefulness if applied to roads with a poor roughness index as opposed to roads with a good roughness index.

Utility is a way of measuring the attractiveness of the result of a decision. In other words, a decision may be the "best results" based on logics and numbers, but the DM may adopt the decision based not on numbers, but rather on the utility (or attractiveness) of the result. The determination of the MAU-ID is conducted through four basic steps:

1. Verifying relevant independence conditions of utility attributes;
2. Assessing single-attribute utility functions;

3. Determining the relative importance of single-attribute utility functions using the AHP; and
4. Calculating the MAU-ID using a decomposition model.

5.1 Verification of independence conditions

To validate the application of the utility theory, a preference structure must be established and various independence conditions must be fulfilled. Independency axioms are the most important concepts in the utility theory. *Preferential independence* among the attributes is required for all the simple additive decompositions (which are used in this research), while *utility independence* is necessary for multiplicative decomposition models. For example, two of the attributes affecting the selection of a MR&R treatment will be construction and maintenance costs. A municipality may be willing to bear the additional construction costs if the alternative has low maintenance costs in the long run. Hence, the two attributes, construction and maintenance costs, are not independent. If the attributes are not independent, then the attributes have to be redefined. For example, construction and maintenance costs can be combined as one attribute (e.g., cost) over a five-year period.

Preferential independence is concerned with the ordinal preferences among attributes. An ordinal scale can be ranked, but no arithmetic transformations can have a useful impact on it. For example, consider two roads: Road 1 is *moderately* congested, and Road 2 is *very* congested. We can rank the roads based on the congestion (e.g., Road 2 is more congested than Road 1), but we cannot add or subtract the degree of congestion of the two roads (e.g., the sum of congestion on Roads 1 and 2 is *highly* congested). In another example, the pair of attributes a_1 and a_2 is preferentially independent of attribute a_3, if the value of the trade-off between a_1 and a_2 is not affected by the given level of a_3. Trade-off is the measure of how much one attribute must be sacrificed to gain a fixed amount of another attribute. For this research, the following attributes were tested for preferential independence:

1. ALOS;
2. Physical Deterioration;
3. Neighbourhood Growth; and
4. Impact on Dependent Networks

To establish the preferential independence between the attributes the following question was posed to the peers: "Suppose you have to select a treatment based on the 'physical deterioration' of roads, 'neighbourhood growth' and the 'impact on dependent networks.' That is, if the trade-offs between 'physical deterioration' and 'neighbourhood growth' is affected by the 'impact on dependent networks'?" In this case, the answer to the question was "No," implying that the "physical deterioration" of roads and "neighbourhood growth" are preferentially independent. At first, both attributes may seem to be strongly dependent upon each other, but further discussions revealed that for urban roads, the "physical deterioration" is more dependent upon weather conditions. Similarly all the attributes were tested and found to be significantly preferentially independent.

5.2 Assessment of Single-Attribute Utility Functions

As described earlier, the MAU-ID is a constituent of various attributes. The impact of these attributes on the MAU-ID can be quantified by deriving the respective single-attribute utility functions. These attribute utility functions can then be combined by using the appropriate aggregation function to calculate the multiattribute utility. For this research, the following single-attribute utility functions have been determined to quantify MAU-ID:

1. Increase in ALOS;
2. Physical Deterioration;
3. Neighbourhood Growth (or future demand); and
4. Impact on Dependent Networks (Emergency Medical Services).

ALOS is measured on a scale from 1.5 to 6.5 (1.5 being the best), where the utility of increasing ALOS will depend on its existing value. For example, an increase in the value of ALOS from 4 to 5 will have more utility than an increase in value from 2 to 3. Physical deterioration is measured by using the International Roughness Index (IRI) on a scale from 1.5 to 6.5 (1.5 being the best). Neighbourhood growth, which impacts the future demand on the roads, is measured by the number of housing permits issued in a particular neighbourhood (or district) of the city (City of Edmonton 2005). The impact on emergency medical services is measured subjectively on a scale from 1 to 9 (9 being the best), and the DM is responsible to assess individual treatment on this scale.

The utility theory is a well-explored area, with a number of methods to create the utility functions. When the DM has limited knowledge about the attribute, the utility function can be constructed using a standard gamble technique by finding indifference conditions between lotteries and sure amounts (Fishburn 1970). In more formal language, the DM is called on to create an equivalent lottery. This method is very labour intensive and is very much dependent upon the DM's skill and consistency in performing the exercise. Another issue is to separate the DM's utility and organization's utility. Personal views and objectives should not interfere with the organization's objectives.

When the DM has in-depth knowledge about the attribute, a linear or exponential utility function can be constructed by providing the best and the worst attribute values and up to three intermediate values with their respective imprecise utilities. Another method suggested by Hughes (1986) can be used to determine the utilities in both single and multiattribute situations. Hughes (1986) utilizes the AHP for converting the weight vector to corresponding utilities. This research uses hypothetical utility functions, which are to be replaced by actual utility functions when implementing the framework in an organization or municipality.

5.2.1 Single-Attribute Utility Function for ALOS

A selected MR&R decision can result in *n* possible values of increased ALOS. Each value of ALOS will have a different utility associated with it. As discussed, six possible ALOS values (or consequences) can be 6.5, 5.5, 4.5, 3.5, 2.5 and 1.5. The least achievable ALOS value is 6.5, while the maximum attainable value is 1.5. The utility scale can be anchored as: $u(ALOS = 6.5) = 0$ & $u(ALOS = 1.5) = 1$. One must assess the utility of the remaining immediate values of ALOS (i.e., ALOS = 5.5, 4.5, 3.5, and 2.5). This research uses hypothetical utility functions for an increase in ALOS (due to the application of a MR&R treatment) based on the above-mentioned linear or exponential utility function. Table 10 gives the utilities of ALOS at values of 6.5, 5.5, 4.5, 3.5, 2.5 and 1.5 as well as the associated fitted functions.

Table 10: Utility values for ALOS.

ALOS (x)	Utility of ALOS (y)
1.5	1
2.5	0.95
3.5	0.85
4.5	0.7
5.5	0.5
6.5	0
$y = -0.0473x^2 + 0.1929x + 0.7904$; $R^2 = 0.984$	

Hence, *u(ALOS)* is given by Eq. (5.1):

$$u(ALOS) = -0.0473(\mathrm{ALOS})^2 + 0.1929(\mathrm{ALOS}) + 0.7904 \quad ...(5.1)$$

Where: ALOS= Asset Levels of Service of a given road section

5.2.2 Single-Attribute Utility Function for Physical Deterioration

Pavement roughness is generally defined as an expression of irregularities or distortions in the pavement surface which contributes to an uncomfortable ride. Roughness is an important pavement characteristic because it affects not only ride quality, but also vehicle delay costs, fuel consumption and maintenance costs. The World Bank found road roughness to be a primary factor in the analyses and trade-offs involving road quality versus user cost (Milla 2002). Roughness is also referred to as "smoothness," although both terms refer to the same pavement qualities.

The International Roughness Index (IRI) is the most accepted and widely used scale through out the world to quantify the roughness of roads and is used by Alberta Infrastructure and Transportation for preventive MR&R decision making (Alberta Infrastructure and Transportation 2006). The US Federal Highway Administration uses it to rate road performance, assess changes in the overall condition of the nation's highways and predict future highway investment needs (Milla 2002). The commonly recommended units for IRI are meters per kilometer (m/km) or millimeters per meter (mm/m).

For new pavement, the IRI should lie in the range of 1.5-3.5, whereas for older pavements, the IRI should lie in the range of 2.5- 6.5 (Milla 2002). Utility is determined through an IRI range between 1.5 and 6.5 (1.5 and 6.5 being the best and worst case scenarios, respectively). The utility scale can be anchored as: *u(IRI=6.5)*=0 & *u(IRI=1.5)*=1. Table 11 gives the utilities of the IRI at 6.5, 5.5, 4.5, 3.5, 2.5 and 1.5 as elicited from the peers.

Table 11: Utility values for the International Roughness Index (IRI).

ALOS (x)	**Utility of ALOS (y)**
1.5	1
2.5	0.95
3.5	0.70
4.5	0.6
5.5	0.4
6.5	0
$y = -0.0277x^2 + 0.0286x + 1.0176$; $R^2 = 0.9818$	

Hence, *u(IRI)* is given by Eq. (5.2):

$$u(IRI) = -0.0277(\text{IRI})^2 + 0.0286(\text{IRI}) + 1.0176 \qquad ...(5.2)$$

Where: IRI= International Roughness Index of a given road section

5.2.3 Single-Attribute Utility Function for Future Growth

Between 1991 and 2001, the City of Edmonton grew at an average annual rate of 1.2% (City of Edmonton 2005). For detailed analysis, the City has been sub-divided into 31 traffic districts. Table 12 shows the number of dwelling units approved for construction during 2003 and 2005 (City of Edmonton 2005). Based on Table 12, the least achievable Neighbourhood Growth Rate (NGR) is 0% and the maximum attainable value is pegged at 14%. So the utility scale can be anchored as: $u(NGR=14)=0$ & $u(NGR=0)=1$. This is due to the fact that the greater the growth of the neighbourhood, the greater the number will be of people served; hence, greater will be the utilization of the asset. Table 13 gives the utilities of NGR at 0, 3.5, 7, 10.5 and 14 as elicited from the peers and the associated fitted function.

Table 12: Dwelling units approved for construction between 2003 and 2005.

Traffic District	**Dwelling units Yr 2003**	**Dwelling units Yr 2005**	**Growth Rate**
Downtown Core	652	762	8%
University	95	26	-36%
Southgate	40	260	275%
Riverbend	659	1,567	69%
Jasper Place	90	145	31%
W. Jasper Place	224	222	0%
N.W. Industrial	160	0	-50%
North Central	325	164	-25%
Calder	60	114	45%
Londonderry	205	306	25%
Beverly	37	10	-36%
Clareview	472	273	-21%
Capilano	13	25	46%
Bonnie Doon	22	133	252%
Mill Woods	9	44	194%
Mistatim	0	0	0%
Castle Downs	858	1,156	17%
Lake District	845	1,245	24%
The Meadows	535	764	21%
Downtown Fringe	539	129	-38%
Ellerslie	776	1,089	20%
Heritage East	987	1,620	32%
Heritage West	6	3	-25%
West Edmonton	895	821	-4%
Land Bank	2	0	-50%
N.E. Edmonton	17	33	47%
Cloverbar	0	0	0%
Total	8536	10917	14%

Table 13: Utility values for the impact of the Neighbourhood Growth Rate (NGR).

NGR (x)	Utility of NGR (y)
0	0
3.5	0.3
7	0.8
10.5	0.9
14	1
y = -0.0047x2 + 0.1396x - 0.0343; R^2 = 0.9753	

Hence, *u(NGR)* is given by Eq. (5.3):

$$u(NGR) = -0.0047(\mathrm{NGR})^2 + 0.009(\mathrm{NGR}) + 1.0057 \qquad ...(5.3)$$

Where: NGR= Neighbourhood Growth Rate of area where given road section is located.

5.2.4 Single-Attribute Utility Function for Impact on Emergency Medical Services (EMS)

The impact of the MR&R of a roadway is quantified using a nine-division scale (Table 3). A treatment on a particular roadway can have a weak or absolute impact on EMS (represented by a scale from 1 to 9). Based on Table 3, the least achievable impact on EMS is 1 (corresponding to "very weak" on the relative importance scale) and the maximum attainable impact value is 9. So the utility scale can be anchored as: $u(EMS=1)=0$ and $u(EMS=9)=1$. Table 14 gives the utilities of impact on EMS at 1, 3, 5, 7 and 9 as elicited from the peers.

Table 14: Utility values for the impact on Emergency Medical Services (EMS)

EMS (x)	Utility of EMS (y)
1	0
3	0.3
5	0.8
7	0.9
9	1
y= 0.125x – 0.125	

Hence, *u(EMS)* is given by Eq. (5.4):

$$u(EMS) = 0.125(\text{EMS}) - 0.125 \qquad ...(5.4)$$

Where: EMS= Emergency Medical Services rating of the given road section.

Figure 14 illustrates the single-attribute utility functions for ALOS, physical deterioration (IRI), neighbourhood growth and EMS.

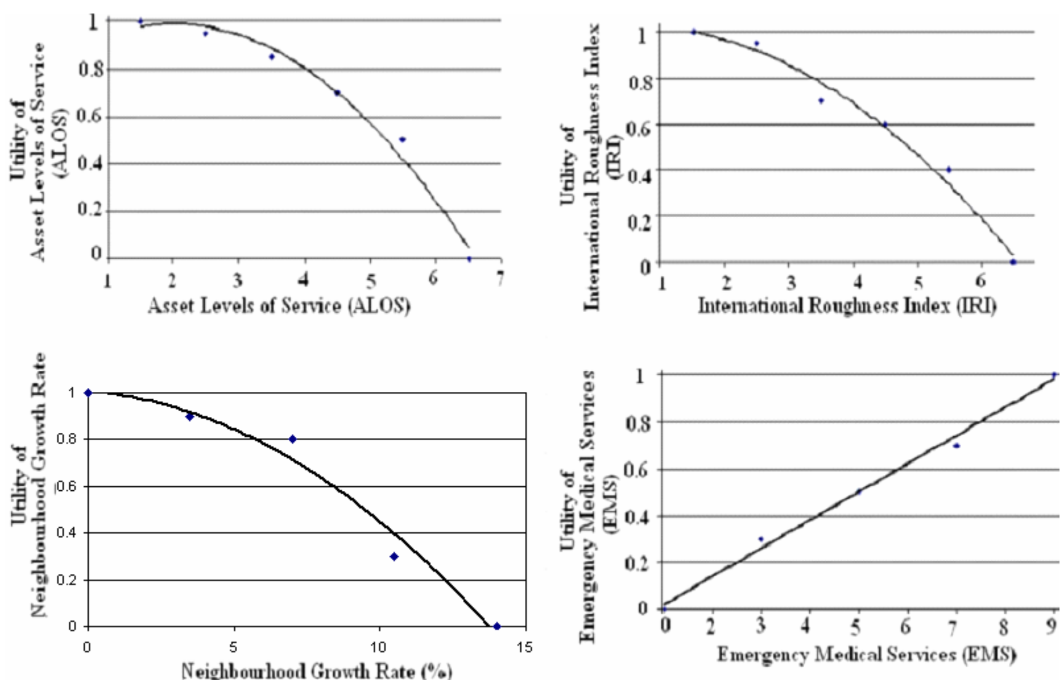

Figure 14: Single-attribute utility functions for ALOS, physical deterioration, neighbourhood growth rate and impact on emergency medical services.

5.3 Quantification of Relative Weights of Single-Attribute Utility Functions

The prioritization vector (***w***), which provides the relative weights (or importance) for the single-attribute utility functions, is calculated based on the AHP. The process began by fragmenting the system into various hierarchies (*Step 1*, Figure 15). The hierarchy was formulated to ensure that all the attributes and interdependencies affecting the utility of single-attribute utility functions are identified. The MAU-ID is the top-level entry in the hierarchy. The attributes grouped in Level 2 of the hierarchy are: visual condition index, surface adequacy index, riding comfort index, populate growth rate, average ownership of vehicles, VLOS, BLOS, PLOS, connectivity and network accessibility. All the Level 2 attributes contribute to the impact of existing ALOS, physical deterioration, future demand in terms of neighbourhood growth and network interdependencies which are placed in Level 3 of the hierarchy.

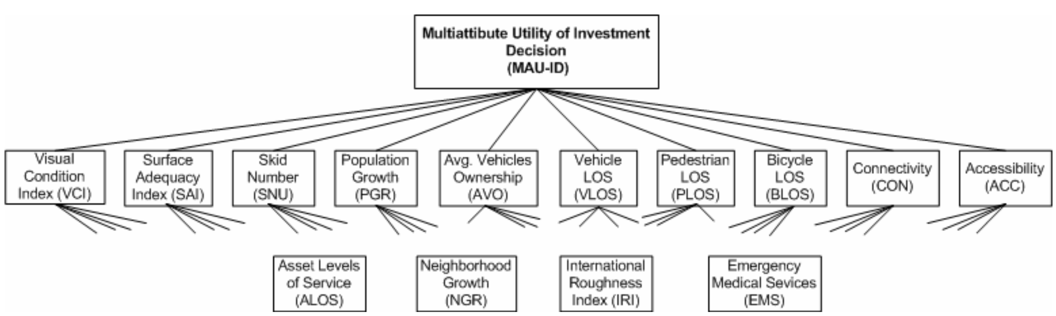

Figure 15: Hierarchy of attributes impacting the utility of Investment Decisions.

Step 2 involves pair-wise comparisons of elements to determine their relative importance. A pair of elements in a given hierarchy is compared with all of the elements in the next higher hierarchy. The comparison results are recorded in a separate "decision matrix" for each level (Tables 15 and 16). To determine the relative priorities of two attributes, the scale listed in Table 3 is used. For example, pair-wise comparison of the visual condition index and surface adequacy index with respect to ALOS shows that the surface adequacy index is much more important than the visual condition index in determining the utility of investment decision (see Table 15). Step 3 involves the calculation of eigenvectors for the decision matrices. Each column of the resultant decision matrices (Table 15 and 16) is normalized. The maximum or principle eigenvalue (λ_{max}) is calculated from the eigenvector. The CR is calculated, and a CR of 0.10 or less is considered acceptable (Saaty 1980). Tables 15 and 16 list the pair-wise comparisons of the hierarchy factors (illustrated in Figure 15) in a matrix form with a corresponding maximum or principle eigenvalue (λ_{max}), a CI and a CR.

Table 15: Decision matrix obtained by pair-wise comparison of Level 2 attributes.

Multiattribute Utility of Investment Decision (MAU-ID)										
	VCI	SAI	SNU	PGR	AVO	VLOS	PLOS	BLOS	CON	ACC
VCI	1	1/5	1	5	3	1/5	1/3	3	3	3
SAI	5	1	3	7	5	1/3	1/2	2	5	5
SNU	1	1/3	1	1	3	1/5	1/3	3	3	3
PGR	1/5	1/7	1	1	1/3	1/7	1/5	1	1	1
AVO	1/3	1/5	1/3	3	1	1/5	1/3	3	3	3
VLOS	5	3	5	7	5	1	3	5	8	9
PLOS	3	2	3	5	3	1/3	1	5	5	7
BLOS	1/3	1/2	1/3	1	1/3	1/5	1/5	1	1/2	1/3
CON	1/3	1/5	1/3	1	1/3	1/8	1/5	2	1	3
ACC	1/3	1/5	1/3	1	1/3	1/9	1/7	3	1/3	1

λ_{max} = 12.6297; CI = 0.16297; CR = 0.10793

VCI=Visual Condition Index, SAI=Surface Adequacy Index, SNU=Skid Number, PGR=Populate Growth Rate, AVO=Average Ownership of Vehicles, VLOS=Vehicle Levels of Service, BLOS=Bicycle Levels of Service, PLOS=Pedestrian Levels of Service, CON=Connectivity and ACC=Accessibility

Table 16: Decision matrix obtained by pair-wise comparison of Level 3 attributes.

Visual Condition Index (VCI)

	ALOS	NGR	IRI	EMS
ALOS	1	1/3	1/7	1
NGR	3	1	1/3	3
IRI	7	3	1	7
EMS	1	1/3	1/7	1

λ_{max} = 4.0079; CI =0.0026; CR = 0.003

Vehicle Levels of Service (VLOS)

	ALOS	NGR	IRI	EMS
ALOS	1	7	3	3
NGR	1/7	1	1/3	1/3
IRI	1/3	3	1	3
EMS	1/3	3	1/3	1

λ_{max} = 4.1645; CI =0.0548; CR = 0.0616

Surface Adequacy Index (SAI)

	ALOS	NGR	IRI	EMS
ALOS	1	1/3	1/7	1
NGR	3	1	1/3	3
IRI	7	3	1	7
EMS	1	1/3	1/7	1

λ_{max} = 4.0079; CI =0.0026; CR = 0.003

Bicycle Levels of Service (BLOS)

	ALOS	NGR	IRI	EMS
ALOS	1	5	7	7
NGR	1/5	1	3	5
IRI	1/7	1/3	1	3
EMS	1/7	1/5	1/3	1

λ_{max} = 4.2457; CI =0.0819; CR =0.092

Riding Comfort Index (SNU)

	ALOS	NGR	IRI	EMS
ALOS	1	1/3	1/7	1
NGR	3	1	1/3	3
IRI	7	3	1	7
EMS	1	1/3	1/7	1

λ_{max} = 4.0079; CI =0.0026; CR = 0.003

Pedestrian Levels of Service (PLOS)

	ALOS	NGR	IRI	EMS
ALOS	1	5	5	7
NGR	1/5	1	3	5
IRI	1/5	1/3	1	3
EMS	1/7	1/5	1/3	1

λ_{max} = 4.2444; CI =0.0815; CR =0.0915

Populate growth Rate (PGR)

	ALOS	NGR	IRI	EMS
ALOS	1	1/7	1	1
NGR	7	1	7	5
IRI	1	1/7	1	1
EMS	1	1/5	1	1

λ_{max} = 4.0142; CI =0.0047; CR = 0.0053

Connectivity (CON)

	ALOS	NGR	IRI	EMS
ALOS	1	1/3	1	1/7
NGR	3	1	1	1/5
IRI	1	1	1	1/7
EMS	7	5	7	1

λ_{max} = 4.1223; CI =0.0408; CR =0.0458

Avg. Ownership of Vehicles (AVO)

	ALOS	NGR	IRI	EMS
ALOS	1	1/7	1	1
NGR	7	1	7	5
IRI	1	1/7	1	1
EMS	1	1/5	1	1

λ_{max} = 4.0142; CI =0.0047; CR = 0.0053

Accessibility (ACC)

	ALOS	NGR	IRI	EMS
ALOS	1	1/3	1	1/7
NGR	3	1	1	1/5
IRI	1	1	1	1/7
EMS	7	5	7	1

λ_{max} = 4.1223; CI =0.0408; CR =0.0458

Matrix **D** (Eq. (5.5)) gives the relative weight (or eigenvector) of attributes which impact the MAU-ID. Matrix E (Eq. (5.6)) lists the relative priorities (or eigenvector) of the attributes contributing to ALOS, NGR, IRI and EMS.

$$\mathbf{D} = \begin{array}{c} \\ \text{VCI} \\ \text{SAI} \\ \text{SNU} \\ \text{PGR} \\ \text{AVO} \\ \text{VLOS} \\ \text{PLOS} \\ \text{BLOS} \\ \text{CON} \\ \text{ACC} \end{array} \begin{array}{c} \text{U-Investment} \\ \begin{bmatrix} 0.088 \\ 0.156 \\ 0.076 \\ 0.032 \\ 0.062 \\ 0.310 \\ 0.176 \\ 0.030 \\ 0.038 \\ 0.032 \end{bmatrix} \end{array} \qquad \text{... (5.5)}$$

$$\mathbf{E} = \begin{array}{c} \\ \text{ALOS} \\ \text{NHG} \\ \text{IRI} \\ \text{EMS} \end{array} \begin{array}{c} \begin{array}{cccccccccc} \text{VCI} & \text{SAI} & \text{SNU} & \text{PGR} & \text{AVO} & \text{VLOS} & \text{PLOS} & \text{BLOS} & \text{CON} & \text{ACC} \end{array} \\ \begin{bmatrix} 0.082 & 0.082 & 0.082 & 0.105 & 0.105 & 0.526 & 0.623 & 0.597 & 0.081 & 0.081 \\ 0.230 & 0.230 & 0.230 & 0.675 & 0.675 & 0.067 & 0.216 & 0.229 & 0.155 & 0.155 \\ 0.607 & 0.607 & 0.607 & 0.125 & 0.125 & 0.255 & 0.106 & 0.119 & 0.104 & 0.104 \\ 0.082 & 0.082 & 0.082 & 0.125 & 0.125 & 0.152 & 0.055 & 0.055 & 0.660 & 0.660 \end{bmatrix} \end{array} \qquad \ldots \text{(5.6)}$$

The priority vector **w** is calculated as **F**= **E*D** in Eq. (5.7):

$$\mathbf{F} = \begin{array}{c} \\ \text{ALOS} \\ \text{NHG} \\ \text{IRI} \\ \text{EMS} \end{array} \begin{array}{c} \text{U-Investment} \\ \begin{bmatrix} 0.332 \\ 0.214 \\ 0.313 \\ 0.141 \end{bmatrix} \end{array} \qquad \text{... (5.7)}$$

5.4 Calculation of Multiattribute Utility of Investment Decision (MAU-ID)

Based on the calculated single-attribute utility functions (Eq. 5.1, 5.2, 5.3 and 5.4) and the calculated prioritization vector (**w**, Eq. (5.7)), the MAU-ID can be calculated. Hence, MAU-ID of treating a road section is given by Eq. (5.8):

MAU-ID $=0.332u(ALOS)+0.214u(NHG)+0.313u(IRI)+0.141u(EMS)$ . .. (5.8)

Where:

MAU-ID = Multiattribute Utility of Investment Decision (due to a MR&R treatment) for the road section;

u(ALOS)= Utility of increased ALOS of the road section due to an investment decision (i.e. MR&R treatment);

u(NGR)= Utility change of a road section due to the projected future neighbourhood growth rate of an area where the road section is located;

u(IRI)= Utility of an increased International Roughness Index of the road section due an investment decision (i.e. MR&R treatment); and

u(EMS)= Utility of an increased Emergency Medical Services rating of the road section due to an investment decision (i.e. MR&R treatment).

Whenever a MR&R treatment is selected for a candidate (or road), it will alter the utility attributes of that candidate. For example, if a spray patch is applied to a road, it will increase ALOS for that road and improve the roughness index and the rating of emergency medical services. The increase in the value of the utility attributes will be primarily dependent on the type of applied MR&R treatment. Table 17 lists the various MR&R treatments considered in this research and their associated impact on the utility attributes. The impact values are based on the literature review.

Table 17: Impact of MR&R Treatments on Utility Attributes.

No.	Treatment	Improvement in ALOS	Improvement in IRI	Improvement in EMS	Impact on NGR
Preventive Maintenance Treatments					
1.	Rout and Seal Crack Treatment	+0.3	+0.2 (But always less than 4.5)	+0	0
Surface Treatment					
2	Spray- Patch	+0.5	+0.4 (But always less than 4.5)	+1	0
3	Micro-Surfacing	+0.8	+0.8 (But always less than 3.5)	+1	0
Rehabilitation Treatments					
4	Hot In-Place Recycling (HIR)	+1	Bring it back to 3	+2	0
5	Cold Mill and Inlay	+1	Bring it back to 3	+2	0
6	Thin Overlay (40 mm or less in thickness)	+1	Bring it back to 3	+2	0
7	Thick Overlay (greater than 40 mm in thickness)	+1.5	Bring it back to 2.5	+2	0

Research considers the impact of various factors such as the visual condition index, surface adequacy index, riding comfort index, populate growth rate, average ownership of vehicles, VLOS, BLOS, PLOS, connectivity and accessibility to calculate the MAU-ID. Depending upon the context and the needs of the municipalities, the model can be modified by the inclusion of other impact attributes. MAU-ID is a time-dependent value which deteriorates with time. In this research, the decision to apply a particular MR&R treatment to a road is based on the time value of the MAU-ID, also known as the "analysis period." The concept of the "analysis period" and the resulting deterioration of MAU-ID are incorporated in the multiobjective resource (i.e., funding) allocation model in Chapter 6 of this thesis report.

Chapter 6: Multiobjective Funding Allocation Model

Once ALOS has been quantified (Chapter 4) and the multiattribute utility of investment decision (MAU-ID) has been quantified (Chapter 5), the next step of the research is to formulate a multiobjective funding allocation model to distribute the budgeted funds in the MR&R of the roads. This chapter outlines the formulation of a multiobjective funding allocation model for MR&R resource allocation in urban roads.

6.1 Multiobjective Optimization Model for Funding Allocation

The problem is formulated in terms of objective functions and related constraints. The model is later solved using a web-based application (OPTIsys) based on GA. The model incorporates two time periods: an analysis period and planning (or budget) period. The analysis period, $1,2,\ldots,t,\ldots,T,$ represents the number of years the selected candidates (or road sections) are evaluated. The budget period, $1,2,\ldots t',\ldots T'$, is the number of years the budget (or resources) is available. For example, in a case where a City Council has designated funds for an infrastructure department (such as transportation or drainage) for a three-year period, that department must plan the spending of the designated funds within the three-year span. This represents the budget or planning period. While allocating resources for MR&R projects, the department, for example, may be interested in quantifying the returns over the next 10 years, representing the analysis period.

$\mathbf{x} = (x_1, x_2, .., x_i, \ldots, x_n)$ for $i = 1,2,\ldots, n$, be an n-dimensional vector of road sections (or candidates) which are to be considered for resource allocation.

$\boldsymbol{\alpha} = (\alpha_1, \alpha_2, ...\alpha_i, ..., \alpha_n)$ for $i = 1,2,\ldots, n$, be an n-dimensional vector of values 0 or 1, depending whether the project is selected $(\alpha = 1)$ or rejected $(\alpha = 0)$.

$\mathbf{P}$ = *1,2,…,p,…,P,* be the P-dimensional vector of treatments which can be applied to vector $\mathbf{x}$ of the road sections (or candidates).

$\mathbf{Z} = (\mathrm{Z}_1, \mathrm{Z}_2, ...\mathrm{Z}_l, ..., \mathrm{Z}_m)$ be the vector of objective functions, where $l=1,2,\ldots,m$. Every alternative x_i will achieve the m^{th} objective to some degree.

The model will maximize the return (or value) of multiple objectives by selecting a set of candidates, such that:

$$\underset{\mathbf{x} \in F}{Max}\, \mathbf{Z}(\mathbf{x}) = Z_1(\mathbf{x}), Z_2(\mathbf{x}), ..., Z_m(\mathbf{x}), \quad \text{... (6.1)}$$

where F is a set of all feasible solutions.

6.1.1 Objective 1: Maximization of the Multiattribute Utility of Investment

$$\text{Max } \mathrm{Z}_1(\mathbf{x}) = \sum_{i=1}^{n} \sum_{t=1}^{T} \sum_{p=1}^{P} \sum_{t'=1}^{T'} \text{MAU-ID}_{ipt}\, \alpha_{ipt'}, \quad \text{... (6.2)}$$

Subject to the following constraints:

1. Multiattribute Utility of the investment decision should lie between 0 and 1 (i.e. $0 \le \text{MAU-ID}_{ipt} \le 1$)

2. The minimum acceptable value for ALOS is 4.5 (i.e., $ALOS \le 4.5$)

Where:

MAU-ID_{ipt} = the multiattribute utility of applying the MR&R treatment (*p*) to the candidate (x_i) in a given time period (*t*) for $i=1,2,\ldots,n$; $p=1,2,\ldots,P$; $t=1,2,\ldots,T$.

$\alpha_{ipt'}$ = 0 or 1 for every MR&R treatment (*p=1,2,…,P*) applied to the candidate (x_i; *i = 1,2,…, n*) in a given time period (*t'=1,2,…,T'*).

$\sum_{i=1}^{n}\sum_{t=1}^{T}\sum_{p=1}^{P}\text{MAU-ID}_{ipt}$ represents the aggregate multiattribute utility increase due to the application of MR&R treatment (*p*) to a candidate (x_i) analyzed over a period of time 1,2,…,t,…,T. A binary variable is represented by $\alpha_{ipt'}$ and takes the value of 1 if the candidate (x_i) is selected and 0 if the candidate (x_i) is not selected during the planning period (*1,2,…t',…T'*). The multiattribute utility of any selected treatment, MAU-ID_{ipt}, will decrease over the analysis period due to physical deterioration. This deterioration has been modeled in *Section 6.2* of this chapter.

6.1.2 Objective 2: Minimization of Budget Idleness (or Maximization of Budget Utilization)

Let $\mathbf{B} = \{B_1, B_2, ...B_{t'}..., B_T\}$ be the set of budgets available during the planning or budget period (*1,2,…t',…T'*) which can be allocated to a set of candidates (feasible solution, *F).*

Let $a_{ipt'}$ be the cost incurred on candidate (x_i) due to treatment (*p*) in the year *t'*; for $1 \le i \le n$; $1 \le p \le P$ and $1 \le t' \le T'$.

The total budget allocated to candidate (x_i) in the year *t'* is given by, $A_{t'}$:

$$A_{t'} = \sum_{i=1}^{n}\sum_{p=1}^{P} a_{ip}\alpha_{ip}$$

After normalization, the objective function (Z_2) can be expressed as:

$$Max\ Z_2(\mathbf{x}) = \sum_{t'=1}^{T'} \frac{\sum_{i=1}^{n}\sum_{p=1}^{P} a_{ipt'}\alpha_{ipt'}}{B_{t'}}, \quad \text{... (6.3)}$$

Where:

$a_{ipt'}$ = the cost incurred on candidate (x_i) (or road section) due to the selection of treatment (p) in year t' for $i=1,2,\ldots,n$; $p=1,2,\ldots,q$; *and* $t'=1,2,\ldots,T'$.

$\alpha_{ipt'}$ = 0 or 1 for every treatment (p) applied to the candidate (x_i) in a given time period (t'), depending whether the candidate is selected or not for treatment (p) in year t' for $i=1,2,\ldots,n$; $p=1,2,\ldots,q$; *and* $t'=1,2,\ldots,T'$.

$B_{t'}$ = the amount of budget available in the year t' for $t'=1,2,\ldots,T'$.

Subject to constraints:

1. The total budget available should be equal or greater than the total amount of the allocated budget.

$$\sum_{t'=1}^{T}\left(B_{t'} - \sum_{i=1}^{n}\sum_{p=1}^{P} a_{ipt'}\alpha_{ipt'}\right) \geq 0$$

2. Non-negativity constraint for every project (i), resource (k) and time period (t')

$$a_{ikt'} \geq 0$$

6.2 Deterioration Modeling

A deterioration model is defined as the link between the measure of a facility's condition and a set of explanatory variables (Ben-Akiva and Gopinath 1995). The measure of a facility's condition is an assessment of the extent and severity of facility damages on a numeric scale. Explanatory variables are the factors which affect the facility deterioration and can be observed or measured (such as physical condition, age, traffic volume, weather variations, etc.).

MAU-ID is the primary asset performance measure used in this research. Hence, it is crucial to quantify the decrease in MAU-ID with respect to time. MAU-ID is primarily dependent on the value of ALOS and the IRI. In this research, it is assumed that the deterioration of MAU-ID is directly proportional to the deterioration of the IRI. For new pavements, the IRI should lie in a range of 1.5-3.5, whereas for older pavements, the IRI should lie in a range of 2.5- 6.5 (Milla 2002).

The deterioration model of the IRI used in this research is based on the study by Raymond et al. (2002). Based on the Canadian Long Term Pavement Performance study data, Raymond et al. (2002) investigated the effects of various MR&R treatments on pavement roughness progression. The Canadian Long Term Pavement Performance study, initiated in 1989, involved the deterioration analysis of various asphalt overlay rehabilitation treatments carried out on 65 road sections located at 24 sites. Between 1989 and 1990, these sections were covered with various thicknesses of asphalt overlay materials on existing flexible pavements. Raymond et al. (2002) also developed models to predict the pavement deterioration rate of various MR&R treatments. IRI measurements were taken with a digital incremental profiler (or dipstick). Pavement performance is quantified as the average rate of roughness deterioration occurring in the first eight years after resurfacing. Using the pavement deterioration rate eliminates the need to incorporate the as-built pavement roughness (i.e., pavement roughness immediately after construction) into the model. Linear regression was used to determine the average rate of deterioration in each pavement section.

Each test site contains two or four adjacent test sections to compare alternative MR&R treatments under identical traffic loading, weather and subgrade soil conditions. The pavement roughness ratio prior to rehabilitation is quantified as the IRI of the pavement. Overlay thickness is quantified as the as-built thickness of asphalt pavement during treatment. Pavement cracking prior to treatment is the total length of cracks from all types of cracking (i.e., sealed and unsealed cracks). The mechanistic-empirical estimations of fatigue damage and rutting damage are based on the analyses of falling-weight deflectometer measurements, which are adjusted to represent the period of maximum pavement deflection based on Benkelman beam measurements taken throughout the year. Fatigue damage is estimated by comparing the tensile strains and the number of Equivalent Single Axle Loads (ESALs) in the first eight years after treatment with the Asphalt Institute's fatigue criteria (1982). Annual precipitation and annual number of days with precipitation are self-descriptive. The annual freezing index is the annual sum of the negative mean air temperatures (e.g., 5 days at –2°C equals a freezing index of 10°C·d). The average monthly temperature gradient is the difference between the mean monthly maximum and minimum temperatures. Subgrade type is categorized as either coarse grained or fine grained based on Canadian Strategic Highway Research Program guidelines (Transportation Association of Canada 1997). Accumulated ESALs after eight years of service are the estimated number of ESALs occurring during the eight years after treatment.

The following is a comprehensive deterioration model of the IRI, Eq. (6.4) (Raymond et al. 2002):

$$PD = \begin{pmatrix} 0.137 - 0.000998OT + 0.000504PC + 0.0354DR - 0.0266OM \\ +0.0380FDE - 0.0000827FI + 0.00117DP + 0.0000000223ESAL_8 \end{pmatrix}^3 \quad \text{... (6.4)}$$

The comprehensive model (Eq. (6.4)) has two predictor variables, deflection ratio and estimate of fatigue damage, which can be difficult to quantify because this information is not always readily available. Hence, Raymond et al. (2002) proposed a simplified version of the model to quantify the deterioration of the IRI, as illustrated in Eq. (6.5):

$$PD = \begin{pmatrix} 0.160 - 0.00120OT + 0.000578PC - 0.0000805FI \\ +0.00147DP + 0.0000000223ESAL_8 \end{pmatrix}^3 \quad \text{... (6.5)}$$

Where:

PD = the rate of Pavement Deterioration (IRI/year)

OT = the Overlay Thickness (mm)

PC = the Prior Cracking (m/150 m)

DR = the Deflection Ratio

OM = the type of Overlay Material (virgin=0, recycled =1)

FDE = the Fatigue Damage Estimate (percentage of design ESAL)

FI = the annual Freezing Index (oC ·d)

DP = the annual number of Days with Precipitation

ESAL8 = the accumulated Equivalent Single Axle Loads after eight years

For the City of Edmonton, the values of the freezing index and annual number of days with precipitation are 1092 °C ·d and 125 days, respectively (Environment Canada 2008). Hence, Eq. (6.5) can be re-expressed as:

$$PD = \left(0.255844 - 0.00120OT + 0.000578PC + 0.0000000223ESAL_8\right)^3 \quad \text{...(6.6)}$$

Eq. (6.6) has been used in OPTIsys to calculate the change in MAU-ID with respect to time.

6.3 Cost Modeling

A treatment is the single application of preventive maintenance, surface restoration or rehabilitation activity to pavement, while a strategy is a series of treatments scheduled over the analysis period. If preventative maintenance is a viable first treatment to meet ride requirements, then it should also be the most cost-effective alternative (Alberta Infrastructure and Transportation 2006). Any low-cost preventative maintenance treatments which increase ALOS to a desirable level should be preferred to costly alternative treatments. This research excludes major reconstruction treatments, which require thorough engineering analysis. The following are examples of major MR&R measures taken by the City of Edmonton:

Preventative Maintenance: This encompasses a broad range of cost-effective treatments intended to preserve the service life of an infrastructure asset and improve its functional condition without significantly increasing the structural strength. Some examples are crack sealing, spray-patching of cracks, thermo-patching of cracks, cold mill and inlay, fog coating, chip seal coating, micro surfacing and thin overlays.

Repair: This treatment is usually unplanned and occurs as a result of failure due to unanticipated events. It entails actions such as spray-patching, pothole patching, skin patching and deep patching.

Rehabilitation: This treatment is a major scheduled event intended to restore a critical component, or an entire asset or facility, to its former condition. Treatments such as cold milling and overlay, structural overlay and white topping improve a system and can also contribute to structural strength. These treatments can be applied to midlife and late-life pavements.

Table 18 (Alberta Infrastructure and Transportation 2006) lists the treatments used in the OPTIsys module. Some treatments related to the repair of transverse cracks would be applied later in the life of the pavement or as pre-overlay repairs. Surface treatments include surface seals and other treatments to address surface deficiencies such as general raveling, segregation or fatigue-cracking distresses. These treatments can be applied to midlife pavements to retard future surface or structural deterioration. Rehabilitation treatments are high-cost treatments such as structural overlays or mill and inlay treatments applied to increase structural capacity and to restore serviceability and ride quality. These treatments could be applied to midlife and late-life pavements.

Table 18: MR&R treatments used in OPTIsys (Alberta Infrastructure and Transportation 2006).

No.	Treatment	Application	Unit Cost	Treatment Service life (Yrs)	Comments
Preventive Maintenance Treatments					
1.	Rout and Seal Crack Treatment	Applied to newer pavements with slight to moderate cracks to seal the pavement from ingress of water and air	$3.15 /ln.m	4 to 5+	- AI&T experience mixed with high rate of installation failure - Effect on extending pavement life not known; research required - Several different rout profiles available
Surface Treatment					
2	Chip Seal Coat; Graded Aggregate Seal Coat	Applied to structurally sound, fairly smooth pavements with surface deficiencies (e.g., ravelling, segregation, etc.) and midlife pavements exhibiting hairline to slight wheelpath fatigue cracks	$3.00 /m²	5 to 7+	- Service life governed by the condition of the underlying pavement structure - Treatments do not add structural strength - Treatments can seal hairline to slight fatigue cracks and defer overlay treatments
3	Micro-Surfacing	Applied to structurally sound, fairly smooth pavements with surface deficiencies (e.g., ravelling, segregation, etc.); can also be used as a rut-fill treatment	$3.50-4.50/ m²	5 to 7	- Micro-Surfacing is a mixture of manufactured fine aggregate and a polymer modified asphalt emulsion - May be appropriate for semi-urban applications
Rehabilitation Treatments					
4	Hot In-Place Recycling (HIR)	Applied to rough but structurally adequate pavements; staged rehabilitation to improve ride quality until overlay thickness reaches a practical or economic thickness	$6.00 /m²	7-10	- May not be suitable for pavements with severe deficiencies (e.g., rutting) - Seal coats, patching and crack sealer may affect recycled mix quality - Treatment generally applied to travel lanes only

No.	Treatment	Application	Unit Cost	Treatment Service life (Yrs)	Comments
5	Cold Mill and Inlay	Applied to rough and/or rutted but structurally adequate pavements; staged rehabilitation to improve ride quality until overlay thickness reaches a practical or economic thickness	$6.00 /m²	9-12	- Cold milled RAP can be recycled - Typically 50 mm cold mill depth, but can be increased to provide modest strengthening - Treatment generally applied to travel lanes only, but can be done on narrow roads - Unit cost based on an assumption of $55.00/tonne for ACP
6	Thin Overlay (less than 40 mm in thickness)	Applied to rough, structurally adequate pavements with or without surface deficiencies; can be applied to structurally inadequate pavements to defer grade widening or reconstruction	$4-5/m²	10 (For structurally Adequate Pavements), 5-7 for structurally inadequate pavements	- Can treat travel lanes or full-width roads - May not be able to meet QA smoothness specifications - Pre-level quantities can significantly affect LCCA - Overlay thickness based on the designer's assessment of the roadway condition - Can be used to defer grade widening
7	Thick Overlay (greater than 40 mm in thickness)	Applied to pavements with severe deficiencies and strengthening needs	$10-11/m²	15 to 20	- Overlay thickness based on structural design - Used in the past to treat severe rutting in the outer lane of divided highways prior to further overlay

Chapter 7: Development of a Computer Application- OPTIsys

This chapter illustrates the development of a web-based computer application known as OPTIsys. OPTIsys integrates all the phases of this research on a single platform, enabling users to use the framework with a simple front-end interface. Users provide the input parameters (budget information, analysis period and GA parameters), and OPTIsys runs the developed mathematical models and algorithms in the backend to provide the results. This chapter explains the architecture of OPTIsys and gives a step-by-step explanation of the algorithms. Various issues such as data structures, coding of strings, enforcement of constraints and fitness calculation are also examined.

7.1 OPTIsys: System Architecture and User Interface

7.1.1 System Architecture

OPTIsys is a web-based application developed using *J# and Apache Tomcat*. OTPIsys is hosted on the *Tomcat* server which implements the Java Sevlets and Java Server Pages (JSP). The *Tomcat* server provides a web (HTTP) environment for the Java code to run. OPTIsys has a central asset information repository which has been developed using *MS Access*. The user can store road and traffic attributes in this database. The database can be edited using the built-in interface in OPTIsys.

The architecture of OPTIsys is illustrated in Figure 16. All the user requests (to save and retrieve data) are handled by JSP. JSP is a Java technology that allows software developers to create dynamically generated web pages, with HyperText Markup

Language (HTML), Extensible Markup Language (XML) or other document types, in response to a web-user request. JSP acts as the interface between the user and the backend database and algorithms. JSP also "talks" to Java Objects, which in turn look through the database to process the requests. Complete OPTIsys logics are written in these Java Objects. As the presentation (or user interface) and research logics (or OPTIsys algorithms) are created in separate layers, it will be easy to modify the application in the future.

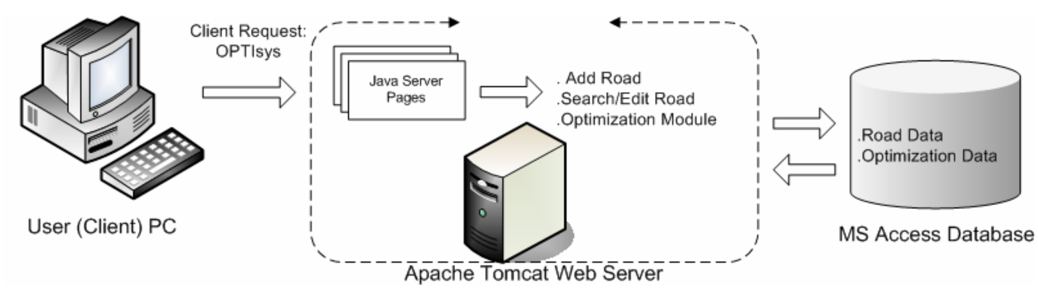

Figure 16: OPTIsys: System architecture

The web-based architecture of OPTIsys has many inherent advantages over the stand alone PC application. To run OPTIsys, all one needs is a web browser: in this case, Windows Internet Explorer. Hence, the application can be run from any place (office, off-site, etc.) around the world where the Internet is available. No additional hardware or software configuration is required to run OPTIsys. Unexpected problems can be solved far more quickly as the source of the problem is generally at the server's end, not with the user's PC.

The following technologies have been used for the development of OPTIsys:

1. Web Server: Apache-Tomcat, version 5.5.27
2. Java Platform: version jdk1.5.0_03

3. Database: MS Access

There are several advantages of using the *Apache Tomcat* Server and Java Platform including:

1. *Apache Tomcat* is an open-source application server completely free of cost;
2. OPTIsys can be deployed on any platform such as Windows, Linux and UNIX. Hence, it is a platform-independent application;
3. OPTIsys requires much less memory during startup time;
4. Java Sun compliant; and
5. Extensive documentation and development support available online.

MS Access has been used as the database for OPTIsys as it has been successfully used in small- and medium-sized applications due to the following reasons:

1. Easy deployment: no database server is required on the clients' machines;
2. *MS Access* is a file-based database. One can copy the database file (.mdb) into the PC's application folder. This makes it easier to take backups; and
3. Simple user interface: it is easy to create or modify tables using the *MS Access* software.

7.1.2 User Interface

OPTIsys has three built-in modules for data management and optimization purposes:

1. Addition/Deletion of Roads
2. Search and Edit Roads
3. Optimization Module

Figure 17 illustrates OPTIsys' entry screen. This screen allows the user to go to the desired module.

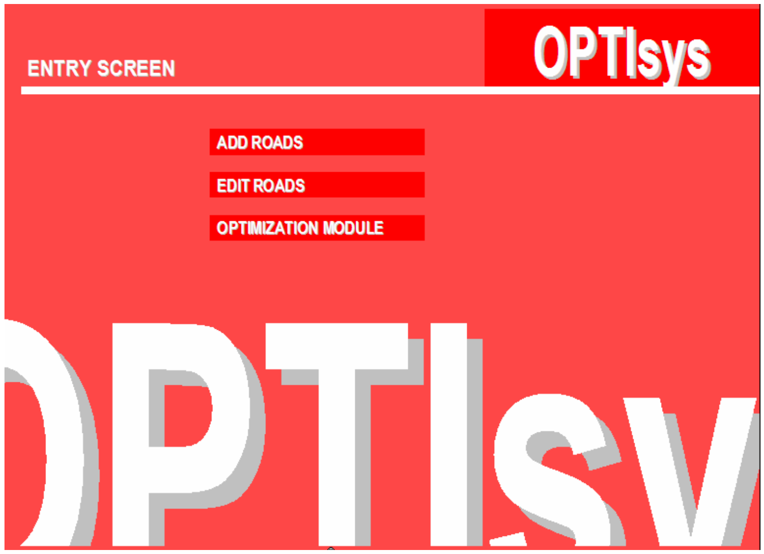

Figure 17: OPTIsys software entry screen.

7.1.2.1 Addition/Deletion of Roads

This module allows the user to add and delete the assets (in this case, roads) in the database. The following road attributes can be stored in the module:

1) Physical attributes: road name, direction (eastbound, northbound, etc.), road names which bound the given asset, road length (m), road age (years), outside lane width (m), shoulder (or bicycle) lane width (m), sidewalk width (m), percentage of the segment with on-street parking, buffer width (distance between the edge of the pavement and sidewalk, m) and total number of lanes;

2) Deterioration attributes: neighbourhood growth rate (%), and IRI (prior to cracking, m/150 m of road section); and

3) Traffic attributes: percentage of time spent following other vehicles, average travelling speed (km/h), posted speed limit (km/h), percentage of heavy vehicles,

annual average daily traffic, passenger car equivalent flow rate at peak conditions for 15 minutes and level of EMS.

Once the road is saved in the database, OPTIsys automatically assigns an identity (ID) to the road. This ID is the combination of the road's name (which is added to the database) and the names of the roads bounding the road in question (which are also added to the database). OPTIsys also runs the algorithm in the backend to calculate ALOS of the road. Figure 18 illustrates the OPTIsys user interfaces for the addition/deletion of roads.

Figure 18: User interfaces for the addition/deletion of roads in OPTIsys.

7.1.2.2 Search and Edit Roads

The Search and Edit Roads module allows the user to search for a particular road and edit its attributes. The search can be performed by road ID or the type of road (e.g., street, avenue, etc.). If the user chooses to modify the road's attributes, OPTIsys recalculates ALOS for the edited road. Figure 19 illustrates the user interface to search for roads and edit their attributes.

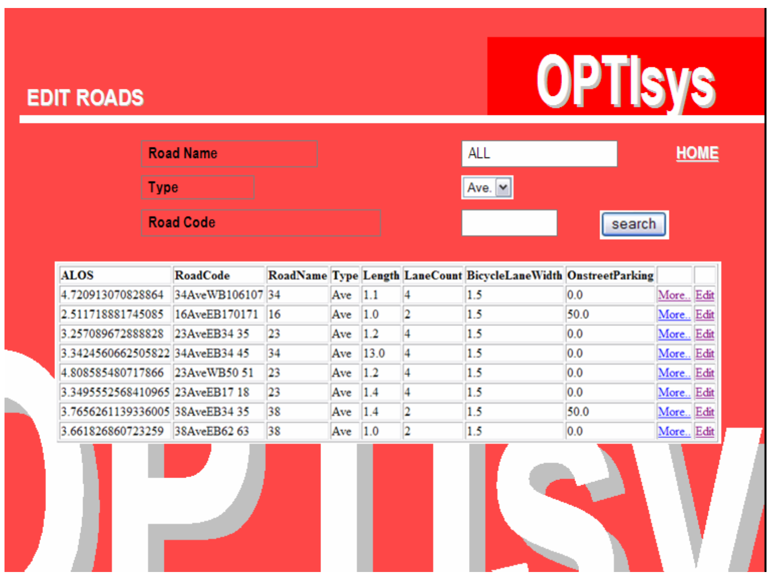

Figure 19: User interface for searching and editing road attributes in OPTIsys.

7.1.2.3 Optimization Module

OPTIsys' Optimization Module allows the user to allocate resources to find the maximum value of the objective functions. This module starts with a screen which allows the user to search a set of roads based on a particular value of ALOS. For example, the user can search for roads with an ALOS value "equal to," "equal or greater than," or "equal or less than" an ALOS value of 3.5. The user can select some or all of the roads (candidates) for MR&R treatment resource allocation consideration by checking the checkboxes next to the individual roads. The next screen displays the various MR&R treatment options which can be applied to the selected set of road candidates. Again, the user can select some or all of the MR&R treatments by means of checkboxes.

Once the road candidates and treatments are selected, the user is asked to provide the budget (up to a maximum of three years) and the analysis period for which the investment has to be evaluated. The user also can change the GA parameter default values (such as population size, mutation rate, crossover rate, etc.). Once the "Optimization" button is pressed, the optimization algorithms run in the backend. The details of the optimization algorithms are provided in the following sections. When the near-optimal solution is reached, the results are displayed to the user for further analysis or decision making. By default, the results are displayed in an HTML page. If needed, the user can display the results in an *MS Excel* file or XML file. Figure 20 illustrates the OPTIsys user interfaces for the Optimization Module.

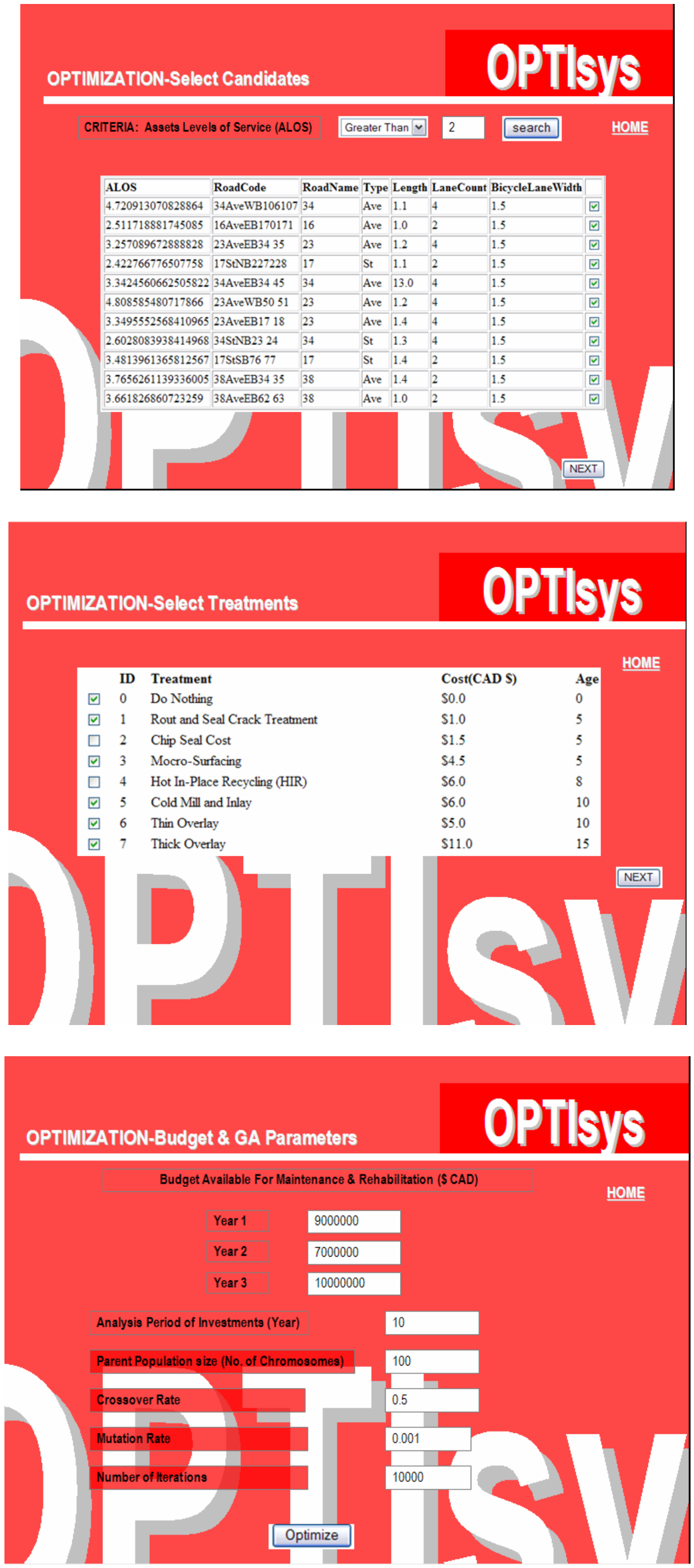

Figure 20: OPTIsys user interfaces for the optimization module.

7.2 Genetic Algorithms in OPTIsys

The initial step in the use of GA is to generate a schema or chromosome. The chromosome incorporates all the problem parameters in its structure, thus representing the parameter space. GA search for the combination of parameters which offer an optimal or near-optimal solution to the problem. Computation commences by randomly generating a set of chromosomes (or parent-pool) for a population. The parent-pool is evaluated using an objective function. In the case of multiobjective optimization, fitness is evaluated using a fitness function (Eq. 7.1). Through continuous iteration—which involves the copying, swapping and modification of chromosomes—a new offspring population is generated. Each parent contributes a certain number of offspring to the population depending upon its relative fitness with respect to other chromosomes within the parent population. This ensures that the fittest parent will produce more offspring in subsequent reproductions. To introduce variability (or diversity) in the new population, various operators can be used. OPTIsys uses two of the most commonly used operators: a crossover operator and a mutation operator. The evolution and regeneration of a population continues until an optimal or near-optimal solution is reached. The following are the generic steps in solving the optimization problem using GA (Figure 21):

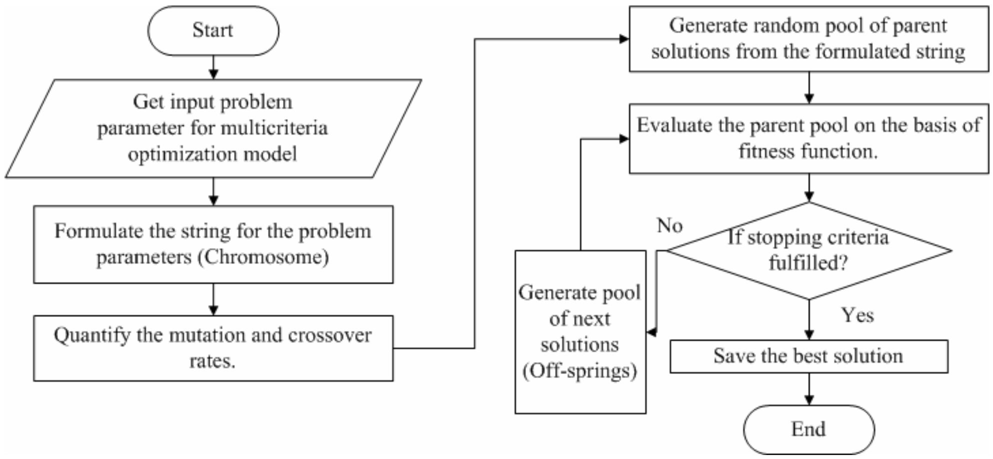

Figure 21: Generic GA for optimization.

Step 1: Choose the problem representation

There are many ways to code the GA parameters (or chromosome) for a given problem. OPTIsys uses integer coding for the parameters. Figure 22 illustrates an example of coding parameters in OPTIsys for a budget period of five years. Chromosome is composed of cells known as 'Bits'. Mathematically, Chromosome is represented as one dimensional array, or a row of cells, and each cell represents a 'Bit'. Each bit can hold one value in it. In OPTIsys, the structure of the chromosome change dynamically based on the number of years in the analysis period as illustrated in Figure 22.

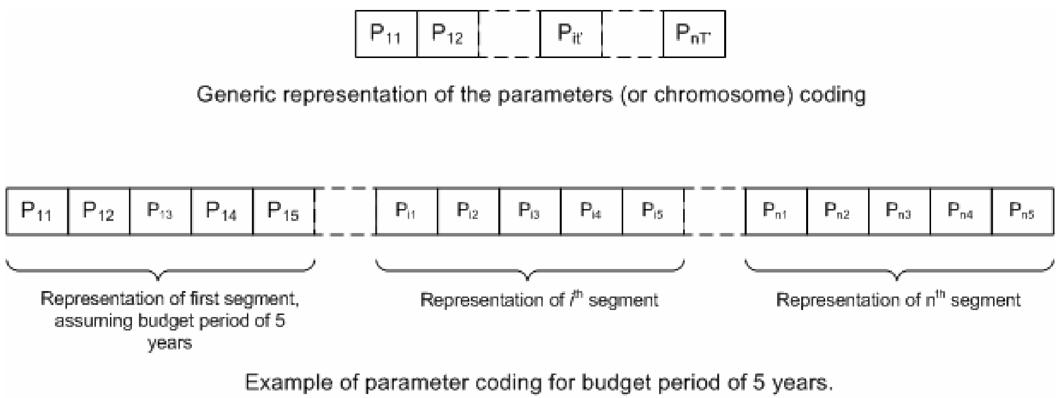

Figure 22: Parameter coding for GA as used in OPTIsys.

As listed in the resource allocation model in Chapter 6, let $\mathbf{x} = (x_1, x_2,.., x_i,\ldots,x_n)$ for $i = 1,2,\ldots, n$ be an n-dimensional vector of the road sections considered for resource allocation. Let 1, 2, … t', …T' be the number of years the budget is available (i.e., planning or budget period). Then cell $P_{it'}$ (see Figure 22) will represents bit of chromosome which will hold the MR&R treatment value or code which can be applied to road section x_i in year t'. The user can select the following treatments in OPTIsys:

Treatment ID = 0 for Do Nothing;

1 for Rout and Seal Crack Treatment;

2 for Chip Seal Coat;

3 for Micro-Surfacing;

4 for Hot In-Place Recycling;

5 for Cold Mill and Inlay;

6 for Thin Overlay; and

7 for Thick Overlay.

Step 2: Initialize the population

There are no strict rules for determining the population size. The population size affects the speed of convergence to a solution. Smaller populations can lead to premature convergence and dominance of a few solutions. Population sizes between 100 and 200 are common in GA. In OPTIsys, the default population size is 100, though the user can choose a different population size.

Step 3: Calculate the Fitness

The fitness of the candidates is calculated based on the fitness function. The fitness function quantifies the relative fitness of objectives accomplished by a given solutions. OPTIsys fitness function is represented as:

$$\mathrm{F}(\mathbf{c}) = w_1 f_1(\mathbf{c}) + w_2 f_2(\mathbf{c}) \ \forall c \in \mathbf{c}$$

Where:

$\mathrm{F}(\mathbf{c}) =$ fitness function of chromosome (or string) *c* such that $\mathbf{c}$ = *(1, 2,.., c,…,C)* be a c-dimensional vector, representing the population size (i.e. the number of chromosomes in the population)

$f_1(\mathbf{c}) =$ fitness function for chromosome *c* based on Objective Function 1: Maximizing Utility of increased ALOS (*Section 6.1*)

$w_1 =$ relative weight of fitness function $f_1(\mathbf{c})$

$f_2(\mathbf{c}) =$ fitness function for chromosome *c* based on Objective Function 2: Maximizing Resource Utilization (*Section 6.2*)

$w_2 =$ relative weight of fitness function $f_2(\mathbf{c})$

The DM has to provide the relative weight for each objective function to assess the fitness of a solution. In OPTIsys, the relative weights for $Z_1(\mathbf{x})$ & $Z_2(\mathbf{x})$, given by Eq.

(6.2) and (6.3), are 0.8 and 0.2 respectively. If **c** = *1,2,…,c,…,C,* be the c-dimensional vector representing the population size (or number of chromosomes or strings), then U_c represents the aggregate utility of c^{th} chromosome (or string) over analysis period T such that:

$$U_c = \sum_{i=1}^{n}\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{t'=1}^{T'} \text{MAU-ID}_{ipt}\ \alpha_{ipt'}$$

Hence, the fitness function ($\mathrm{F}(\mathbf{x})$) can be rewritten as:

$$\mathrm{F}(\mathbf{x}) = 0.80\left(\frac{U_c}{\max\left(U_c\right)}\right) + 0.20\left(\sum_{t'=1}^{T'}\frac{\sum_{i=1}^{n}\sum_{p=1}^{P} a_{ipt'}.\alpha_{ipt'}}{B_{t'}}\right) \qquad \text{... (7.1)}$$

Where:

MAU-ID_{ipt} = the multiattribute utility of applying the MR&R treatment (*p*) to the candidate (x_i) in a given time period (*t*; *i=1,2,…,n; p=1,2,…,P; t=1,2,…,T*).

$\alpha_{ipt'}$ = 0 or 1 for every MR&R treatment (*p*) applied to the candidate (x_i) in a given time period (*t'*); for *i=1,2,…,n; p=1,2,…,q; and t'=1,2,…,T'.*

U_c = aggregate utility of chromosome (*c*); for *c= 1, 2,…,C*

$a_{ipt'}$ = the cost incurred on candidate (x_i) due to the selection of treatment (*p*) in year *t';* for *i=1,2,…,n; p=1,2,…,q; and t'=1,2,…,T'.*

$B_{t'}$ = the amount of budget available in the year (*t'=1,2,…,T'*).

Step 4: Perform Selection

There are a number of ways to select a solution (or chromosome) from the solution set. If the selection is done in a heavy-handed fashion, then the population will converge quickly; however, this may compromise the solution quality. OPTIsys uses the Genitor Selection Algorithm for the selection of candidates. According to this method, the population is ranked according to fitness, and then the best individual replaces the worst individual.

Step 5: Perform Crossover

"Crossover" refers to the exchange of parameters (or bits) between two parent chromosomes. Two parent chromosomes are split at a crossover point, and their strings are swapped to form a new chromosome. Depending on the nature of the problem, single- or multi-point crossovers can be used. Crossovers do not change the value of the bits in the offspring achieved by a mutation operator. Goldberg (1989), for one, recommends a crossover rate of 0.5 to 1. OPTIsys' default crossover rate is 0.6, though the user can choose a different crossover rate. To perform crossover, two potential parents are randomly chosen from the population. A random number is generated to decide whether to crossover or not. If the decision is to crossover, a splitting point (or crossover point) is randomly chosen. The final step is to swap the tail ends of the two selected parents to generate two children. The concept of crossover is illustrated in Figure 23.

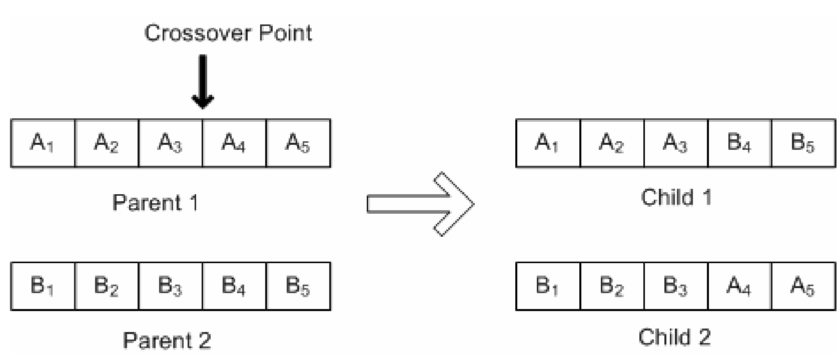

Figure 23: Example of single-point crossover as used in OPTIsys.

Step 6: Perform Mutation

Mutation operator involves the changing the values of the bits of the chromosome. The rate of mutation may be slow, but it ensures genetic diversities within the population. Mutation can lead to significant changes in the population over longer time periods. Goldberg (1989) recommends a mutation rate of 0.001-0.01. OPTIsys' default crossover rate is 0.01, though the user can choose a different crossover rate. In OPTIsys, the value of the selected bit will be changed to random selected value from the set of integers between 0-7. This set represents the treatments which can be applied to the road sections.

Step 7: Check Convergence

When the bit values are identical in all bits, the population is said to be fully converged. Convergence is measured by using the concept of "bias," which is defined as a measure of agreement among the population. Bias assumes a value between 50 and 100%. For example, consider a population of 100 strings (or chromosomes) having 10 bits each, assuming that bit position 7 of all 100 strings can contain either a 0 or 1. If 70 string bits have 1s and 30 string bits have 0s, then the split is 70-30. If 30 string bits have 1s and 70 string bits have 0s, then the split is 30-70. The bit bias is still 70%, as bit bias is the greater of the two percentage split numbers. The average "bit bias" of all the bits will give the string bias. A population with a string bias of 95% is fairly uniform.

7.3 OPTIsys Algorithms

Figure 24 illustrates the comprehensive OPTIsys algorithms. The algorithm starts by consolidating the road data (Function 1) and treatment data (Function 2) which is used in calculations as necessary. The first population of the solutions is initialized as per Function 2. The fitness value of multiattribute utility of investment decision is calculated based on Functions 4 and 5. Functions 6 and 7 calculate the normalized fitness values of the population and assign them to the child population. Functions 8, 9, 10 and 11 are used to calculate the cost associated with the solutions (chromosomes) and populate them in the child population. Function 12 calculates the overall fitness of the child population based on the cost of MR&R treatment and multiattribute utility of investment decision of ALOS. Function 15 is used to replace the worst-fit chromosome with the best-fit chromosome in the population. Functions 16 and 17 are used to implement the crossover and mutation operators for the GA. Function 13 summarizes and records the characteristics of each population.

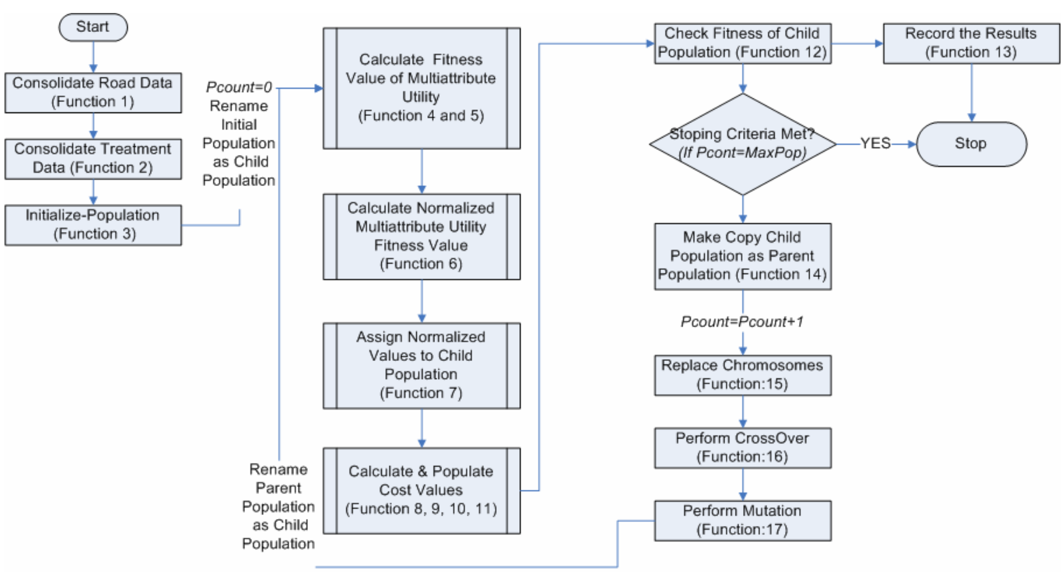

Figure 24: Optimization algorithm used in OPTIsys.

7.4 OPTIsys: A Numerical Example

This section presents a numerical example illustrating the application of OPTIsys. For this example, roads with ALOS greater than 2.5 were selected from the existing database. All the selected roads (45 in total) were considered as potential candidates for MR&R resource allocation. As stated before the value of ALOS for a road section lie between 1.5 to 6.5 (1.5 being the best and 6.5 being the worst). Table 19 (City of Edmonton 2008) lists the physical and traffic attributes of the selected candidates. Once the road candidates were selected for MR&R treatments, the next step was to select specific MR&R treatments to be applied to the candidate roads. The following five MR&R treatments (out of eight possible treatments) were used for resource allocation:

Treatment ID = 0 for Do Nothing;
1 for Rout and Seal Crack Treatment;
3 for Micro-Surfacing;
5 for Cold Mill and Inlay;
6 for Thin Overlay; and

The analysis period for the investment is 10 years. Various combinations were tried to identify the optimum GA parameters to produce the optimization results without compromising the quality of the results. In this example, the size of the population (i.e., the number of chromosome or solution sets) is 100. The crossover rate and mutation rate is 0.6 and 0.01, respectively. The maximum number of iterations has been limited to 40,000.

In the best case scenario (i.e., with an unlimited budget), the solution to the resource allocation problem would be to provide Cold Mill and Inlay or Thin Overlay treatments to all the road candidates. The approximate cost for this would be $6.1 million. But in the real world, the available MR&R budget is almost always less than the required budget. Hence, OPTIsys has been used in this research to illustrate resource allocation under two scenarios: Scenario 1 assumes adequate resources ($5 million) while Scenario 2 assumes limited resources ($4 million).

Table 19: Details of the road sections (candidates) considered for MR&R resource allocation.

Road ID	Location	Dir.	Length (km)	L	WOL	WI	% SOP	WB	WS	PTSF	VP	ATS (km/hr)	HV	PSL (km/h)	AADT	Road Age	IRI	NGR	EMS	PC (m/150 m)
1	16 Ave. NW E of 170 St. NW	E/W	2.0	2	3.5	1.5	50	2	1.5	45%	183	35	6	40	4,388	6	2	9	5	53
2	17 St. NW S of 76 Ave. NW	N/S	2.4	2	3.5	1.5	100	2	1.5	50%	550	35	10	40	13,188	17	6.1	5	3	131
3	23 Ave. NW E of 17 St. NW	E/W	2.4	4	3.5	1.5	0	1.5	1.5	60%	395	45	9	60	9,482	8	2.5	5	7	58
4	23 Ave. NW E of 34 St. NW	E/W	2.2	4	3.5	1.5	0	1.5	1.5	50%	358	50	8	60	8,594	8	1.9	7	7	54
5	23 Ave. NW E of 50 St. NW	E/W	2.2	4	3.5	1.5	0	1.5	1.5	70%	909	45	15	60	21,817	8	1.8	6	5	56
6	34 Ave. NW W of 34 St. NW	E/W	2.3	4	3.5	1.5	0	1.5	1.5	45%	569	50	13	60	13,662	11	5.5	8	5	122
7	34 Ave. NW E of 106 St. NW	E/W	2.1	4	3.5	1.5	0	1.5	1.5	60%	1062	45	18	60	25,496	11	4.1	6	5	88
8	34 St. NW S of 23 Ave. NW	N/S	2.3	4	3.5	1.5	0	1.5	1.5	35%	259	50	8	60	6,224	11	4.5	3	7	95
9	38 Ave. NW E of 34 St. NW	E/W	2.4	2	3.5	1.5	50	2	1.5	70%	467	30	8	40	11,213	13	4.7	7	3	111
10	38 Ave. NW W of 62 St. NW	E/W	2.0	2	3.5	1.5	0	2	1.5	55%	500	35	13	40	12,007	13	3.8	4	5	87
11	44 Ave. NW E of 50 St. NW	E/W	2.3	2	3.5	1.5	0	2	1.5	55%	496	35	10	40	11,893	15	5.3	11	5	118
12	45 Ave. NW E of 199 St. NW	E/W	2.5	2	3.5	1.5	75	2	1.5	70%	319	35	6	40	7,648	19	5.7	11	5	121
13	50 St. NW S of 23 Ave. NW	N/S	2.0	6	3.5	1.5	0	1.5	1.5	60%	1182	50	14	60	28,366	12	4.9	7	5	104
14	50 St. NW S of 34 Ave. NW	N/S	2.4	4	3.5	1.5	0	1.5	1.5	60%	1290	50	13	60	30,952	12	3.9	8	3	84
15	50 St. NW S of 76 Ave. NW	N/S	2.2	6	3.5	1.5	0	1.5	1.5	60%	1604	45	15	60	38,490	12	4.1	11	5	88
16	51 Ave. NW E of 89 St. NW	E/W	2.0	4	3.5	1.5	0	1.5	1.5	70%	920	50	16	60	22,080	19	5.9	12	5	131
17	51 Ave. NW E of 97 St. NW	E/W	2.2	4	3.5	1.5	0	1.5	1.5	65%	977	50	16	60	23,443	19	6.5	7	5	145
18	51 Ave. NW W of 107 St. NW	E/W	2.5	4	3.5	1.5	0	1.5	1.5	65%	754	50	13	60	18,096	19	5.5	4	5	125
19	66 St. NW N of 23 Ave. NW	N/S	2.3	6	3.5	1.5	0	1.5	1.5	50%	924	50	14	60	22,164	15	3.6	7	3	78
20	66 St. NW N of 41 Ave. NW	N/S	2.3	4	3.5	1.5	0	1.5	1.5	65%	1494	45	14	60	35,854	15	3.8	7	3	94
21	66 St. NW N of 118 Ave. NW	N/S	2.4	2	3.5	1.5	50	2	1.5	70%	329	35	7	40	7,884	15	3.4	9	5	77
22	66 St. NW N of 153 Ave. NW	N/S	2.2	4	3.5	1.5	0	1.5	1.5	45%	468	50	5	60	11,229	15	3.9	12	5	86
23	75 St. NW N of 95 Ave. NW	N/S	2.0	4	3.5	1.5	0	1.5	1.5	60%	1800	50	17	60	43,192	15	4.2	5	3	92
24	75 St. NW N of 51 Ave. NW	N/S	2.2	4	3.5	1.5	0	1.5	1.5	60%	1650	50	15	60	39,606	15	5.6	6	3	130
25	76 Ave. NW E of 34 St. NW	E/W	2.3	2	3.5	1.5	50	1.5	1.5	65%	383	35	10	40	9,181	18	5.2	6	5	110
26	82 St. NW N of 112 Ave. NW	N/S	2.2	4	3.5	1.5	0	1.5	1.5	60%	792	55	14	60	19,009	10	3.8	3	5	94
27	82 St. NW N of 116 Ave. NW	N/S	2.5	4	3.5	1.5	50	1.5	1.5	55%	675	60	13	60	16,203	10	3.9	5	5	97
28	82 St. NW S of 119 Ave. NW	N/S	2.0	4	3.5	1.5	0	1.5	1.5	70%	1082	55	14	60	25,960	10	1.9	6	5	58
29	86 St. NW S of 51 Ave. NW	N/S	2.1	4	3.5	1.5	0	1.5	1.5	45%	487	50	7	60	11,689	17	5.7	7	5	121
30	86 St. NW N of 63 Ave. NW	N/S	2.1	4	3.5	1.5	50	1.5	1.5	50%	168	50	6	60	4,043	17	5.7	7	5	133
31	86 St. NW S of 114 Ave. NW	N/S	2.3	4	3.5	1.5	0	1.5	1.5	60%	422	45	7	60	10,128	17	5.5	3	7	123
32	87 Ave. NW E of 156 St. NW	E/W	2.4	4	3.5	1.5	0	1.5	1.5	55%	945	60	18	60	22,671	14	3.5	6	3	76
33	87 Ave. NW W of 170 St. NW	E/W	2.5	4	3.5	1.5	0	1.5	1.5	65%	1026	60	18	60	24,619	14	3.3	6	5	75
34	87 Ave. NW W of 178 St. NW	E/W	2.4	4	3.5	1.5	0	1.5	1.5	50%	618	60	13	60	14,826	14	3.6	6	5	84
35	90 Ave. NW E of 75 St. NW	E/W	2.0	4	3.5	1.5	0	1.5	1.5	55%	586	50	14	60	14,066	16	4.5	6	5	103
36	90 Ave. NW W of 170 St. NW	E/W	2.3	4	3.5	1.5	0	1.5	1.5	60%	292	50	6	60	6,999	16	4.9	9	7	107
37	91 St. NW S of 23 Ave. NW	N/S	2.3	4	3.5	1.5	0	1.5	1.5	55%	598	55	14	60	14,351	14	4.8	7	5	109

L = Total Number of Lanes; WOL = Width of the Outside Lane; WI = Width of the Shoulder or Bicycle Lane; % SOP = % of the Segment with On-Street Parking; WB = Width of the Buffer (dist. between edge of the pavement and sidewalk); PTSF = % of Time Spent Following Other Vehicles; VP = Passenger Car Equiv. Flow Rate for Peak conditions for15 minutes; ATS = Average Traveling Speed; HV = % of Heavy Vehicles; PSL = Posted Speed Limit; AADT = Average Annual Daily Traffic; NGR = Neighborhood Growth Rate; EMS = Level of Emergency Medical Services; PC = Percentage of Cracking

Road ID	Location	Dir.	Length (km)	L	WOL	WI	% SOP	WB	WS	PTSF	VP	ATS (km/hr)	HV	PSL (km/h)	AADT	Road Age	IRI	NGR	EMS	PC (m/150 m)
38	91 St. NW S of 51 Ave. NW	N/S	2.2	4	3.5	1.5	0	1.5	1.5	65%	1282	50	13	60	30,767	14	4.7	4	3	110
39	91 St. NW S of 63 Ave. NW	N/S	2.0	4	3.5	1.5	0	1.5	1.5	50%	793	55	11	60	19,034	14	6.1	6	5	130
40	95 Ave. NW E of 148 St. NW	E/W	2.3	2	3.5	1.5	0	2	1.5	50%	256	40	8	40	6,143	20	6	7	5	126
41	95 Ave. NW E of 155 St. NW	E/W	2.5	2	3.5	1.5	50	2	1.5	55%	450	35	7	40	10,796	20	5.4	13	3	124
42	95 Ave. NW W of 157 St. NW	E/W	2.0	2	3.5	1.5	100	2	1.5	40%	533	35	10	40	12,793	20	5.9	10	3	123
43	97 St. NW S of 45 Ave. NW	N/S	2.5	4	3.5	1.5	0	1.5	1.5	40%	504	55	13	60	12,095	12	4.1	6	5	95
44	97 St. NW N of 103 Ave. NW	N/S	2.5	4	3.5	1.5	0	1.5	1.5	40%	609	55	13	60	14,616	12	4.2	5	5	93
45	97 St. NW N of 104 Ave. NW	N/S	2.0	4	3.5	1.5	50	1.5	1.5	50%	728	55	14	60	17,470	12	3.9	8	5	90

L = Total Number of Lanes; WOL = Width of the Outside Lane; WI = Width of the Shoulder or Bicycle Lane; % SOP = % of the Segment with On-Street Parking; WB = Width of the Buffer (dist. between edge of the pavement and sidewalk); PTSF = % of Time Spent Following Other Vehicles; VP = Passenger Car Equiv. Flow Rate for Peak conditions for 15 minutes; ATS = Average Traveling Speed; HV = % of Heavy Vehicles; PSL = Posted Speed Limit; AADT = Average Annual Daily Traffic; NGR = Neighborhood Growth Rate; EMS = Level of Emergency Medical Services; PC = Percentage of Cracking

7.4.1 Scenario 1: Adequate Budget

As stated before, OPTIsys allows the asset manager to specify the budget for three years (i.e., the Planning or Budget Period). In this example, a \$5-million budget is distributed over three years. The budget availability for Years 1, 2 and 3 is \$2 million, \$1.5 million and \$ 1.5 million, respectively.

As GA are based on evolutionary computation techniques, the fitness of the population increases with the number of iterations. Figure 25 summarizes the fitness of the populations (or solution sets) during the optimization process. As evident from the graph, the fitness of the populations increased with the number of iterations. The increase in fitness is steep during the initial 2,000 iterations (increasing from 0.5 to 0.77). As optimization continued, the rate of improvement of fitness decreased with the number of iterations. The gain in population (or solution set) fitness decreased substantially after 20,000 populations. The population fitness increased by a fraction of 0.02 in the last 20,000 iterations (i.e., iterations from 20,000 to 40,000).

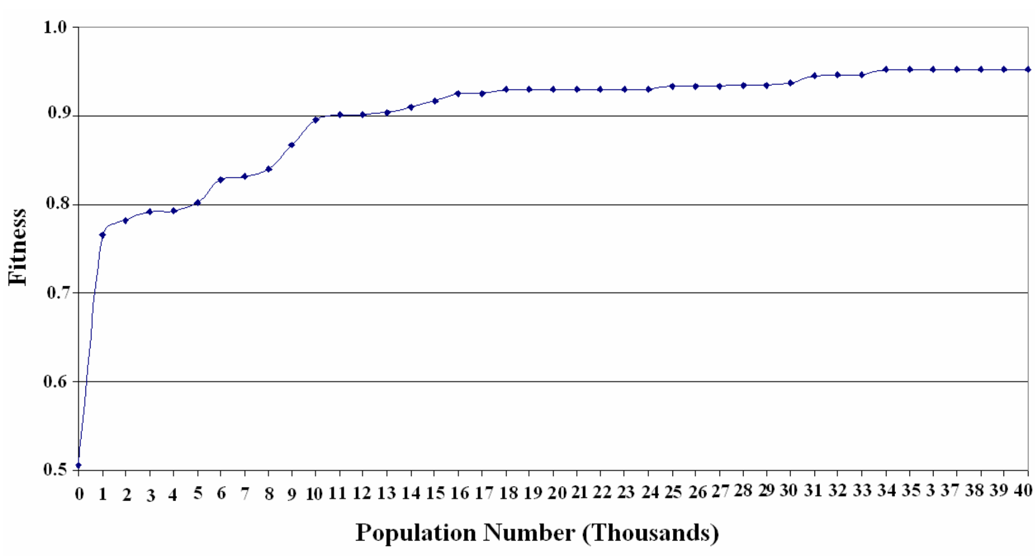

Figure 25: Fitness of populations with respect to the number of iterations: Scenario 1

OPTIsys can generate detailed results of the population (i.e., details of all the chromosomes in the population) in an XML file (Figure 26). The user can specify the number of populations (and hence, the number of XML files containing the population details) required the output of optimization results. The software has been programmed to generate the files at specific percentiles of the population. The percentile interval is one of the input parameters provided by the user. For example, if the user sets the "number of XML files to be generated" at 10 and the "number of iterations" (after which the optimization will stop) at 10,000, then the software will generate one XML file each for population number (or iteration number) 1,000, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000 and 10,000. Each file will contain the details of all the chromosomes for the respective population. Generated file will show the bits of the chromosomes with the corresponding values. This function is useful in monitoring the structure of the chromosome as the optimization proceeds. By looking at the structure of the chromosome, the user can identify commonly occurring problems in GA such as premature convergence. In this example, 10 XML files were generated.

```
- <Chromosome>
    <TotalFitness>495.74835761122654</TotalFitness>
    <UtilityFitness>1.0</UtilityFitness>
    <TotalCost>4846200.0</TotalCost>
    <CostFitness>0.96924</CostFitness>
    <TotalCostUtilityFitness>0.9938480000000001</TotalCostUtilityFitness>
  - <ChromosomeBit>
      <RoadCode>66StNB118119</RoadCode>
      <BudgetYear>3</BudgetYear>
      <TreatmentId>5</TreatmentId>
    </ChromosomeBit>
  - <ChromosomeBit>
      <RoadCode>45AveEB198199</RoadCode>
      <BudgetYear>3</BudgetYear>
      <TreatmentId>5</TreatmentId>
    </ChromosomeBit>
  - <ChromosomeBit>
      <RoadCode>34AveEB34 45</RoadCode>
      <BudgetYear>1</BudgetYear>
      <TreatmentId>6</TreatmentId>
    </ChromosomeBit>
  - <ChromosomeBit>
      <RoadCode>66StNB153154</RoadCode>
      <BudgetYear>3</BudgetYear>
      <TreatmentId>5</TreatmentId>
    </ChromosomeBit>
```


Figure 26: Sample XML file generated by OPTIsys listing chromosome details.

Table 20 illustrates the best-fit chromosome associated with the every tenth percentile of the population. For example, the 10^{th} percentile population will correspond to the population up to the $4,000^{th}$ iteration; the 20^{th} percentile population will correspond to the population up to the $8,000^{th}$ iteration; and the 100^{th} percentile population will correspond to the population up to the $40,000^{th}$ iteration. The best-fit chromosome related to the last population (i.e., the 100^{th} percentile) gave the near-optimal solution to Scenario 1. The chromosome has three bits for each road candidate, containing the road ID, the MR&R treatment ID to be applied to the road candidate along with the treatment year. For example, looking at the values of the 100^{th} percentile chromosome for the 66 Street road section (Road Code = 66StNB118119, i.e., 66 Street bound between 118 Avenue and 119 Avenue), OPTIsys recommend to apply Cold Mill and Inlay treatment (Treatment ID = 5) in Year 3. Similarly for the 76 Avenue road section (Road Code = 76AveEB3435, i.e., 76 Avenue bound between 34 Street and 35 Street), OPTIsys recommended to apply Thin Overlay treatment (Treatment ID = 6) in Year 2. Table 20 illustrates the solution to Scenario 1 using OPTIsys.

As evident from the values of the chromosome, the optimum solution to the problem is to apply Cold Mill and Inlay (Treatment ID= 5) and Thin Overlay (Treatment ID = 6) to most of the road candidates. This can be attributed to the abundance of resources.

Table 20: OPTIsys solution: MR&R resource allocation for Scenario1.

Road Code	BYr/ T-ID	Chromosome (solution set) at the given percentile of iterations									
		10th	20th	30th	40th	50th	60th	70th	80th	90th	100th
66StNB118119	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	6	5	5	5	5	5	5	5	5	5
45AveEB198199	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	5	5	5	5	5	5	5	5	5	5
34AveEB3435	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	1	1	6	6	6	6	6	6	5	5
66StNB153154	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	5	5	5	5	5	5	5	5	5	5
76AveEB3435	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	6	6	6	6	6	6	6	6	6	6
91StNB6364	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	6	6	6	6	6	6	6	6	6	6
95AveEB157158	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	3	3	3	6	6	6	5	5	5	5
66StNB4041	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	5	5	5	5	5	5	5	5	5	5
34AveWB106107	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	3	3	3	3	3	3	3	5	5	5
90AveEB170171	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	6	5	5	5	5	5	5	5	5	5
86StNB5152	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	6	6	6	6	6	6	6	5	5	5
50StNB33 33	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	5	5	5	5	5	5	5	5	5	5

Budget Year = BYr; Treatment ID (T-ID): 0 = Do Nothing; 1 = Rout and Seal Crack Treatment; 2 = Chip Seal Coat; 3 = Micro-Surfacing; 4 = Hot In-Place Recycling; 5 = Cold Mill and Inlay; 6 = Thin Overlay; and 7 = Thick Overlay

Road Code	BYr/ T-ID	Chromosome (solution set) at the given percentile of iterations									
		10th	20th	30th	40th	50th	60th	70th	80th	90th	100th
87AveEB170171	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	0	0	5	5	5	5	5	5	5	5
87AveEB156157	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	6	6	5	5	5	5	5	5	5	5
86StNB114115	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	5	5	5	5	5	5	5	5	5	5
82StNB112113	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	5	5	5	5	5	5	5	5	5	5
44AveEB5051	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	5	5	5	5	5	5	5	5	5	5
97StNB4546	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	5	5	5	5	5	5	5	5	5	5
86StNB6364	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	5	5	5	5	5	5	5	5	5	5
97StNB103104	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	1	5	5	5	5	5	5	5	5	5
95AveEB148149	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	3	3	3	6	6	6	6	6	6	6
23AveEB3435	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	6	6	6	5	5	5	5	5	5	5
87AveEB178179	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	5	5	5	5	5	5	5	5	5	5
95AveEB155156	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	6	6	5	5	5	5	5	5	5	5
50StNB2324	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	6	6	6	5	5	5	5	5	5	5
66StNB23 23	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	5	5	5	5	5	5	5	5	5	5
90AveEB7576	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	3	6	6	5	5	5	5	5	5	5
82StNB116117	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	5	5	5	5	5	5	5	5	5	5
34StNB23 23	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	6	6	5	5	5	5	5	5	5	5
75StNB9596	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	3	3	6	6	6	6	6	6	6	6
51AveWB9798	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	3	3	3	6	5	5	5	5	5	5
50StNB7576	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	5	5	5	5	5	5	5	5	5	5

Budget Year = BYr; Treatment ID (T-ID): 0 = Do Nothing; 1 = Rout and Seal Crack Treatment; 2 = Chip Seal Coat; 3 = Micro-Surfacing; 4 = Hot In-Place Recycling; 5 = Cold Mill and Inlay; 6 = Thin Overlay; and 7 = Thick Overlay

Road Code	BYr/ T-ID	Chromosome (solution set) at the given percentile of iterations									
		10th			10th			10th			10th
51AveEB107108	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	5	5	5	5	5	5	5	5	5	5
38AveEB3435	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	3	5	5	5	5	5	5	5	5	5
75StNB5051	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	5	5	5	5	5	5	5	5	5	5
91StNB5152	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	3	3	3	5	5	5	5	5	5	5
16AveEB170171	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	1	3	5	5	5	5	5	5	5	5
97StNB104105	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	6	6	6	6	6	6	6	5	5	5
82StNB119120	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	6	6	6	6	6	6	6	6	6	6
23AveWB5051	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	5	5	5	5	5	5	5	5	5	5
51AveEB8889	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	5	5	5	5	5	5	5	5	5	5
23AveEB1718	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	5	5	5	5	5	5	5	5	5	5
91StNB2324	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	6	6	6	6	6	6	5	5	5	5
17StSB7677	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	5	5	5	5	5	5	5	5	5	5
38AveEB6263	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	1	3	6	5	5	5	5	5	5	5

Budget Year = BYr; Treatment ID (T-ID): 0 = Do Nothing; 1 = Rout and Seal Crack Treatment; 2 = Chip Seal Coat; 3 = Micro-Surfacing; 4 = Hot In-Place Recycling; 5 = Cold Mill and Inlay; 6 = Thin Overlay; and 7 = Thick Overlay

7.4.2 Scenario 2: Limited Budget

In this scenario, all the parameters and input values are the same as Scenario 1 except the budget availability. The budget for this scenario is \$4 million with \$2 million, \$1 million and \$1 million available for Years 1, 2 and 3, respectively. Figure 27 summarizes the fitness of the populations (or solution sets) during the optimization iterations. The increase in fitness is steep during the initial 1,000 iterations (increasing from 0.68 to 0.95). As optimization continued, the rate of fitness decreased with the number of iterations. The fitness of the population increased by a fraction of 0.04 in the last 20,000 iterations (i.e., iterations from 20,000 to 40,000). The fitness value was primarily based on the multiattribute utility increase due to investment decision; hence, Figure 27 is indicative of the utility increase of ALOS as well.

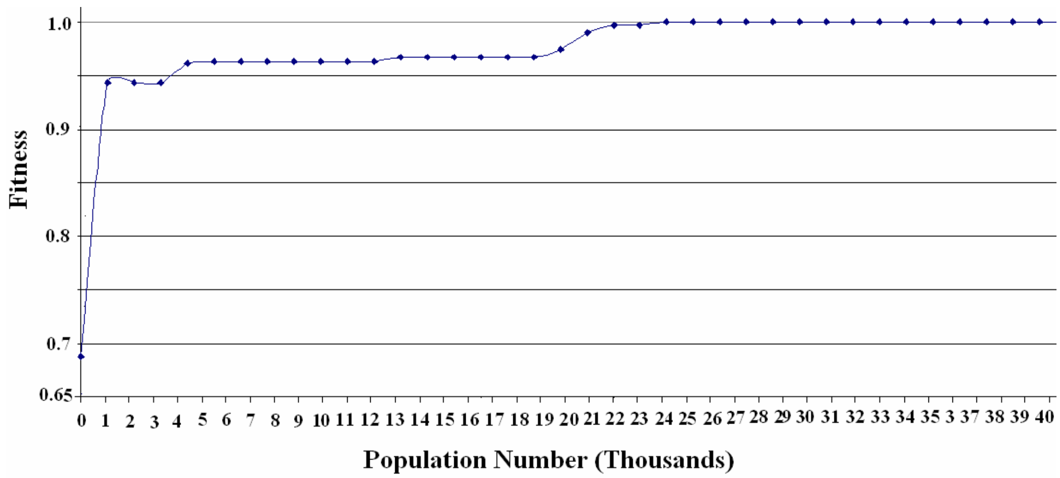

Figure 27: Fitness of populations with respect to the number of iterations: Scenario 2

Table 21 illustrates the best-fit chromosome associated with every tenth percentile of the population. The best-fit chromosome related to the last population (i.e., the 100th percentile) gives the near-optimal solution to the problem. The chromosome has three bits for each road candidate, containing the road ID, the MR&R treatment ID to be applied to the road candidate along with the treatment year. As evident from the values of chromosome, when resources were limited, the optimization module assigned a combination of high- and low-cost MR&R alternatives to road candidates.

For example, for the 34 Avenue road section (Road Code = 34AveEB34 45), the OPTIsys results recommended to apply Micro-Surfacing (Treatment ID = 3) in Year 1. Similarly for the 90 Avenue road section (Road Code = 90AveEB170171), OPTIsys recommended to apply a Chip Seal Coat (Treatment ID = 2) in Year 1. Table 21 illustrates the solution to Scenario 2 using OPTIsys.

Table 21: OPTIsys solution: MR&R resource allocation for Scenario 2.

Road Code	BYr/ T-ID	Chromosome (solution set) at the given percentile of iterations									
		10th	20th	30th	40th	50th	60th	70th	80th	90th	100th
66StNB118119	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	6	5	5	5	5	5	5	5	5	5
45AveEB198199	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	5	5	5	5	5	5	5	5	5	5
34AveEB34 45	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	1	1	6	6	6	6	3	3	3	3
66StNB153154	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	5	5	5	5	5	5	5	5	5	5
76AveEB34 35	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	6	6	6	6	6	6	6	6	6	6
91StNB63 64	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	6	6	6	6	6	6	6	6	6	6
95AveEB157158	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	3	3	3	6	6	6	3	3	3	3
66StNB40 41	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	5	5	5	5	5	5	5	5	5	5
34AvWB106107	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	3	3	3	3	3	3	3	3	3	3
90AveEB170171	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	2	5	5	5	5	2	2	2	2	2
86StNB51 52	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	6	6	6	6	6	6	6	5	5	5
50StNB33 34	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	5	5	5	5	5	5	5	5	5	5
87AveEB170171	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	0	0	5	5	5	5	0	0	0	0
87AveEB156157	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	6	6	5	5	6	6	6	6	6	6
86StNB114115	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	5	5	5	5	5	5	5	5	5	5
82StNB112113	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	5	5	5	5	5	5	5	5	5	5

Budget Year = BYr; Treatment ID (T-ID): 0 = Do Nothing; 1 = Rout and Seal Crack Treatment; 2 = Chip Seal Coat; 3 = Micro-Surfacing; 4 = Hot In-Place Recycling; 5 = Cold Mill and Inlay; 6 = Thin Overlay; and 7 = Thick Overlay

Road Code	BYr/ T-ID	Chromosome (solution set) at the given percentile of iterations									
		10th	20th	30th	40th	50th	60th	70th	80th	90th	100th
44AveEB50 51.	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	5	5	5	5	5	5	5	5	5	5
97StNB45 46	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	5	5	5	5	5	5	5	5	5	5
86StNB63 64	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	5	5	5	5	5	5	5	5	5	5
97StNB103104	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	5	5	5	5	5	5	5	5	5	5
95AveEB148149	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	3	3	3	6	6	6	3	3	3	3
23AveEB34 35	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	6	6	6	5	5	5	5	5	5	5
87AveEB178179	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	6	6	6	6	6	6	6	6	6	6
95AveEB155156	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	6	6	5	5	5	5	6	6	6	6
50StNB23 24	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	6	6	6	5	5	5	5	6	6	6
66StNB23 24	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	5	5	5	5	5	5	5	5	5	5
90AveEB75 76	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	6	6	6	6	6	6	6	6	6	6
82StNB116117	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	5	5	5	5	5	5	5	5	5	5
34StNB23 24	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	0	0	0	5	5	5	3	3	3	3
75StNB95 96	BYr	2		2	2	2	2	2	2	2	2
	T-ID	3		6	6	6	6	6	6	6	6
51AveWB97 98	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	3	3	3	6	5	5	5	5	5	5
50StNB75 76	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	3	0	0	0	5	5	5	0	0	0
51AveEB107108	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	5	5	5	5	5	5	5	5	5	5
38AveEB34 35	BYr	3	2	2	2	2	2	2	2	2	2
	T-ID	5	5	5	5	5	5	5	5	5	5
75StNB50 51	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	0	0	0	0	0	0	0	0	0	0
91StNB51 52	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	3	3	3	5	5	5	5	5	5	5

Budget Year = BYr; Treatment ID (T-ID): 0 = Do Nothing; 1 = Rout and Seal Crack Treatment; 2 = Chip Seal Coat; 3 = Micro-Surfacing; 4 = Hot In-Place Recycling; 5 = Cold Mill and Inlay; 6 = Thin Overlay; and 7 = Thick Overlay

Road Code	BYr/ T-ID	Chromosome (solution set) at the given percentile of iterations									
		10th	20th	30th	40th	50th	60th	70th	80th	90th	100th
16AveEB170171	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	1	3	1	1	1	1	1	1	1	1
97StNB104105	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	6	6	6	6	6	6	6	5	5	5
82StNB119120	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	6	6	6	6	6	6	6	6	6	6
23AveWB50 51	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	1	1	1	1	0	0	0	0	0	0
51AveEB88 89	BYr	3	3	3	3	3	3	3	3	3	3
	T-ID	5	5	5	5	5	5	5	5	5	5
23AveEB17 18	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	5	5	3	3	3	5	3	3	3	3
91StNB23 24	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	6	6	6	6	6	6	5	5	5	5
17StSB76 77	BYr	1	1	1	1	1	1	1	1	1	1
	T-ID	5	5	5	5	5	5	5	5	5	5
38AveEB62 63	BYr	2	2	2	2	2	2	2	2	2	2
	T-ID	1	3	6	5	5	5	1	1	1	1

Budget Year = BYr; Treatment ID (T-ID): 0 = Do Nothing; 1 = Rout and Seal Crack Treatment; 2 = Chip Seal Coat; 3 = Micro-Surfacing; 4 = Hot In-Place Recycling; 5 = Cold Mill and Inlay; 6 = Thin Overlay; and 7 = Thick Overlay

This section illustrated the use of OPTIsys to solve a resource allocation problem. Five MR&R treatments and a set of 45 roads (or candidates) were selected from the database based on their ALOS values. As needed, the database can be appended with additional candidates as well as MR&R treatments. The optimization results will vary upon the user's available budget, budget period and analysis period.

There is no rule for identifying the number of iterations (or the number of populations) to reach the optimum solution. The number of iterations to achieve optimal results will primarily depend upon the number of candidates, budget availability, analysis period and the GA parameters. Low crossover and mutation rates will require more iterations.

Chapter 8: Conclusion

This research presents the framework to develop an interactive ALOS-based decision support system. The proposed decision support system allows the allocation of resources between various MR&R alternatives based on ALOS, interdependencies and future demand. In this research, the framework has been implemented for the MR&R of urban roads. The proposed framework can also be applied to all municipal infrastructure networks, with minimal modifications.

Based on the literature review and the research objectives, a number of tools have been evaluated and selected for this research. The AHP is used as a decision analysis method to incorporate the qualitative factors in decision making. The AHP can reduce complex systems and interdependencies into hierarchies which can be solved by a sequence of pair-wise comparisons.

The MAUT, employed widely in various fields, is another tool used to quantify the utility of investment decision. MAUT is based on the decomposition hypothesis, according to which the utility of a multiattribute alternative is an aggregate of the individual utility components. This allowed the calculation of the multiattribute utility of investment decisions based on the utility of various singular impact factors.

Given the complexity of the problem, GA were particular useful to find the near optimal solution for the resource allocation model. The complexity of multiobjective optimization problems, such as large search spaces, noise, discontinuity in Pareto curves, etc., may render most of the traditional multiobjective optimization techniques useless. GA have proven to be very robust tools in this regard.

8.1 Research Contributions

The following are the specific research contributions:

1. The development of a framework to quantify the ALOS for infrastructure networks;
2. The development of a framework to allocate resources for various MR&R treatments for urban roads based on ALOS, interdependencies, future demand and other multiple objectives as dictated by the organization's goals; and
3. The development of a web-based application (OPTIsys) to implement the developed research framework for urban roads (i.e., allocation of resources for various MR&R treatments for urban roads based on ALOS).

Various challenges were addressed in the process of quantification of ALOS (e.g., the inclusion of qualitative factors such as neighbourhood safety, condition of road, etc.). In addition, interdependencies between various factors were identified and accounted for while quantifying ALOS. The calculated ALOS was used in the resource allocation model for MR&R alternatives for urban roads.

A MAUF has been derived for ALOS, which is based on ALOS of roads, the physical condition of roads, neighbourhood growth and the level of EMS. The MAUF is incorporated in a resource allocation model which is optimized using a GA-based web application (OPTIsys).

The research methodology is implemented by developing a web-based application (OPTIsys) through *J# and Apache Tomcat*. The web-based nature of OPTIsys enables the software to be hosted on the internet. This will enable multiple users to access the software concurrently from the office as well as at off-site locations. The implementation of OPTIsys will optimize the maintenance of network LOS, reduce the infrastructure deficit by better management of resources, and fulfill user expectations. OPTIsys will assist city councils in developing better budget allocations based on ALOS. Table 22 shows a list of potential users along with user-specific benefits.

Table 22: Benefits of the implementation of OPTIsys for stakeholders.

User	**User-specific benefits**
Customers/Users	• Efficient, reliable and safe services that meet the agreed levels of service.
Owner/Operator (Government Stakeholders/Shareholders)	• Economic returns are maximized. • Operational capability of the asset is maintained. • Anticipation and management of future demand to ensure returns on investment.
Decision Maker	• Generation of optimal resource allocation plans using multiobjective decision making based on ALOS, interdependencies and future demand. • Enhance analysis and decision-making capabilities through an interactive environment. • Maintenance of network at optimal ALOS. • Incorporation of qualitative factors in decision making.
Policy Makers/Auditors	• Responsible management of budget. • Compliance with service standards and applicable codes and regulations.

8.2 Future Research

Future prospects of the research include the development of a 3D, ALOS-based decision support system. The present research framework can be integrated with a 3D model of the city. This can be achieved by exploring the combination of Geographic Information Systems (*ArcInfo 3D analyst*) and 3D modeling software (*AutoCAD or 3D StudioMax*). A central asset information repository (Spatial Asset Database) can be developed in *ArcInfo*. This will allow the storing of the assets' geographical locations along with their physical/functional attributes. The Visual Basics for Application module of *ArcInfo* can be used to integrate the mathematical models with the optimization model. Figure 28 illustrates the conceptual architecture of the proposed 3D prototype.

The development of 3D proto type will allow the user to make MR&R decisions in an interactive integrated 3D environment. The prototype will also allow the user to make harness the functionality of the Geographic Information Systems. In other words, user will be able to carry out the spatial analysis of the networks and also make the MR&R decisions for the networks. Proposed 3D prototype will serve as common platform for other infrastructure networks such as water supply, sewerage and waste water systems, etc. This will enable the data sharing between the various infrastructure networks, hence eliminating the redundancies due to multiple infrastructure DSSs.

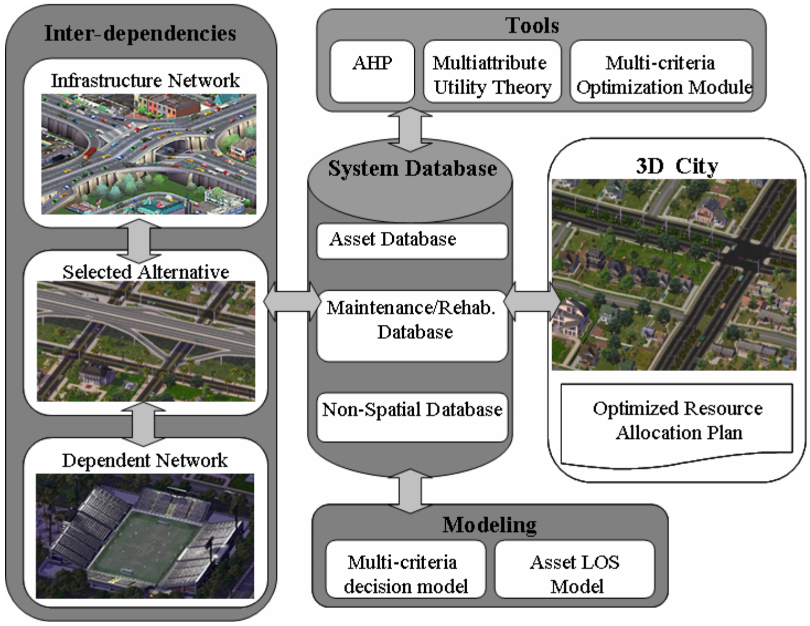

Figure 28: Architecture of the proposed future 3D prototype.

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