Community Driven Framework for Sustainable Municipal Asset Management

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ABSTRACT

Community Driven Framework for Sustainable Muncipal Asset Management

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Best practices for municipal asset management require municipalities and communities to clearly define their expectations and to express that in terms of achievable goals for levels of service. The challenge lies in the fact that asset performance from a community perspective may be quite different from a municipality perspective. The real problem is to inter-relate these two perspectives and to determine the optimum quantity of improvement required in the condition of municipal assets to meet community expectations. The literature reveals the need for development of such methods and management tools to support solutions for sustainable municipal assets that take the above into consideration. To address these issues, a community driven level of service based methodology is developed for municipal corridor management that integrates technical and financial plans of a municipality. The concept of municipal corridor is augmented for the purpose of determining integrated repair/ rehabilitation interventions for pavement, water distribution and sewer collection assets and is termed here as municipal corridor rehabilitation. The developed methodology comprises of three phases. In the first phase, performance modelling and mapping the targeted levels of service to condition rating is developed to quantify asset condition improvement. This is achieved via three models; (1) Analytical Hierarchy model to relate Level of Service with required performance, (2) Fuzzy weighted average model to assess the capacity to deliver targeted performance and (3) Fuzzy Alpha Cut model to map the asset improvement requirement and asset capability. The output of this phase is fed into the second phase, where prioritization of corridors' intervention plans is established, using an Artificial Neural Network model. In the last phase, the outputs of the preceding two phases are utilized as input to develop a Goal Programming based optimization model which generates optimised intervention plans of municipal corridors. The developed methodology was applied to a case study in the City of Riyadh in KSA to demonstrate its use and to illustrate its capabilities. The results obtained were found acceptable by management of that city. The case demonstrated the flexibility and utility of the developed methodology and its models in support of integrated optimized intervention plans for water, sewer and municipal roads.

DEDICATION

I dedicate this thesis to my parents; Asad Ullah Khan and Aqila Asad whose sincere wishes and prayers had been silent but the most important contributor in this endeavor.

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Above all, I have to express my deepest gratitude to Almighty ALLAH for all the blessings and guidance that enabled me to undertake and accomplish this work. I pray to Allah that this work be of true benefit to the body of knowledge and to the industry.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

AE_{ij} - Attribute Effect Value of Measure ‘j’ in Indicator ‘i’

AHP - Analytical Hierarchy Process

ANN - Artificial Neural Network

ASTT - Australasian Society of Trenchless Technology

C.R - Consistency Ratio

CAD - Computer Aided Design

CCS - Corridor Criticality Score

CI - Consistency Index

CIPP - Cured in Place Pipe

CIT - Post Intervention Condition of Asset for Technique Under Consideration

CL – Corridor Length

CR - Condition Rating

C'T - Cost of Technique per Unit Length for Asset Size

C'T - Cost of Technique per Unit Length for Unit Size

DBE - Distress-based evaluation

DSS - Decision support system

FCM - Federation of Canadian Municipalities

FCP - Fuzzy Composite programming

GIS - Geographic Information System

GIS - Geographic Information System

HMA - Hot Mix Asphalt

IAs - Intervention Alternatives

LOS - level of service

M&R - maintenance and rehabilitation

MIMS - Municipal Infrastructure Management Systems

NASSCO - National Association of Sewer Service Companies

NDE - Non-Destructive Evaluation

NDT - Non Destructive Techniques

NRC - National Research Council

NUCA - National Utility Contractors Association

PCCP - Pre-stressed Concrete Cylinder Pipe

PCI - Pavement Condition Index

R - Overall Fuzzy Condition Rating of Asset

RCI - Rider Comfort Index

R_d – Road Major Rehabilitation

RFEC/TC - Remote Field Eddy Current / Transformer Current

RIVA - Real-Time Asset Valuation Analysis

ROW - Right of Way

RSL - Remaining Service Life

RSL - Remaining Service Life

RSLT - Remaining Service Life of Asset by Technique Under Consideration

TAG-R - Trenchless Assessment Guide for Rehabilitation

TTC - Trenchless Technology Center

UWMDI - Unified Water Main Distress Index

VHB - Vanasse Hangen Brustlin, Inc.

V_{ij} - Weight of Measure ‘j’ in Indicator ‘i’

W/S - Water / Wastewater Open Cut

W_i - Weight of Indicator 'i '

WMSP - Water Main Service Percentile

WRc - Water Research Centre

Z - Objective Function for Optimization

CHAPTER 1: INTRODUCTION

Municipal Infrastructure encompasses infrastructure assets that relate to municipal roads, water, wastewater and sewer systems (InfraGuide 2003a). Further to the above definition of municipal assets, municipal infrastructure and services typically include police, fire, solid waste, transit, parks, library, shelter, housing and social services (Moselhi 2005).

Owners of large municipal infrastructure portfolios such as large cities, regional governments, municipalities and the armed forces are usually responsible for a diversified set of constructed facilities. These assets range from interrelated underground networks to complex buildings, as well as roadway systems, parks, and any other equipment necessary to maintain this infrastructure (Vanier 2001). A sound, well-functioning infrastructure in a country is essential for its sustained economic growth, international competitiveness, public health, and overall quality of life. These characteristics are closely linked to the adequacy of the transportation infrastructure, water quality, and waste disposal (Mirza 2006).

1.1 State of Affairs of Municipal Infrastructure

City managers and elected officials in many municipalities are frequently faced with competing demands during the budget allocation process. The challenge is to cater for public expectations at one end and comply with technical/engineering requirements on the other. The state of municipal infrastructure in most developed countries is characterised by increasing age, growing demand, higher expectations of communities, political priorities towards capital investments and accumulated deficit on repair/rehabilitation. In North America a broader awareness of the current infrastructure crisis emerged during the mid-1970s and the early 1980s, when serious problems were noted in the municipal infrastructure systems (Mirza 2006). The problems were due to budgetary constraints during the recessions, some post-World War II infrastructure approaching the end of its service life, the rapid North American inflation of the 1970s, a competing demand for municipal services and deferred maintenance as a result of reduced funding from all levels of government (Mirza 2006). The United States, Canada and Australia are countries which have world's largest infrastructure and therefore are among the most concerned ones about the above issues.

Earlier in 1998, the American Society of Civil Engineers (ASCE) undertook a detailed survey of selected infrastructure categories in the United States. Subsequently, there were a few more advanced and detailed surveys in the years 2001, 2003, and 2005. The 1998 survey divided highways into two categories: roads and bridges. Rail, security and energy were later added as new categories in the 2005 survey. The surveys evaluated each designated category for all states and the overall country, and the results were tabulated in the format of report cards, which were passed on to federal officials and were made available to the media. The national results for each infrastructure category provided in six report cards are summarized in Table 1.1. The individual grades were based on examination of condition and capacity and on funding versus need but they also summarized the opinions of 2000 engineers, solicited to determine what was happening in the field. The final grade for all USA infrastructures was derived by averaging the grades in all categories. The overall infrastructure grades ranged from C in 1998 to D in 2005, with projected 5-year needs increasing from US$1.0 trillion in 1988 to US$1.6 trillion in 2005. After having received a D+ in 2001, the USA infrastructure showed little or no improvement in the next two surveys, with some areas sliding even toward failing grades (ASCE 1988, 1998, 2001, 2003, 2005). The current situation as of 2013 report card is even worse with an overall GPA of the country as D+ and a total investment need of $3.6 trillion by the year 2020 (ASCE 2013). The individual category grades are shown in Table 1.1.

In 2003, Infrastructure Canada, while reviewing the 2003 ASCE report card, realised the main issue as the need for new federal legislation and increased federal funding (Mirza 2006). In 2002, the federal government of Canada had committed itself to long-term measures to modernize Canada's infrastructure. Unfortunately, infrastructure surveys similar to those of the ASCE did not exist in Canada prior to 2012. The Technology Road Map (CSCE 2003) recommended the creation of an inventory of Canada's infrastructure, along with its existing state of health. Such an inventory would be essential for developing a strategic long-term policy for decision-making and for establishing priorities and future directions. In 1995, a survey (McGill-FCM 1996) undertaken by McGill University and the Federation of Canadian Municipalities (FCM) divided the entire Canadian municipal infrastructure into four population groups and analysed its state in relation with the population.

Table 1.1: Summary of USA infrastructure survey findings (ASCE1988.1998, 2001, 2003, 2005 and 2013).

	1988	1998	2001	2003	2005	2013
Infrastructure category evaluated						
Aviation	**B-**	**C-**	**D**	**→**	**D+**	**D**
Bridges	**C+**	**C-**	**C**	**→**	**C**	**C+**
Dams	**–**	**D**	**D**	**→**	**D**	**D**
Drinking water	**B-**	**D**	**D**	**→**	**D-**	**D**
Energy	**–**	**–**	**–**	**–**	**D**	**D+**
Hazardous waste	**D**	**D-**	**D+**	**→**	**D**	**D**
Navigable waterways			**D+**	**→**	**D-**	**D-**
Public parks and recreation	**D**				**C-**	**C-**
Rail	**–**	**–**	**–**	**–**	**C-**	**C+**
Roads	**C+**	**D-**	**D+**	**→**	**D**	**D**
Schools		**F**	**D-**	**→**	**D**	**D**
Security	**–**	**–**	**–**	**–**	**I**	
Solid waste	**C-**	**C-**	**C+**	**→**	**C+**	**B-**
Transit	**C-**	**C**	**C-**	**→**	**D+**	**D**
Waste and Energy	**–**	**–**	**D+**	**D**	**–**	
Waste water	**C**	**D+**	**D**	**→**	**D-**	**D**
Water resources	**B**	**–**	**–**	**–**	**–**	
Infrastructure GPA	**C**	**D**	**D+**	**D+**	**D**	**D+**

The groups were as under:

1) <10 000

2) 10 000 – 100 000

3) 100 000 – 400 000

4) >400 000

Although some of the problems, such as the funding shortage, were common to all four population groups, there were some differences in the needs, problems, and deficiencies in the different infrastructure categories, as well as in the issues revolving around them. In general, transit, roads, and curbs were worsening in all municipalities. However, in group 1 municipalities, roads and hazardous-waste disposal were the prime concern, whereas in group 2 the sanitary and combined sewers were of most concern. The larger municipalities, in groups 3 and 4, faced the most significant worsening of transit facilities and roads. The population of a city had a direct impact on its infrastructure needs, problems, deficiencies, and related issues, and these needs were to be considered in developing long-range plans for infrastructure renewal and new facilities (McGill-FCM 1996). The survey determined that Canada's municipal infrastructure deficit was CAD 44 billion and CAD 100 billion for all infrastructures under various jurisdictions — federal, provincial, and others. It was then forecasted that by 2005, these infrastructure deficits would reach up to CAD 60 billion and CAD 125 billion, respectively (McGill– FCM 1996). A much more recent status can be assessed from the Infrastructure Canada 2012 report, as given below:

Table 1.2: Canada Infrastructure Status (Infrastructure Canada 2012)

S.No.	Asset Class	Condition	Percentage (%)	Total Estimated Cost of Report
1	Municipal Roads	Fair	32	91.1 billion
		Poor to Very Poor	26.6	
2	Wastewater	Fair to Very Poor	30.1	39 billion
3	Drinking Water	Fair to Very Poor	15.4	25.9 billion
4	Plants, Reservoirs and Pumping Stations	Fair to Very Poor	14.4	
		Very good	12.6	
5	Stormwater	Below good	12.5	15.8 billion

In Australia, a national study (ALGA 2006) of the financial sustainability of local governments, published by the Australian Local Government Association, released in November 2006, identified that local governments are responding to ever-rising community expectations by providing a growing range of services and infrastructure. However, rising costs exceeding revenue growth was pushing a significant number of councils into a situation of substantial financial deficits. The report states that, in the absence of major reforms, Australian local governments will have to cut back on services and reduce their asset base or obtain additional revenue, if they were to be sustainable in the longer term. Champion (2007) while referring to other sustainability reports highlighted how infrastructure is a significant core function, responsibility and even a liability of Australian local government. Pertinent here is to mention that in Australia most infrastructures were built in the 1950s and 1960s and are now nearing the end of their service life.

The current experiences in the United States, Canada and Australia highlight that, municipalities are facing increasing challenges due to aging and deteriorating infrastructure assets, inadequate renewal budgets, climbing renewal deficits, increasing demand levels, and new requirements to comply with stricter environmental and accounting regulations (Danylo and Lemer 1998; Grigg 1999; Halfawy 2004, ASCE 2013). Besides, the increasing complexities of infrastructure management processes have resulted in creating diverse areas of knowledge, expertise, and responsibilities within and across municipal departments i.e. water, sewer and roads. Altogether, these challenges have placed significant pressures on municipalities to improve the effectiveness of managing their infrastructure by adopting more efficient, sustainable, and proactive asset management strategies (Halfawy and Dridi 2008).

1.2 Sustainability and Integrated Management in Municipal Context

It is now a well-established fact that there is no such thing as unlimited natural resources. Adeli (2002), states that there is need to rehabilitate the aging infrastructure in the US together with a national consensus and concern for preservation of environment. Sustainability requires creation of new technologies such as green design/technology and should also employ established approaches such as optimization and more recent developments such as life-cycle cost optimization (Adeli and Sarma 2006, Azeez, Zayed and Ammar 2013). Adeli (1993) stated that “interdisciplinary thinking and synergistic collaboration of disciplines can solve complex problems, open new frontiers, and lead to true innovations and breakthroughs”. He also suggested to promote interdisciplinary research collaboration, not only among various disciplines within civil engineering, but also with other departments within and outside engineering and expected that exciting developments will occur when multiple disciplines are involved (Adeli 2009). Keeping in view, on one hand the critical condition of the built infrastructure and the complexities in the course of action, and on the other hand the potentials of the sustainability concepts and integrated approach, it is now quite essential to develop frameworks and decision support systems that function on these concepts.

The integrated approach towards municipal infrastructure management is the need of the day, however; there are a few stern challenges in the development and implementation of such systems. Many large municipalities have separate departments responsible for road, sewer and water networks. Furthermore, in some larger municipalities, there may even be separate departments responsible for planning, design, construction and maintenance of each network. On the contrary, in smaller municipalities there may be only a few persons responsible for managing the entire infrastructure of the municipality. These factors offer a significant challenge against the standardization of the procedure itself and create difficulty for the municipalities in managing their systems in an efficient integrated manner. It should also be noted that sewer and water mains on a given section of road i.e. the municipal corridor, typically have longer life expectancies than the pavement. In addition, sewer and water mains typically have different useful lives and level of service expectations. This further increases the challenge of managing these systems in an integrated manner. Municipalities should recognize that decisions made at any stage in the life cycle of one group of assets could affect other assets (InfraGuide 2003b). Another area of consideration is due to the maturity achieved by the trenchless methods of rehabilitation. This is due to the increase in the number of options and the level of treatments that can now be applied to municipal assets. True adherence to sustainability should demand the use of the most appropriate technique.

1.3 Problem Statement

Efforts to renew and rehabilitate ageing infrastructure should focus on prolonging the functional life of municipal assets and their components by providing reliable and cost effective solutions that meet community expectations and consume lesser resources in order to be sustainable (Mirza 2006). To have such sustainable solutions, these activities must be performed in a coordinated and integrated manner so as to cause on one hand, the least amount of disruption to public and environment and on the other to fulfil agency objectives of better performance, lesser cost and longer service life. Asset management systems typically support the management of different classes of municipal assets (e.g. roads, water and sewer networks), with little or no consideration to their inter-dependencies. Most of the existing systems operate on one utility at a time and deals with the analysis and decision making processes of that particular utility only. Alternatively stated, they perform process or vertical integration only. The absence of interdisciplinary integration i.e. horizontal integration of asset management classes has created significant inefficiencies in maintenance coordination and asset rehabilitation planning. There is need to develop rehabilitation methodologies that are capable to simultaneously deal with all the essential asset management activities of all the selected asset classes. Such systems should be based on a holistic, integrated, and multidisciplinary approach. These systems should not only move vertically to perform various processes of an asset but also move horizontally to integrate the different asset classes or utility types. Preferably the renewal plans for assets in a particular corridor should be coordinated to encompass multiple infrastructure assets, as many as possible, thus minimizing the disruption, cost and risks associated with rehabilitation operations.

1.4 Research Scope and Objectives

The objectives of the research are as follows:

1. To study current practices, methods and systems prevailing in municipal asset management with a focus on issues related to sustainable and integrated systems, referred here as Corridor Rehabilitation.
2. To develop a reference framework for small and medium sized municipalities that can facilitate value driven asset management of municipal infrastructure.
3. Reduce subjectivity in community and agency decision making.

Scope of the developed methodology comprises of the following:

- It addresses the three primary municipal asset types i.e. roads, water distribution and wastewater collection.
- It deals with performance modelling and mapping levels of service to condition ratings for quantification of required improvement.
- It builds on an integrated need based prioritization of corridors and ultimately leads to optimised work intervention plans of municipal corridors.

As a result of the overall development, several areas of further investigation are also pointed out that invite the attention of asset management researchers.

1.5 Research Methodology

To achieve the objectives, the overall research methodology comprises of three phases, each addresses a distinct issue and at the same time provides input to the one following:

Phase 1: Identify and study the performance indicators of different asset types and develop a method to objectively quantify corridor condition improvement needed to sustainably meet community expectations.

Phase 2: Taking the benefit of integration in the municipal context, to develop a method to integrate and prioritize condition improvement requirements of corridor.

Phase 3: Investigate rehabilitation techniques of different asset types and develop a method to assess their effectiveness in providing performance based sustainable solutions to corridor condition improvement needs

This methodology developed to cater for the above mentioned scope and objectives comprises of the following developments:

1. Scaling Asset Condition and Performance - Performance indicators and measures for the three asset types are identified. Their respected threshold and desired values are suggested. Their ranges of values are divided in levels of service from a community perspective. The last two exercises are repeated for condition rating from an agency perspective.

II. Measurement and Quantification of Level of Service - An Analytical Hierarchy based model of level of service is developed to measure and quantify community expectations in terms of service points.

III. Measurement and Quantification of Asset Condition - A Fuzzy weighted average Model of Condition Rating is developed to measure and express asset condition.

IV. Mapping Level of Service to Asset Condition - A mapping function based on Fuzzy Alpha-Cut Theorem is used to map the level of service to corresponding condition of the asset.

V. Identification and Prioritization of Municipal Corridors - Segment Criticality Analysis is done. Also the Segment Un-serviceability Scores are calculated using the level of service model. These serve as inputs to the developed Artificial Neural Network of the Corridor Prioritization model which clusters the corridors into five priority groups with priority serial number within each group.

VI. Identification of Feasible Alternatives for Rehabilitation - A Flexible system of expressing the existing and targeted condition of the asset was designed taking into consideration the effect of each distress measure. Rehabilitation techniques for road, water and Wastewater mains were thoroughly investigated firstly in general, about their applicability to a certain condition level, then in particular about their capability to address each of the distress measures. A Technique Applicability and subsequently a Techniques Capability Matrix were developed for the three asset types. This created the asset rehabilitation feasible solutions space. Parametric estimation of costs of different types of intervention / rehabilitation for water, sewer and road assets were identified separately.

VII. Developing the Corridor Optimum Intervention Work Plan – Work plan comprising of techniques that provide optimum rehabilitation to each of the three asset types is determined using Goal Programming Optimization. Criteria for optimization included condition improvement, cost of intervention and post intervention remaining service life. The final solution can be tested on rules developed to decide whether the intervention shall be done in an integrated or non-integrated manner.

1.6 Thesis Organization

The thesis contains of seven chapters. In Chapter 2, the literature is reviewed on topics pertinent to the scope of the research conducted. Concepts prevailing in literature and the current practices in industry are investigated. The limitations of available methods and tools are explored to gather background information necessary to develop the framework proposed in this research. Chapter 3 describes the framework design of the proposed methodology and its data requirements. The different models of the framework are introduced here. Chapter 4 briefly discusses the data collection process as well as the case study used to demonstrate the use of the developed methodology. Chapter 5 describes the developed methodology and its models, functions and matrices. Chapter 6 demonstrates the application of the methodology framework on a case study. A sensitivity analysis is also carried out to determine the impact of changing the decision criteria on the final solution / corridor work intervention plan. Lastly, chapter 7 provides a summary of the research and its findings. It highlights the contributions of the research and provides suggestions on future work in the domain.

CHAPTER 2: LITERATURE REVIEW

A review of literature on the existing asset management systems and tools was carried out to investigate the prevailing asset management approaches. Focus was also kept on the topics of infrastructure sustainability, performance indicators, levels of municipal service, and asset inspection and condition assessment techniques. It has been reported (NRCC 2006a) that almost all the existing asset management systems typically deal with the management of a single particular class of municipal assets i.e. either roads, or water or sewer networks, with little or no consideration to their inter-dependencies. This lack of interdisciplinary integration of asset management activities has created significant inefficiencies in maintenance coordination and asset renewal planning.

2.1 Sustainability: A Management Strategy

Sustainability is broadly understood, in terms of sustainable communities, as "…meeting the needs of the present generation without compromising the ability of future generations to meet their own needs" (Infraguide 2005).

Sustaining municipal services call for a new management approach that could balance a growing portfolio of aging infrastructure with increased demands arising from new growth – all while staying within the financial means of the community. Neither stopping growth nor ignoring the problem of aging facilities is an affordable option for present day municipal managements. This problem is not unique to Canada. As already referred in the preceding section municipalities in countries such as United States and Australia having vast fully developed infrastructures, also are pursuing similar approaches to deal with this maturing issue.

2.1.1 Sustainable versus Traditional Asset Management Practices

History has shown that the traditional approach of managing on the basis of project priorities can result in important and necessary infrastructure needs going unmet indefinitely due to budget constraints. This approach often overlooks provisions or planning for long-term revenue generation and allocation. There is no consideration of the technical and financial demands of the system over its useful life (FCM 2002).

A "sustainable" asset management approach differs from the traditional model by identifying the annual capital works needed to achieve the desired outcome. A sustainable approach considers investment needs (i.e. sustainable funding) to develop a long term plan to balance the technical and financial needs for the infrastructure and then determines, on an annual basis, the program spending needed to sustain the level of service provided by the infrastructure over that long term (strategic level) period".

Traditional asset management activities as practiced in many municipalities include infrastructure data management and work management activities as different components (Figure: 2.6). With the help of the sustainability model (i.e. representation of the characteristics of the infrastructure systems), asset managers can evaluate long-term technical and financial performance of their assets. This evaluation includes priority planning, life cycle profile management, long-term capital planning, risk management, corporate policy development and other issues of interest. A sustainability model built on the basis of some broad assumptions about the assets, without the need of extensive data, has proven useful in its initial application as a management tool (FCM 2002).

The preceding review of literature highlights that municipalities across the world need to move towards adopting more proactive and optimized approaches to manage their municipal assets and should plan for short and long-term renewal in a more sustainable manner. The approaches should primarily aim to maximize the return on investment by optimizing budget allocation. Returns on investment in such complex systems is based on elements such as high asset performance, low risk of failure, and low life-cycle costs (Mahmoud & Leila 2008). As these elements are inherently conflicting, an integrated multi-objective approach is needed to develop renewal plans that satisfy these concerns in a balanced and optimized manner.

This necessitates that, renewal plans for assets at a particular site should be coordinated to encompass multiple infrastructure assets, thus minimizing the disruption, cost, and risks associated with maintenance operations. Integrated asset management is therefore a critical area that future systems will need to investigate.

2.1.2 Sustainability and Integrated Management in Municipal context

Within the municipal sector, sustainable community development requires consideration of the following:

(i) Social well-being of the community, rendered through meeting the expected level of service translated in terms of convenience, capacity and reliability

(ii) Environmental integrity, including protection of natural resources

(iii) Financial/economic viability of the community

The Federation of Canadian Municipalities (FCM) sponsored a study (FCM 2002) that suggests a generic framework of Sustainable Asset Management. This framework shown in Figure 2.1, illustrates that today's asset managers must balance the demands of physical growth, increasingly strict environmental protection regulations, and public health protection with the realities of financial constraints.

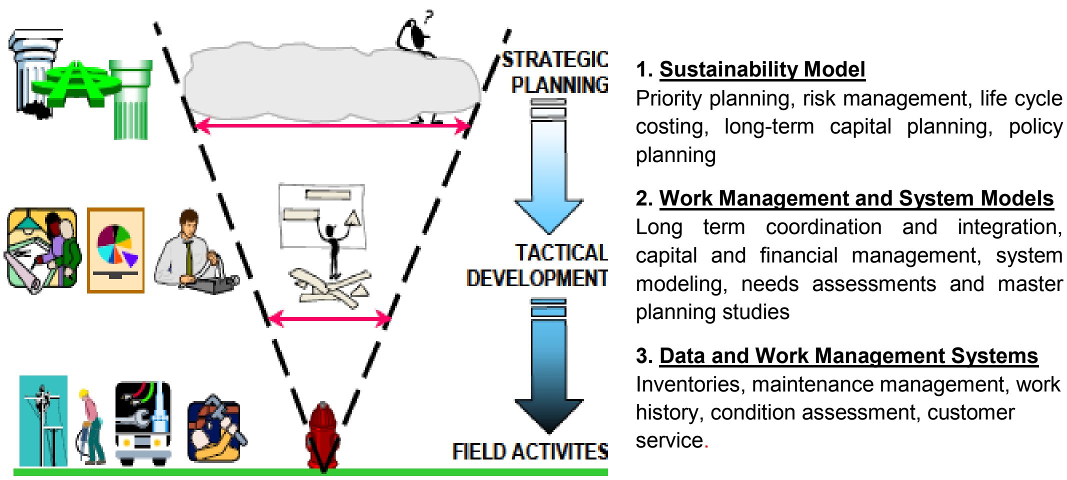


Figure 2.1: Sustainable Asset Management Framework (FCM 2002)

2.1.3 Sustainable Asset Management: The Framework

Figure 2.2 illustrates three components of municipal infrastructure management, which are strategic planning, tactical development and field activities. The fundamental difference between current asset management practices and sustainable asset management lies at the strategic planning level.

A brief review of the three levels is provided to highlight the sustainability gap that currently exists. Field Activities comprise all physical works, including the collection of data used for operational and planning purposes. Maintenance management systems are often used to monitor and control daily work activities (e.g. work order systems) and to house system inventories (data). Also included are the programs for monitoring, cleaning, repairing and operating the system.

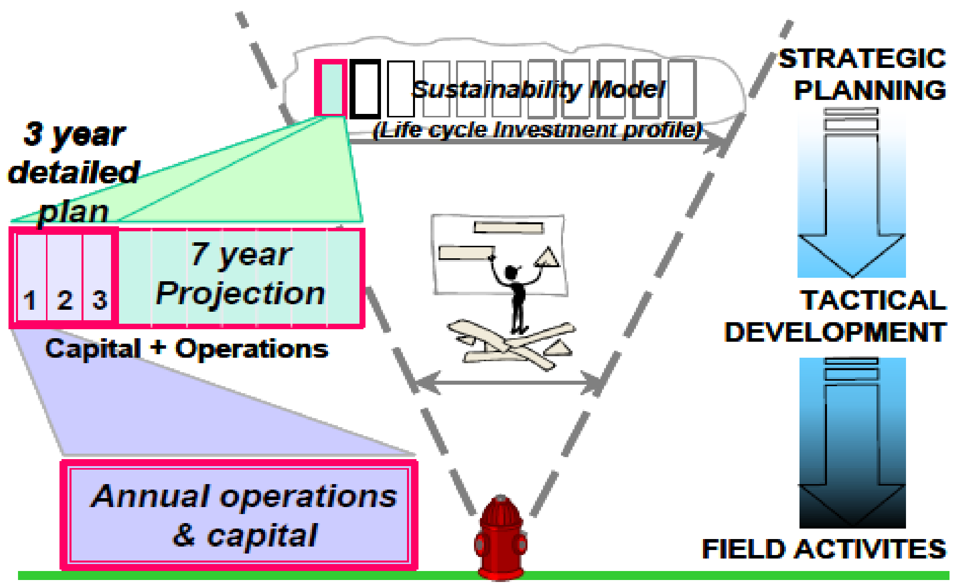


Figure 2.2: Sustainable Capital Planning (FCM 2002)

Tactical Development includes the preparation of capital plans that identify the projects to expand, improve and maintain the system in response to technical, public and political demands. Projects and programs developed at the tactical level are implemented at the field level. Activities include studies employing 5 to 20 year planning horizons to identify long-term infrastructure improvement, expansion and replacement projects. Projects are prioritized and funds allocated to recommended activities through the annual budget setting process. The linking of technical and financial requirements relates generally to balancing these needs in the context of setting project priorities. Strategic Planning is a function of broader municipal priorities. It involves the review of priority planning between departments, policy planning, risk management, long range financial planning and life cycle costing. A key differentiation with tactical development is capital planning on the basis of programs instead of projects. It is a level of management considering broader municipal objectives. The fundamental difference between current asset management practices and sustainable asset management lies here at the strategic planning level.

2.1.4 Sustainable Asset Management: Integrated Model

For many municipalities, size and resource limitations have dictated the confinement of asset management just to field activities and tactical development. Where strategic planning occurs, it is often completed in isolation from tactical and field level activities that may themselves be carried out by different departments (e.g. Engineering Branch and Operations Branch.) It is difficult to avoid an ultimate disconnect between the technical planners and the financial planners within organizations where these activities are managed in different departments. Such circumstances give rise to the term “silo structure,” in which departments and planning functions operate in isolation of each other (FCM 2002).

In a sustainable asset management process, these “silos” are broken down. Strategic planning activities are linked to tactical development and field activities and integrated with financial planning. The key to implementing sustainable asset management is the strategic planning process. The strategic planning component of sustainable asset management, as described in Figure 2.2 achieves the goals described in the previous section by answering the following six questions:

1. What do we have?
2. What is it worth?
3. What condition is it in?
4. What do we need to do to it?
5. When do we have to do it?
6. How much will it cost?

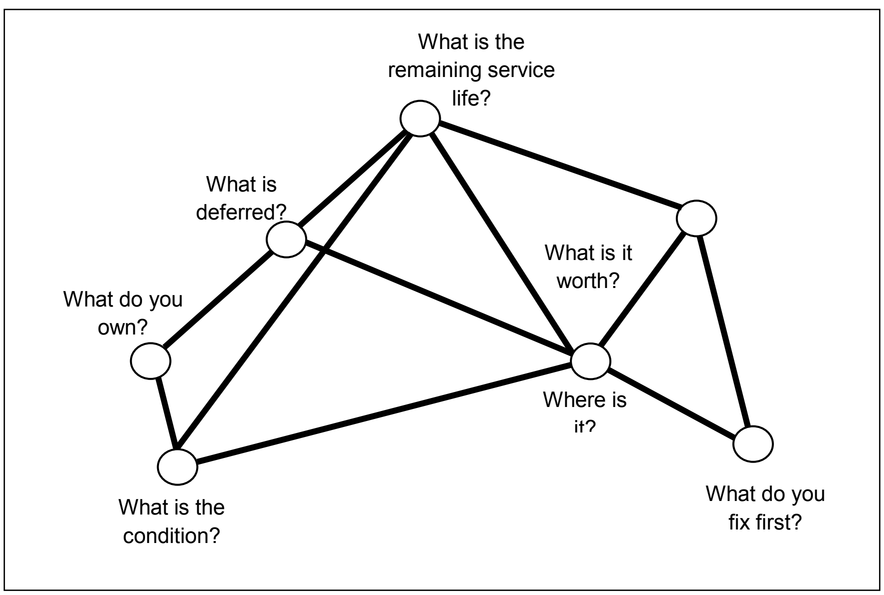


Figure 2.3: The step in Sustainable Asset Management

The development of a sustainability model can be achieved by answering these six questions in the context of water, wastewater and road systems or other municipal assets. The model can be used to undertake analytical evaluations, including the effectiveness of various investment strategies. Figure 2.4 portrays the sustainability model as an investment profile with links to financial management (i.e. capital planning) processes.

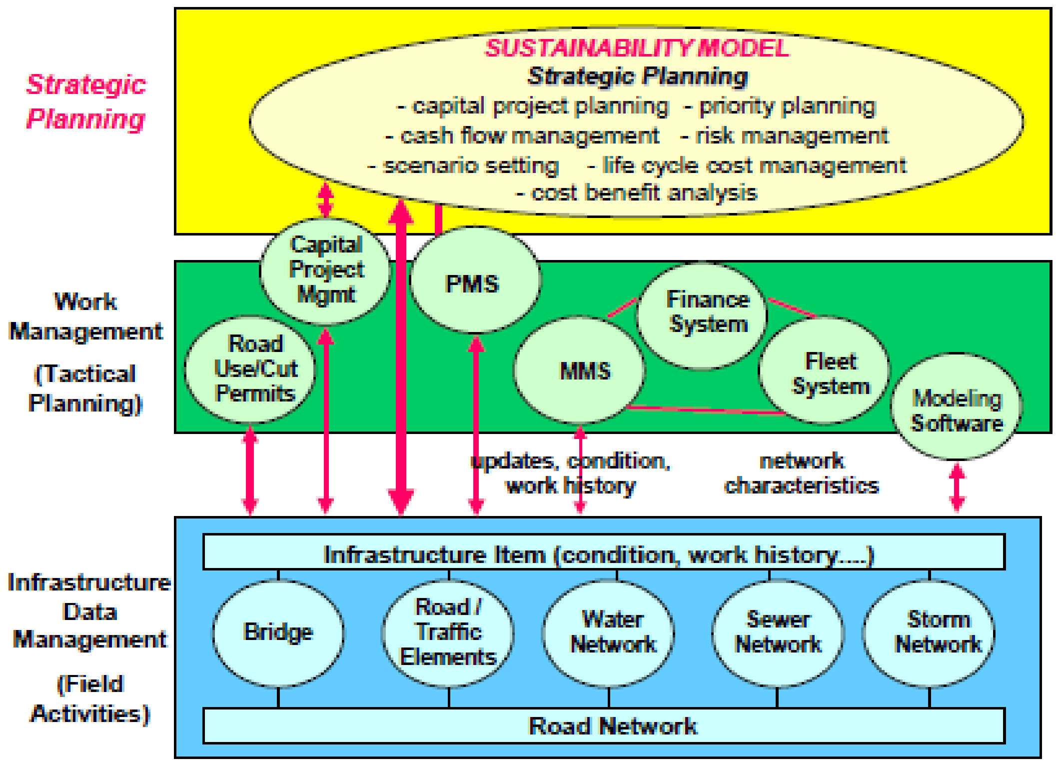


Figure 2.4: Municipal Asset Management Sustainability Model (FCM 2002)

2.2 Integrated Management Approach – Municipal Corridor Rehabilitation

The federation of Canadian Municipalities reports a number of case studies where municipalities have adopted the fundamentals of sustainability such as integrated and coordinated management of different asset classes and meeting a targeted level of service. The summary pages of a couple of such case study reports are reproduced at Appendix A and Appendix B. The first template mentions the benefits that the Halifax Regional Municipality had by coordinating some of its capital works. The other one describes the experience of the municipality of Richmond Hills Ontario, in adopting a level of service approach in their storm water management program.

The InfraGuide Best Practices (InfraGuide 2003b) reports several benefits of an integrated approach to municipal asset management i.e. to concurrently assess, plan and execute the rehabilitation of road, water and sewer systems of a municipality. The benefits include:

- The approach minimises social cost, impact on the environment and disruption to local traffic and residents
- Infrastructure management is more proactive and a higher level of service can be maintained
- Coordination among municipal departments is improved with increased opportunities for cross-training of municipality staff
- Road, water and sewer works can be coordinated with growth related needs
- Full cost accounting is improved as a step towards the implementation of PSAB 3150

- Integration provides for the improvement of long range planning for technical financial and risk management

However there are some potential challenges as well in the implementation of the integrated approach:

- The integrated approach is a long term engagement and in cases where the renewal programs had been under funded, the renewal cost in the beginning can be relatively high
- There can be a lack of support for an integrated system from certain stakeholders such as operators and / or politicians.
- Integrated decisions that are apparently disadvantages to an asset class may be opposed by the respective stakeholder
- Additional resources may be required to conduct an integrated assessment and evaluation of the systems

It can be seen that the benefits of an integrated approach weigh much more than the drawbacks and challenges and therefore necessitates advancements in this domain and development of such a system, if nothing already exists. In order to explore the state of affairs of the existing Municipal Infrastructure Management Systems (MIMS) concerning the issue discussed here, a thorough review of the available information was carried out and is documented below:

2.3 Overview of the Existing Municipal Infrastructure Management Systems

1) Synergen

Synergen (2205) is a web-based work management and procurement system that is mainly targeted to large organizations with extensive data and process management requirements. According to the taxonomy of asset management systems described in this Section, Synergen can be classified as a general-purpose system. Synergen defines a set of applications organized in a hierarchy of subsystems and modules. The *subsystems* include: Resources, Maintenance, Purchasing, Inventory, Customer, and Administration (Figure 2.5).

A *module* represents a group of functions that can be accessed through a set of "*Views*" or forms to display and edit the data records selected by the user. A module roughly corresponds to a "table" in a relational database, where each View or form displays a subset of the fields in that table. For example, the Asset module in the Resource subsystem would correspond to an Asset table in the database, where each record in the table represents an asset, and each View displays a group of the data fields that are related to a particular aspect of the Asset record, such as Manufacturer data, Cost, Operational data, Work history, Depreciation, etc. Some of the views (such as attachments, or notes) are common to many modules.

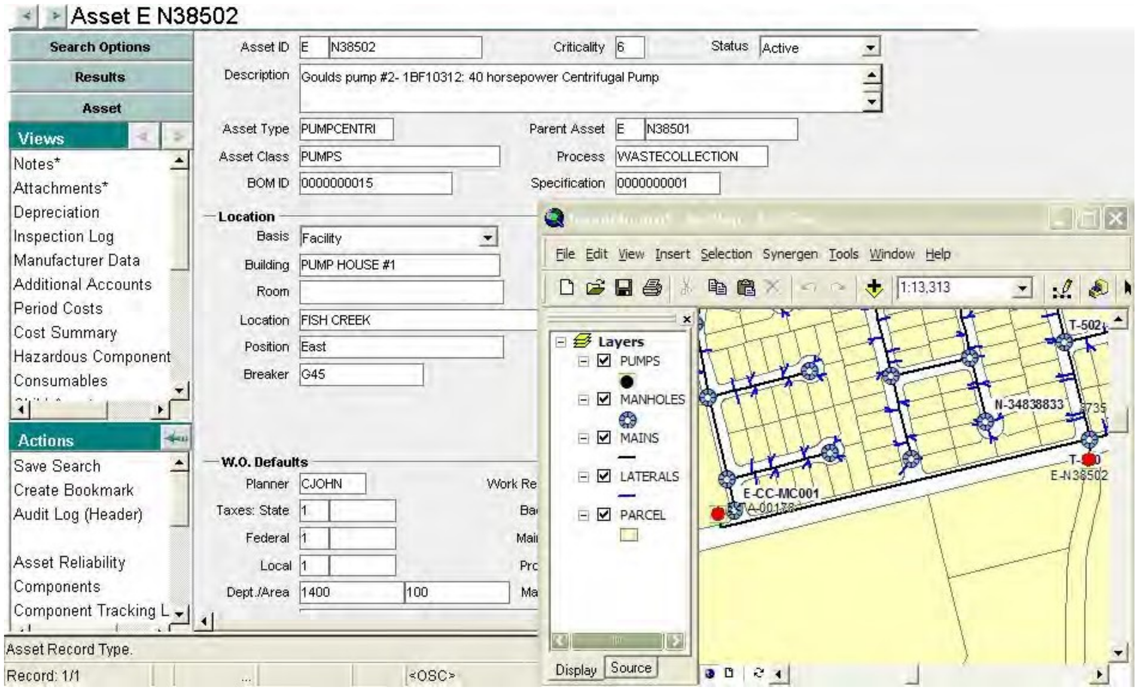


Figure 2.5: Synergen Asset module in the Resource subsystem, and GIS view of selected assets (Syneren 2009)

2) CityWorks

CityWorks (2009) is a GIS-based solution for operational and maintenance management of municipal assets. CityWorks supports functions including asset data management, work order management, recording inspection and condition data, and report generation. It also supports logging and tracking of service requests using the add-on “Call Center” module, and supports procurement and inventory management operations, using the “Storeroom” module. CityWorks includes several built-in spatial data models based on the schemas defined by ESRI (2005). The models support a wide range of municipal assets such as water, wastewater, storm water, and road networks. Users can modify or override the schemas to suit the specific requirements of their organizations. A distinguishing feature of CityWorks is its tight integration with GIS. Unlike most of other applications described in this paper, CityWorks uses the GIS database (or geodatabase) to maintain and integrate asset data. Figure 2.6 shows the ArcGIS add-on showing a map of water mains and associated work orders, and the forms for Work Order and Service Requests.

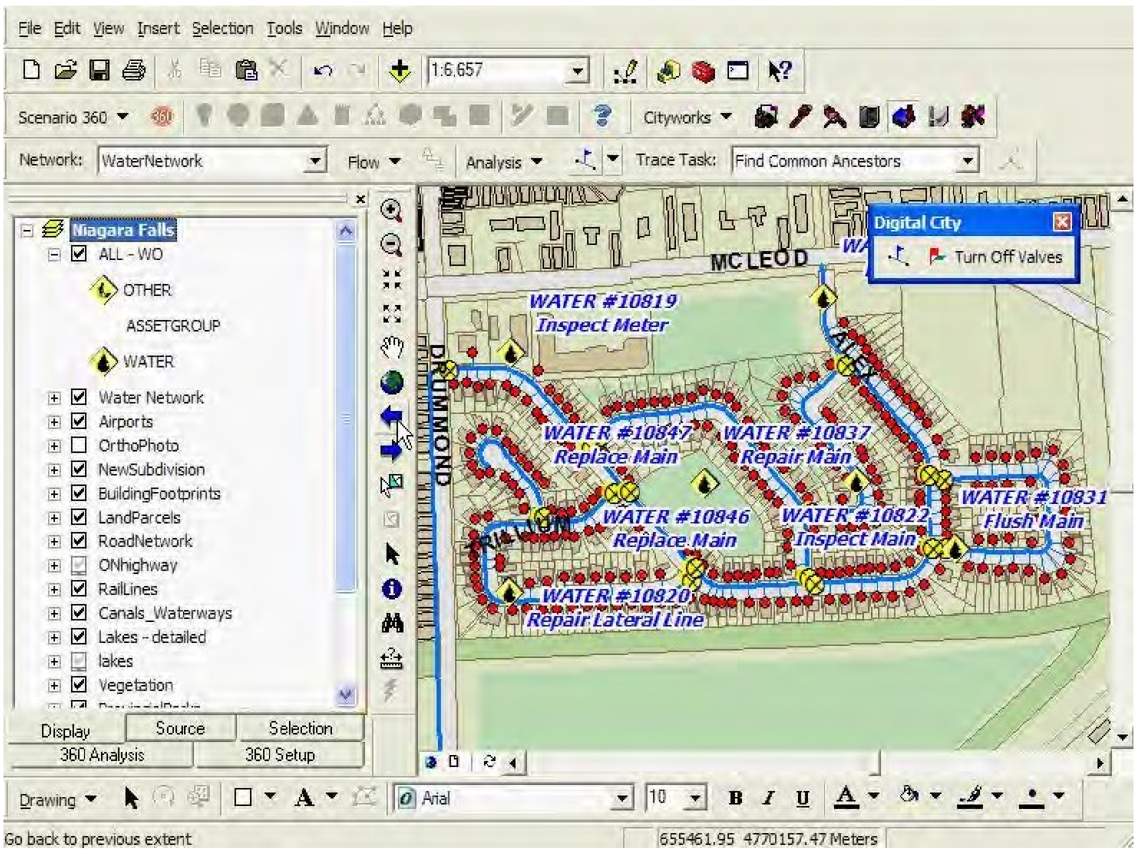


Figure 2.6: CityWorks ArcGIS add-on showing a map of water mains and associated work orders (Cityworks 2009)

3) Municipal Infrastructure Management Systems (MIMS)

The Municipal Infrastructure Management System (MIMS, 2009) is primarily a data management system for water, wastewater, storm water, and road networks. It also includes modules for managing gas pipelines and municipal buildings. The system is targeted to small and medium size municipalities. MIMS has extensive data import/export and reporting capabilities, and incorporates a wide range of pre-formatted reports. MIMS provides the users with a consistent set of forms and tools for managing different infrastructure assets, and thus enables users to become familiar with the system fairly quickly.

Each class of assets is broken down into its main components, which are in turn subdivided into asset types. Each asset type is represented as a table in the underlying relational DBMS. For example, the water, sanitary and storm water network asset classes are broken down into lines, features, facilities, and equipment components, and the lines component is subdivided into pressure mains, gravity mains, service/leads, and channels asset types. Figure 2.7 shows a screen capture of the main form of the four main asset classes, their components, and asset types.

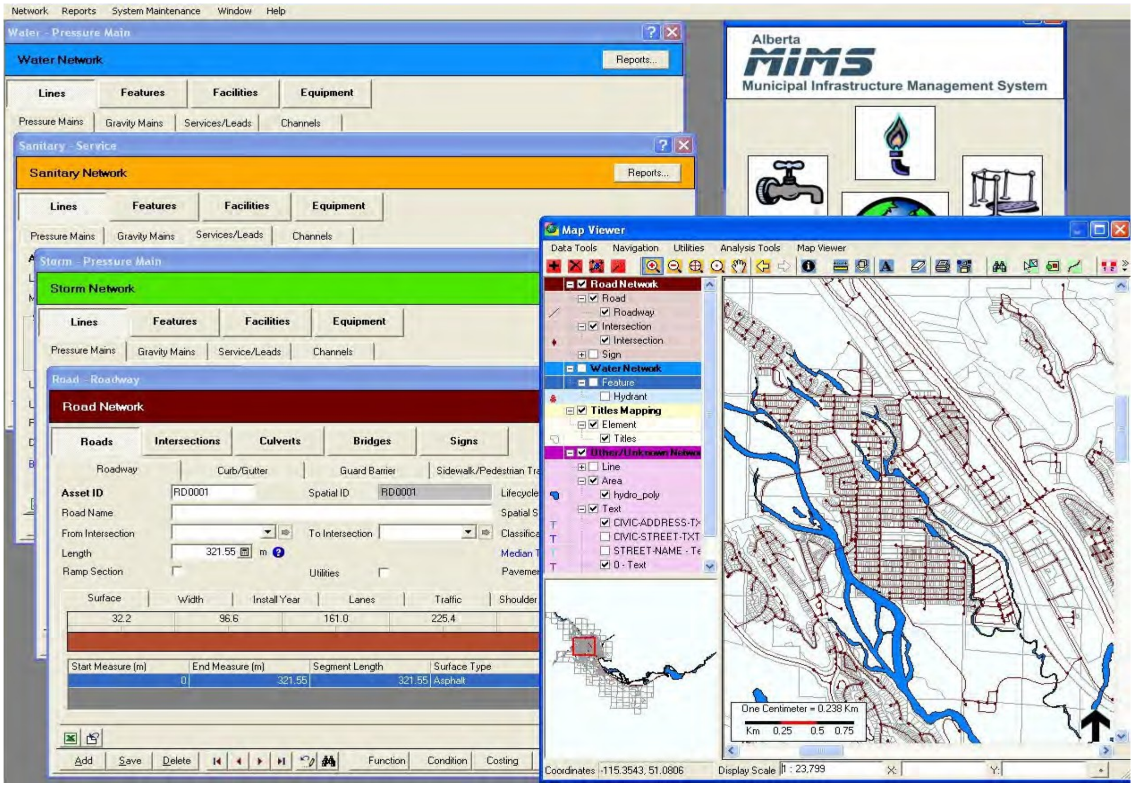


Figure 2.7: MIMS main windows showing breakdown of the network to primary components (MIMS2009)

4) RIVA

Real-time Asset Valuation Analysis (RIVA 2010), developed by Loki Innovations (www.loki.ca), provides capabilities for long-term asset management planning in a 10 to 200 year planning horizon. RIVA is a web-based client-server application that can interface with most common applications. RIVA has a modeling capability that can be used for asset valuation, determination of deferred maintenance, condition assessment, estimating remaining service life (RSL), and prioritization of maintenance and rehabilitation (M&R) processes. Deterministic and probabilistic models can be created using the Formula Builder tool. The Formula Builder tool allows users to create, change and test the formulae that drive calculations and models. Models can be trial models, in which the user can vary the model parameters to undertake a comparison of various asset management scenarios, or corporate models. Changes made to the models are automatically reflected in data and model outputs (e.g. deterioration curves, priorities, etc).

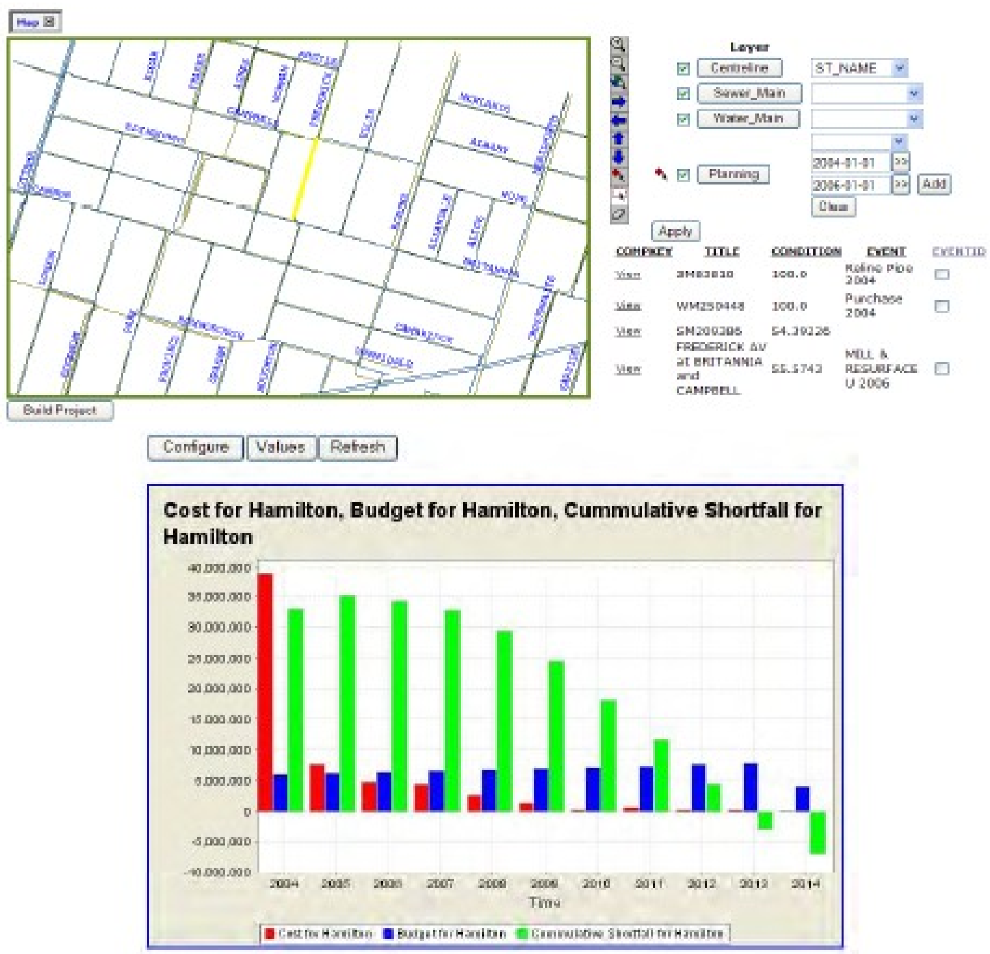


Figure 2.8: View of Riva showing GIS Integration & long term impact of Infrastructure Funding (RIVA 2010)

Figure 2.8 shows sample screens that demonstrate the GIS integration capabilities of RIVA and the ability to roll up costs to a network level.

5) Hansen

Hansen (2010) is a major asset management application developed by Hansen Information Technologies to provide capabilities for managing government operations including asset and property management, utility billing, permits, financial and human resources management. The software supports inventory data collection, asset valuation, determination of deferred maintenance, condition assessment, estimating remaining service life, and prioritizing M&R options. The software can interface with two major GIS products: Intergraph's GeoMedia and ESRI ArcGIS. The software also has extensive data import/export capability. Hansen applications are typically used by medium to large municipalities or organizations.

Hansen's asset management tools are contained in two major modules: *Public Works* solutions and *Transportation* solutions. Each module is GASB Statement 34 compliant, with an asset-specific infrastructure accounting model. The *Public Works* module contains divisions for: industrial waste management, parks management, plant and fleet management, water and wastewater management, and work management. The *Transportation* module contains: bridge management, facilities and equipment, inventory management, pavement management, property management, railway management, roadway management, sign management, and street management.

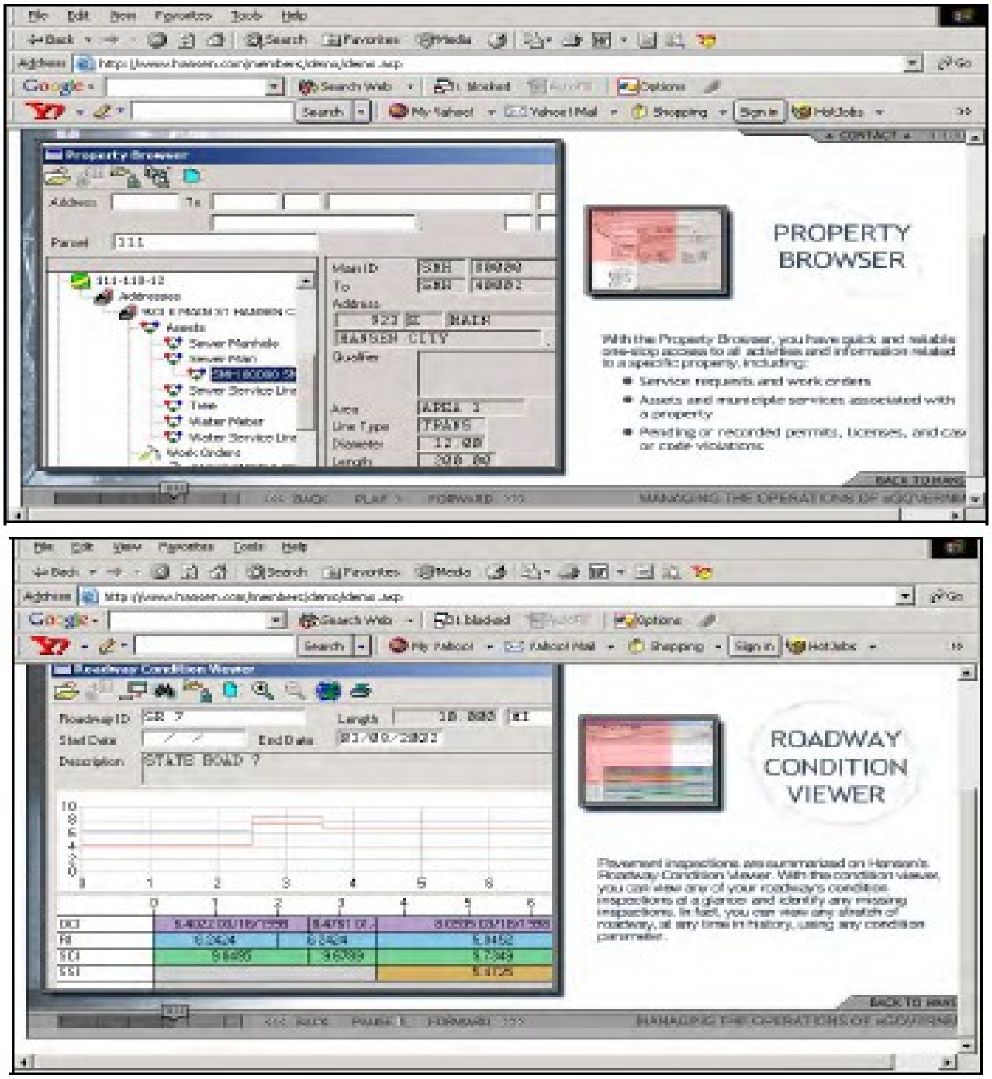


Figure 2.9: (Top) Property Browser from Public Works module (Bottom) Roadway condition viewer (Hansen 2010)

6) Infrastructure2000

Infrastructure2000 (2010), developed by Vanasse Hangen Brustlin, Inc. (VHB), provides capabilities for asset management planning, and is targeted at small to medium size organizations. It supports inventory data collection, asset valuation, determination of deferred maintenance, condition assessment, estimating remaining service life, and prioritizing maintenance and rehabilitation (M&R)

options. The software can be integrated with popular GIS applications such as ESRI's ArcGIS

Infrastructure2000 consists of RoadManager2000, with five asset management modules, and three work management tools: WorkManager2000, EquipmentManager2000, and PermitManager2000. The five RoadManager2000 modules include: Pavement, Sidewalk, Traffic Control, Drainage/Utility, and Budget Analysis. The pavement module is the most comprehensive of the five. It also provides a condition assessment capability using the standard rider comfort index (RCI) or the pavement condition index (PCI) protocols as a measure of pavement condition. The 0–100 index score is mapped to a condition score where "1" (one) is defined as a "do nothing" intervention and "5" (five) is defined as a "reconstruct" intervention. Figure 2.10 shows sample screens from RoadManager2000, demonstrating the Pavement module notebook, table options, pavement assessment, as well as deterioration curves from the Budget Analysis module.

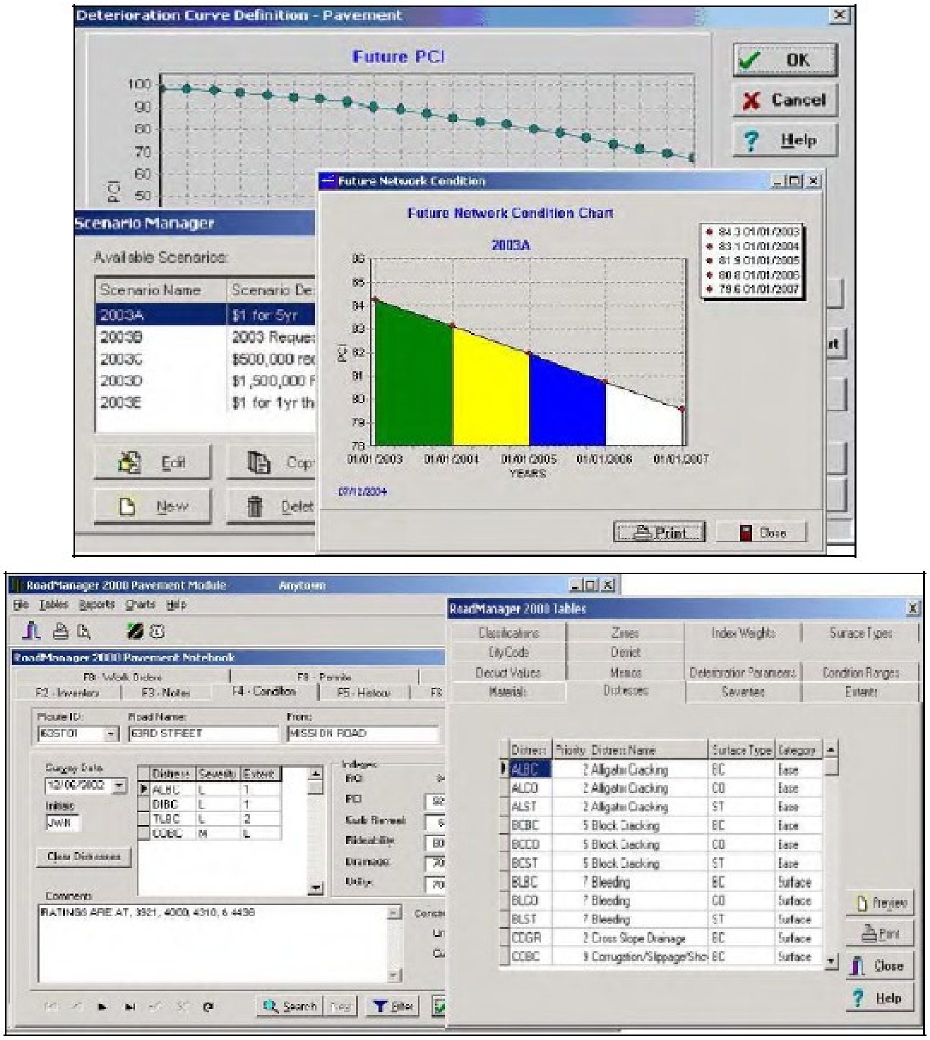


Figure 2.10: Sample screens Road Manager2000 (Infrastructur2000 (2010))

7) Harfan

Harfan's (2010) method is geared to be a generic solution for long-term management of municipal assets. It attempts to be flexible in its design, so that it can be adapted to support: (1) extending the asset service life, and (2) optimizing the long-term investments. The software can be applied to diverse areas such as: water and sewer networks, roads, gas and telecommunications networks, electricity networks, street lighting, buildings, marine assets, airports, and rail systems. Harfan allows integration with the most popular GIS systems (e.g., Autodesk MapGuide and ESRI ArcGIS).

Harfan recommends a five-step methodology that includes addressing typical asset management issues of: what do you own, what is it worth, what is the condition, what is the remaining service life, how much you should invest to ensure sustainability, and what needs to be done and when. As a result, the software modules are designed to produce answers to these questions.

Figure 2.11 shows a screen capture of integrated capital plan and the resulting Global Condition 10 years into the future, after having applied a scenario of roughly $22.4 million of rehabilitation and reconstruction works.

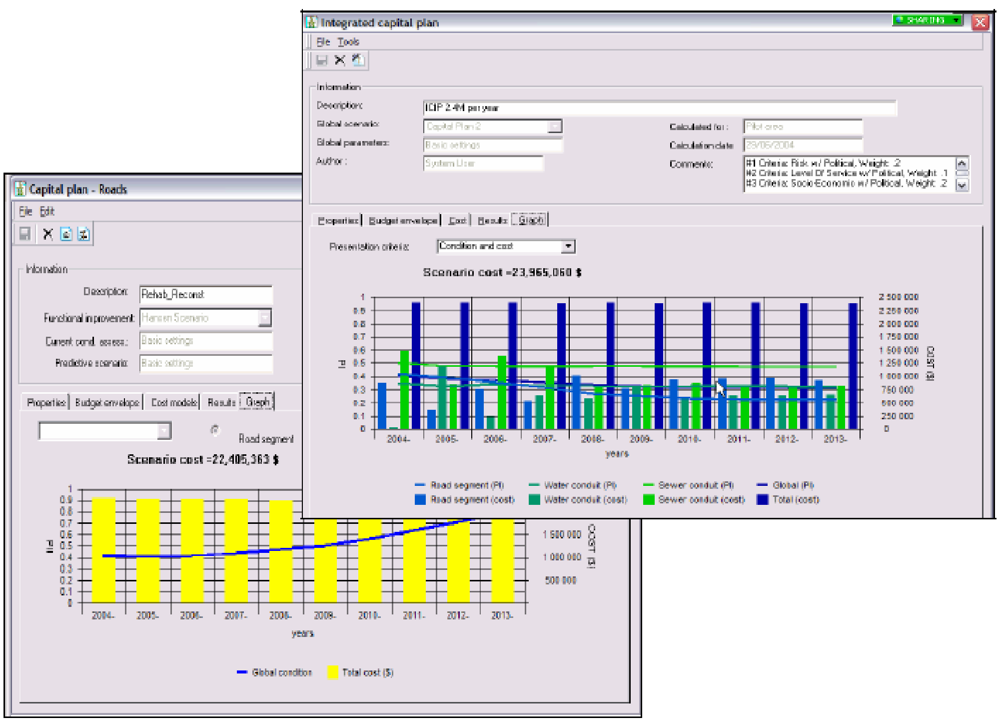


Figure 2.11: View of Integrated Capital Plan for integrated right-of-way and the associated costs (Harfan 2010)

A review of a number of municipal infrastructure asset management systems was presented. The main features, capabilities, and limitations of the evaluated software were briefly discussed. Compared to the decision support systems developed in other sectors in the construction industry, the systems developed for asset management are relatively limited in number and scope, and are generally less mature. This review is limited to seven well-known systems available in North America that are commonly used by municipalities, and that constitute a representative sample of the currently available asset management systems in terms of functionality, features, and limitations.

In light of the above review, some directions for future research can be identified. The vast majority of the existing systems focus primarily on supporting the operational day-to-day management activities, and a small number of software tools implemented limited support for long-term renewal planning. Also, many fundamental asset management functions, such as performance modeling, and maintenance prioritization, are not supported by most of these applications. Part of this scarcity can be attributed to the lack of a clear and systematic approach to tackle this problem. The data models supported by existing software are mostly proprietary, which restricts the software systems to interoperate and share asset data. Developing standard integrated data models for infrastructure systems is another critical area for future research.

Last, but not the least, only Harfan is capable to simultaneously handle the road, water and sewer asset classes. However, it fails to provide the objective solution of meeting the community expectations through a renewal plan that is optimized with respect to the community and agency concerns. In this context, it just describes the cost of different renewal strategies with resulting condition and remaining service life. Therefore, there is need to augment the renewal planning practices and to develop more objective and integrated renewal planning solutions.

2.4 Performance Indicators and Condition Assessment Measures and Ratings

2.4.1 Performance Indicators

In creating a useful methodology for municipalities, several considerations are required. First among these considerations is that the people making funding decisions in municipalities often do not have an in-depth understanding of infrastructure engineering considerations. It is therefore important to identifying indicators that are meaningful to decision makers. A three level hierarchy of indicators shown in the Figure 2.12, below is mostly used by the municipalities who are doing a performance oriented management (InfraGuide 2002).

Indicator at its simplest is data that identify the condition or state of something being measured. There is a hierarchy of indicators and these are aggregated and combined with related data to form higher levels of indicators, moving from the specific (operational) to more abstract (strategic). Also pertinent here is to differentiate between the terms “distress indicator” and “performance measure” as used in this research. A distress indicator is data that can be attributed only to the physical state of an asset whereas a performance measure can represent any aspect of the physical state of an asset as well as its functional efficiency. Alternatively, performance measure is the data suited to express the quality of service an asset is rendering.

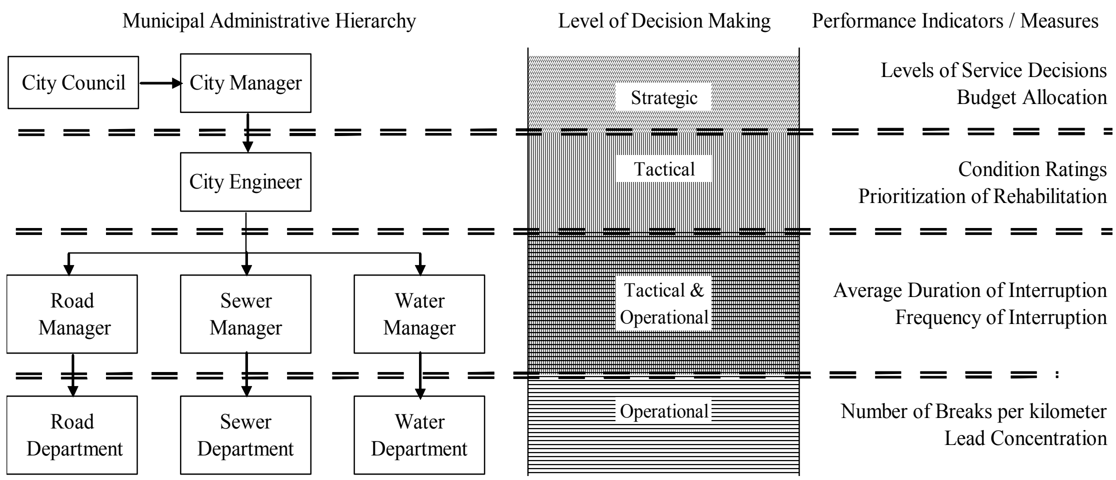


Figure 2.12: Municipal hierarchy and decision /indicators under its purview

The hierarchy of performance indicators as described by InfraGuide Best Practices (InfraGuide 2002) is as under:

Operational indicators — An operational indicator is generally raw data collected about an infrastructure asset by road or work crews while performing their duties or as part of an asset inventory process. In the case of roads, it may be such as "counting cracks." Operational indicators are often expressed by municipalities as survey results or scorecards. Some indicators can also be a dollar value, expressed as the cost of an individual asset repair.

Tactical indicators — Tactical indicators result from analyzing different but related operational indicators to obtain an overview of an infrastructure asset's condition. For example, a number of operational indicators, such as number and types of cracks, smoothness, etc., can be combined to produce an overall pavement quality index (PQI). A tactical indicator provides an overview of an infrastructure asset's condition, state or value to the managerial-level municipal decision makers (e.g., city engineers, public works managers).

Strategic indicators — Strategic indicators are the highest and most abstract type of indicators. They are set and reviewed by the highest level of municipal decision makers. Examples include a measurement of a municipality's quality of life or meeting an annual infrastructure budget.

Below is a case study that used operational and tactical level indicators to set pipeline rehabilitation priorities. Condition and criticality are the tactical level indicators whereas indicators such as I/I rates, material and age are operational level indicators.

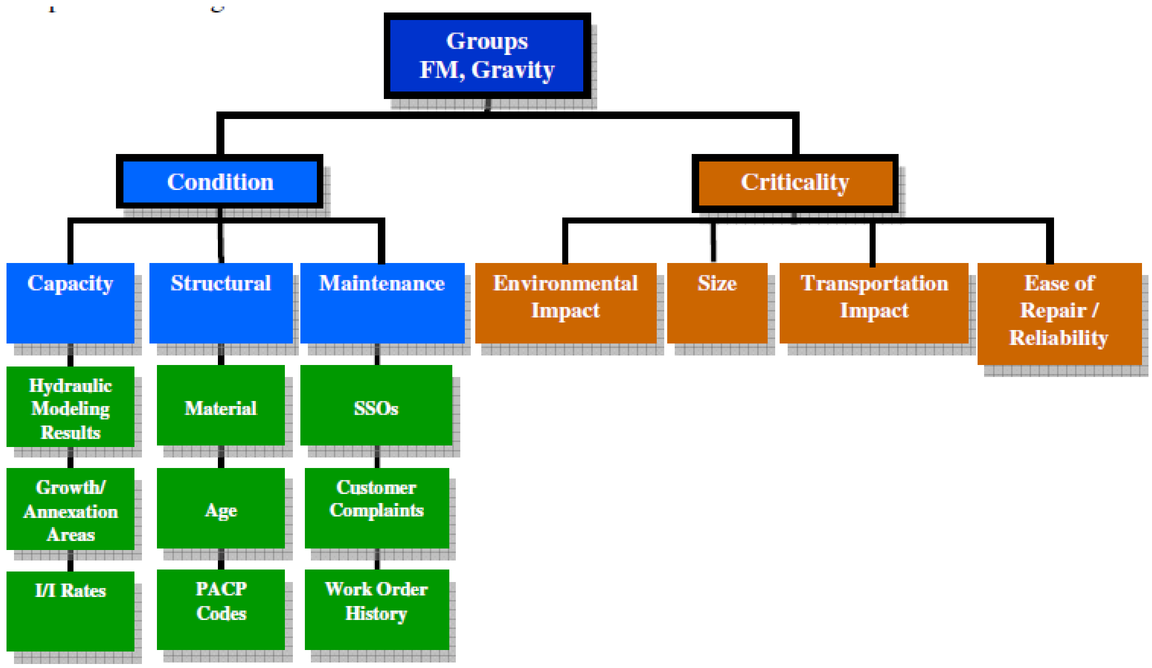


Figure 2.13: Setting a Pipeline Performance Indicators Hierarchy
(Miles et al 2007)

2.4.2 Asset Inspection Approaches

Condition assessment evaluates and compares the current physical state or performance of an asset to a “like new” asset. Infrastructure managers need good quality inventory and inspection data to perform a proper condition assessment. The challenge is to provide a combined or overall condition grade for the infrastructure, or sections of the network, that accurately represents the actual condition. Typical methods for inspection in use today include subjective grading, distress-based evaluation, and non-destructive evaluation. Here the term ‘inspection’ refers to all methods of observing distress indicators, including visual and various methods of NDT.

Taking water utilities in North America as an example, it is found that most municipalities have not conducted routine inspections and condition assessments of their large-diameter water transmission mains (many utilities have not inspected their transmission mains even once) Typically, inspection is triggered ad-hoc, following a catastrophic failure or opportunistically when a pipe is taken off-line for repair (NRCC 2006a).

Currently, all pipe inspection techniques that are commercially available for large water mains (including visual and NDT) require that the inspected pipe be drained. Large-diameter water transmission mains are expensive components of the water supply system, and therefore the system often does not have enough built-in redundancy, i.e., ability to deliver water while these pipes are off-line. This is the main reason why water utilities are reluctant to inspect these pipes. The cost of the large amounts of treated water that is lost on pipe drainage, as well as possible difficulties in disposing of this water is a secondary reason for the low rate of inspection. The condition of large-diameter water transmission mains is of little concern at an early age since a well-designed pipe would have an adequate built-in margin of safety. However, it is expected that failure rates may increase significantly as the pipes age and margins of safety diminish.

Jackson et al. (1992), Dorn et al. (1996), Makar and Chagnon (1999) and Dingus et al. (2002) have reported comprehensive reviews of pipe inspection methods. However, most of the reviewed inspection methods are specific to small-diameter mains. Mergelas and Kong (2001) and Elliott et al. (2002) described the development and application of a technique based on remote field eddy current/transformer coupling (RFEC/TC) that is applicable to large diameter PCCP pipes. It detects the presence of broken wires and estimates their number.

The condition assessment of a buried infrastructure asset is a costly procedure, and can be viewed as consisting of two distinct components. The first component involves the inspection of the asset using direct observations (visual, video) and/or non-destructive evaluation (NDE) techniques (radar, sonar, ultrasound, sound emissions, eddy currents, etc.). Inspection of an asset yields quantification and location(s) of distress, e.g., 2 mm wide crack at spring level located 2 m from the pipe bell, or 19 broken wires located 4 m from the spigot. (NRCC 2006)

The second component of condition assessment is the translation of these inspected distress indicators into an overall condition rating of the asset. Thus, a condition rating reflects the combined result of all observed distress indicators for one pipe segment.

2.4.3 Condition Assessment Methods and Protocols

As already discussed, inspection is followed by the assessment of asset condition and the observations/readings of inspection are transformed into a condition Index. This is usually done by following some condition assessment protocol. Condition assessment looks at the current condition of an asset and establishes a reference for prioritizing maintenance and rehabilitation activities. Assessing asset condition is a primary activity in implementing a successful asset management program because the cost of the system failure can have a significant impact on the municipality or utility and its taxpayers, as well as on long-term health and/or environmental issues.

Taking the example of sewer systems we find that since the physical condition of sewer systems is not readily visible; therefore, sewers are often overlooked while setting maintenance or rehabilitation priorities. In addition, many older municipalities do not have maps or records of maintenance activities for their aged sewer systems, let alone the location, age, condition, or attribute information about individual pipe segments required to facilitate condition assessment. Allouche and Freure (2002) conducted a survey of maintenance and management practices for storm and sanitary sewers to determine the use of condition assessment techniques in Canadian municipalities. Survey questionnaires were sent to 38 municipalities across Canada and 24 responded (62%). This represents municipalities serving 5.2 million people or approximately 17% of the population of Canada. The survey results showed that 68% of the respondents used the Water Research Centre (WRc) protocol. Most large

Canadian municipalities in the survey were directly or indirectly using WRc assessment methods or had developed their own system based on WRc guidelines. In addition, a large number of these Canadian municipalities were using North American Association of Pipeline Inspectors (NAAPI) certified operators or reviewers. It was suggested (NRCC 2004), that to overcome huge maintenance backlogs and to improve the condition and performance of sewer systems, a unified consistent condition assessment protocol is essential.

In case of water distribution systems also, the distress indicators are physical exhibits of the ageing process. An important step towards the assessment and management of failure risk in large-diameter (transmission) water mains is to observe distress indicators through scheduled inspections (using non-destructive or visual techniques) and translate these into condition ratings. Condition rating reflects an aggregate state of the pipe's health. The type (or form) and location of observed distress indicators in large-diameter mains are dependent on the pipe material and its surrounding environment. The physicochemical processes that promote ageing are often not understood well enough to merit an adequate physicochemical model. Further, the encoding of distress indicators into condition rating is inherently imprecise and involves subjective judgment.

Operational defects also play an important role in the overall performance of a sewer system. For an explanation of the distress indictors and assignment of deduct values for operational defects for light, moderate, and severe distress levels, see Table 2.1. Also see Figure 2.14 to have an idea of the variations in assigning deduct values of operational defects of the same sewer mains under three different condition assessment protocols. The light, moderate, and severe distress levels for each type of defect are represented as a relative percentage of the maximum score (100%). It is noticeable from Figure 2.14, that operational light-level defects range from 10% to 33% and moderate-level defects range from 50% to 80% of the maximum deduct value. Edmonton suggests higher deducts for most of the light-level defects while the NRC provides higher deducts for most of the moderate-level defects as shown in Figure 2.14.

It has been seen that in water distribution systems the most widely used protocol is that by American Water Works Association whereas as for Wastewater collection systems the most commonly used ones are the WRc and NRC (Canada only). These protocols have their specific criteria to transform the type and severity of the performance/distress indicators into condition rating. Therefore the condition rating for the same set of observation for an asset worked out by each protocol may be different from others. There is no standard condition rating for a particular state of condition of a segment.

Table 2.1: Comparison of Deduct Values for Operational Defects (NRCC 2004)

Defects	Distress Level	Deduct Values		
		NRC	Edmonton	WRc
Roots (R)	*Light*: fine roots: reduction in diameter <10%	2	1	
	Fine roots			1
	Mass roots: reduction in diameter <5%			2
	Moderate: reduction in diameter 10% - 25%	8	2	
	Mass roots: reduction in diameter 5% - 20%			4
	Tap roots			5
	Severe: reduction in diameter > 25%	10	3	5
	Mass roots: reduction in diameter 20% - 25%			10
	Mass roots: reduction in diameter 50% - 75%			15
	Mass roots: reduction in diameter 75%			20
Debris (DE)	*Light*: reduction in diameter <10%	5	1	
	Silt/grease: reduction in diameter 5%			1
	Moderate: reduction in diameter 10% - 25%	8	2	2
	Silt/grease: reduction in diameter 5% - 20%			2
	Severe: reduction in diameter > 25%	10	3	
	Silt/grease: reduction in diameter 20% - 50%			5
	Silt/grease: reduction in diameter 50%- 75%			8
	Silt/grease: reduction in diameter > 75%			10
Encrustation (E)	*Light* reduction in diameter <10%	2	1	1
	Moderate: reduction in diameter 10% - 25%	8	2	2
	Severe: reduction in diameter > 25%	10	3	5
Protruding (P)	*Light*: reduction in diameter 10%	2	1	-
	Intruding lateral: reduction in diameter 5%			1
	Intruding lateral: reduction in diameter 5% - 20%			2
	Moderate: reduction in diameter 10% - 25%	8	2	-
	Intruding lateral: reduction in diameter 20% - 50%			5
	Severe: reduction in diameter > 25%	10	3	-
	Intruding lateral: reduction in diameter 50% - 75%			8
	Intruding lateral: reduction in diameter >75%			10
Infiltration (I)	*Light:* seeping dripping	2	1	-
	Moderate: running, trickling	5	2	-
	Severe: gushing, sporting	10	3	-

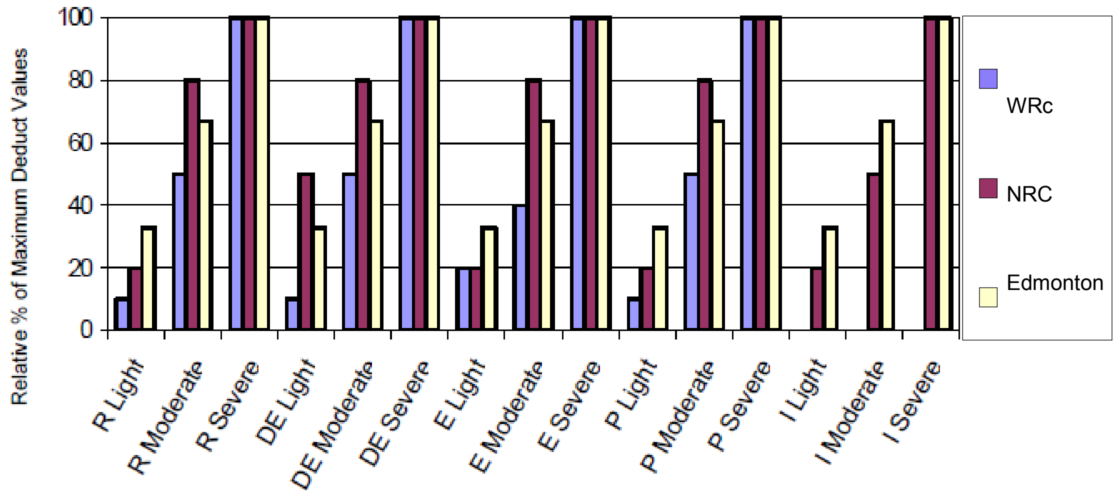


Figure 2.14: Comparison of Light, moderate and Severe Operational Defects (NRCC 2004)

Further to be noted that among the three broad categories of inspection techniques i.e. the visual inspection, non-destructive technique (NDT) and the distress-based evaluation (DBE) reviewed earlier the most widely used i.e. the visual inspection is entirely a human input and is prone to subjectivity and error. In such a situation if it is required to use particular performance parameters that a community is interested in then there is an essential need to develop a customised condition assessment system. This system should be based on the same performance parameters that are used to quantify and express the level of service. It should also attempt to encode the performance indicators into a more precise and less subjective manner. In this connection, fuzzy logic tools (NRCC 2006a, NRCC 2006b, NRCC 2006c and NRCC 2006d) are considered to help in using of engineering judgement, experience and scarce field data to translate the observations into condition rating.

Atef, Osman and Moselhi (2010) reported the lack of reliable data as a tremendous impediment to any asset management program and determined that water and waste water infrastructure condition assessment is costly and uncertain compared to other surface infrastructure. There should be a balance between the value of information attained by the condition assessment technology and the cost associated with the process. This can be done by considering certain factor simultaneously. The first factor identified to be considered is the quantification of direct, indirect and social cost associated with an asset failure. It is more likely that to prevent costly failures, decision makers would spend more money to obtain condition information for assets that have a high cost of failure. Desired level of service (LOS) is the second factor, identified for consideration. It is the user expectation about asset performance. The higher level of service will translate into more proactive asset management practices that involve more comprehensive assessment of asset condition. The integrated framework of optimised condition assessment policies developed by Atef, Osman and Moselhi in 2010 is targeted to assist asset managers in dealing with this delicate balance between value and cost of condition assessment information. The approach is depicted below:

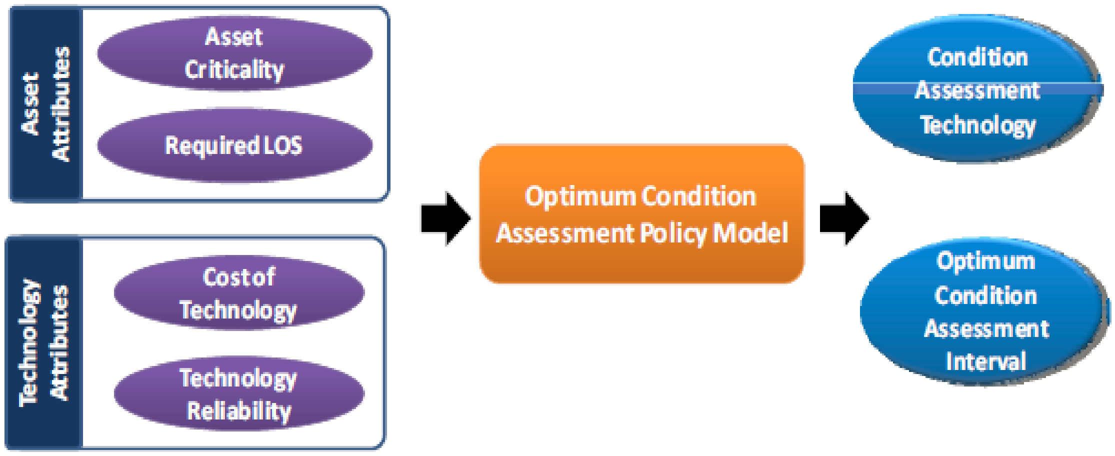


Figure 2.15: Framework for optimum condition assessment model
(Atef, Osman and Moselhi, 2010)

2.5 Asset Level of Service

Levels of service reflect social and economic goals of the community and may include any of the following parameters: safety, customer satisfaction, quality, quantity, capacity, reliability, responsiveness, environmental acceptability, cost, and availability. They may also be any combination of the above parameters deemed important by the municipality (InfraGuide 2003c).

"Levels of service in municipal context is a flexible vehicle to assist in performing quality-cost trade-off analysis for municipal services" (Moselhi 2005). This trade-off depends on the willingness of a community to pay as well as on the condition of the assets. Community perspective of performance of an asset from service point of view may be quite different from municipality / agency perspective of performance of the same asset from condition point of view. The levels of service require a series of activities that overlap one another, yet are linked to achieve levels of service. This can best be understood by the Figure 2.16.

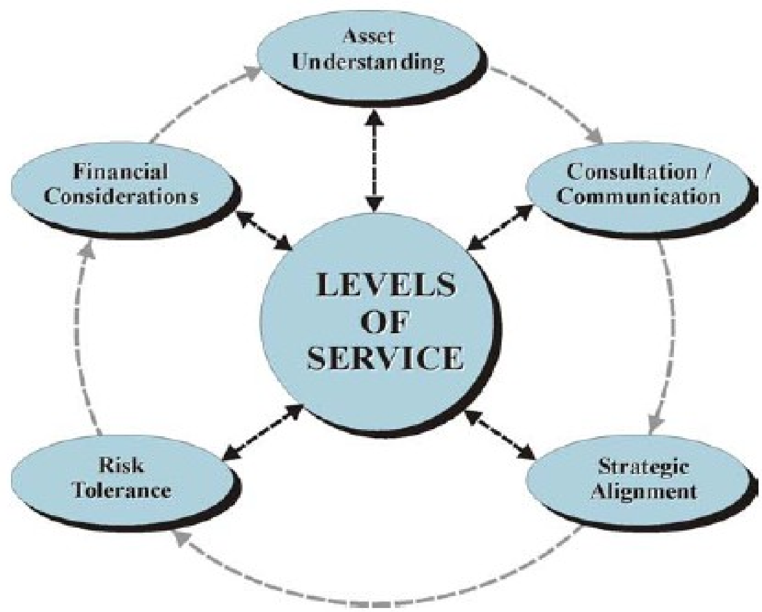


Figure 2.16: Delivery of Level of Service / Linkages (InfraGuide 2003c)

Sharma et al. (2008), attempted to combine the levels of service of a municipal asset experienced by different users, into a composite level of service, termed as ALOS. Another objective was to drift from the quantitative analysis of level of service and build on qualitative factors. The developed framework uses analytical hierarchy process to model level of service. The developed framework is applied to calculate the ALOS for municipality/urban roads, to combine LOS for vehicle users, bicyclists, and pedestrians; accounting for qualitative factors, such as neighborhood safety and aesthetics. However, ignoring entirely either the quantitative or the qualitative set of related parameters is not rational and cannot lead to the true condition assessment of the asset. Besides, in order to identify rehabilitation techniques for condition improvement quantitative parameters are essential. Actually, there should be a combination of quantitative and qualitative parameters and to process information on those the Analytical Hierarchy process is one of the most suitable methods.

Establishing Levels of Service

There are eight basic steps to develop levels of service. As indicated in Figure 2.17, the process tends to be iterative. The level of effort in each activity might vary considerably for municipalities / organizations with differing demographics and for different types of assets. For example, the process and emphasis for establishing levels of service for transportation systems might be quite different than for a wastewater treatment facility, but the basic activities identified in Figure 2.17, should still be an appropriate best practice process to be followed.

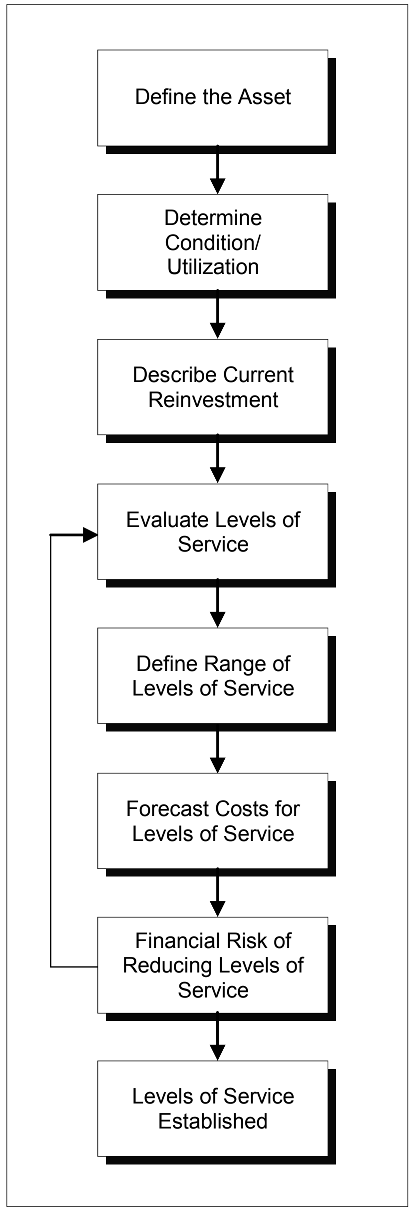


Figure 2.17: Developing Level of Service (InfraGuide 2003c)

Rationale for Perusing Level of Service

Levels of service represent service-cost trade-offs, established in a flexible, rational, and transparent manner. They serve the following purposes:

- Assist and support decision making and investment planning related to planning, development, operation, maintenance, rehabilitation, and replacement of municipal infrastructure
- Promote good practice, sustainable development, and environmental stewardship
- Facilitate community involvement and a public sense of ownership, and incorporate community values

The obvious benefits in achieving and maintaining levels of service include health and safety, physical/natural development, economic/social development, quality of life/living standards and reducing life cycle cost.

2.6 Asset Rehabilitation Techniques - Categories and Capabilities

The operations, maintenance and management of municipal assets are complex and ever-changing processes and so rehabilitating or replacing existing assets to meet a community's needs is an ongoing occurrence across Canada. InfraGuide Canada was an initiative that operated from 2001 to 2007, as a partnership between the Federation of Canadian Municipalities, the National Research Council and Infrastructure Canada. InfraGuide national network of experts produced a collection of case studies, best practice reports and e-learning tools for sustainable municipal infrastructure, all based of Canadian experience and knowledge. Among many, one important feature of InfraGuide was to provide best practices on the selection of available technologies for replacement or rehabilitation of municipal assets, primarily including water and wastewater mains and pavements.

The process outlined in these best practices assumes the municipality has already determined that a section of the water or wastewater main requires remedial action. That determination should have been based on a prioritization scheme that is in the best interests of the entire community. This best practice provides flow diagrams for water and wastewater mains, for a municipality to follow in determining the technologies available for the rehabilitation or replacement of the main in their specific situation. The flow diagrams of water and wastewater mains rehabilitation alternatives presented respectively at Fig. X1 and Fig X2, identify the problems, addresses the possible causes of the problem, and provides two options (full replacement/structural rehabilitation or non-structural/semi-structural rehabilitation). The current available technologies are also identified and discussed. Effort of similar nature for pavements are reported here is from the Minnesota Department of Transportation (Hicks et al., 2000) and is presented at Fig. 2.18.

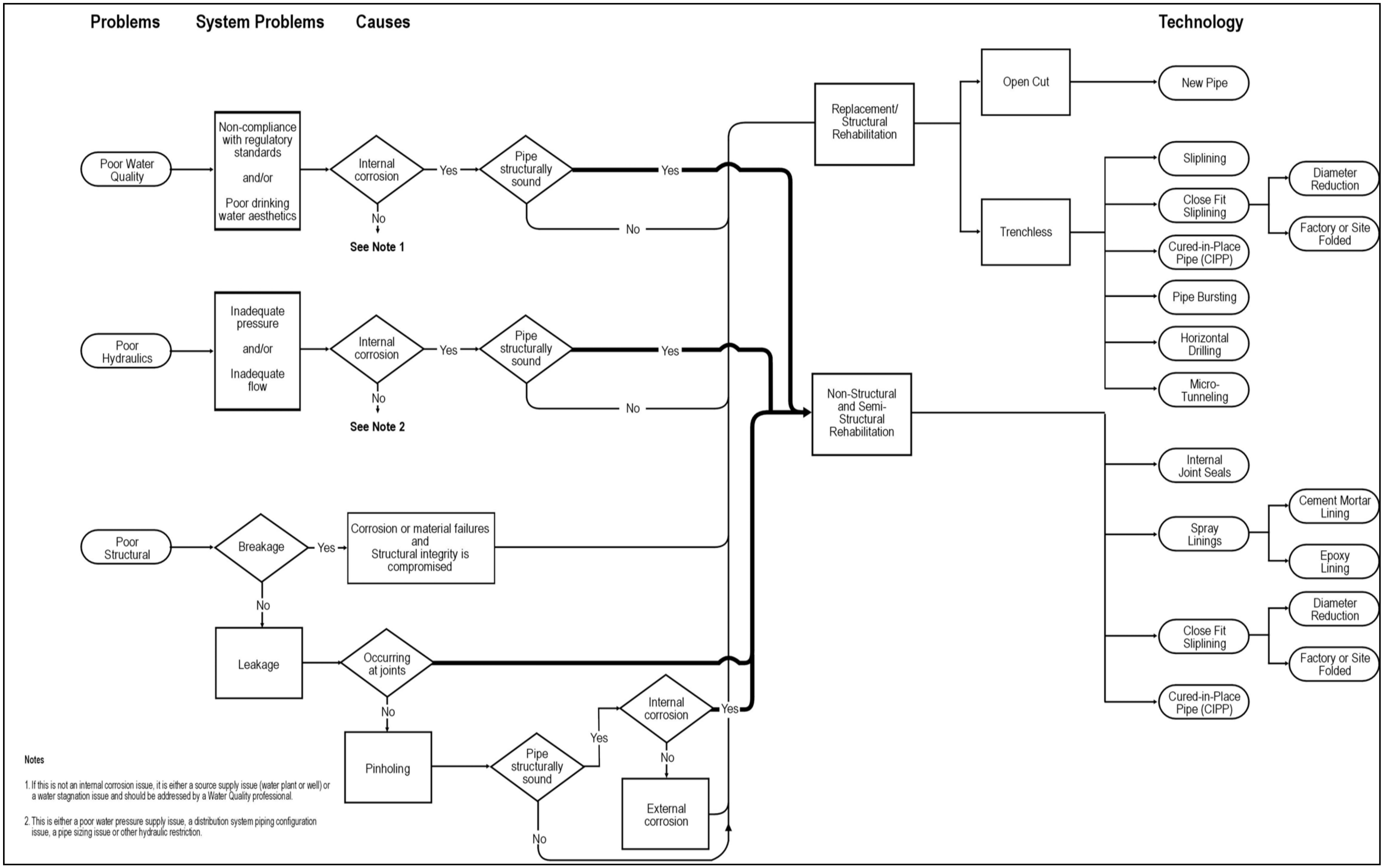


Figure 2.18: Appropriate Technologies for Rehabilitation of Water Mains (InfraGuide 2003f)

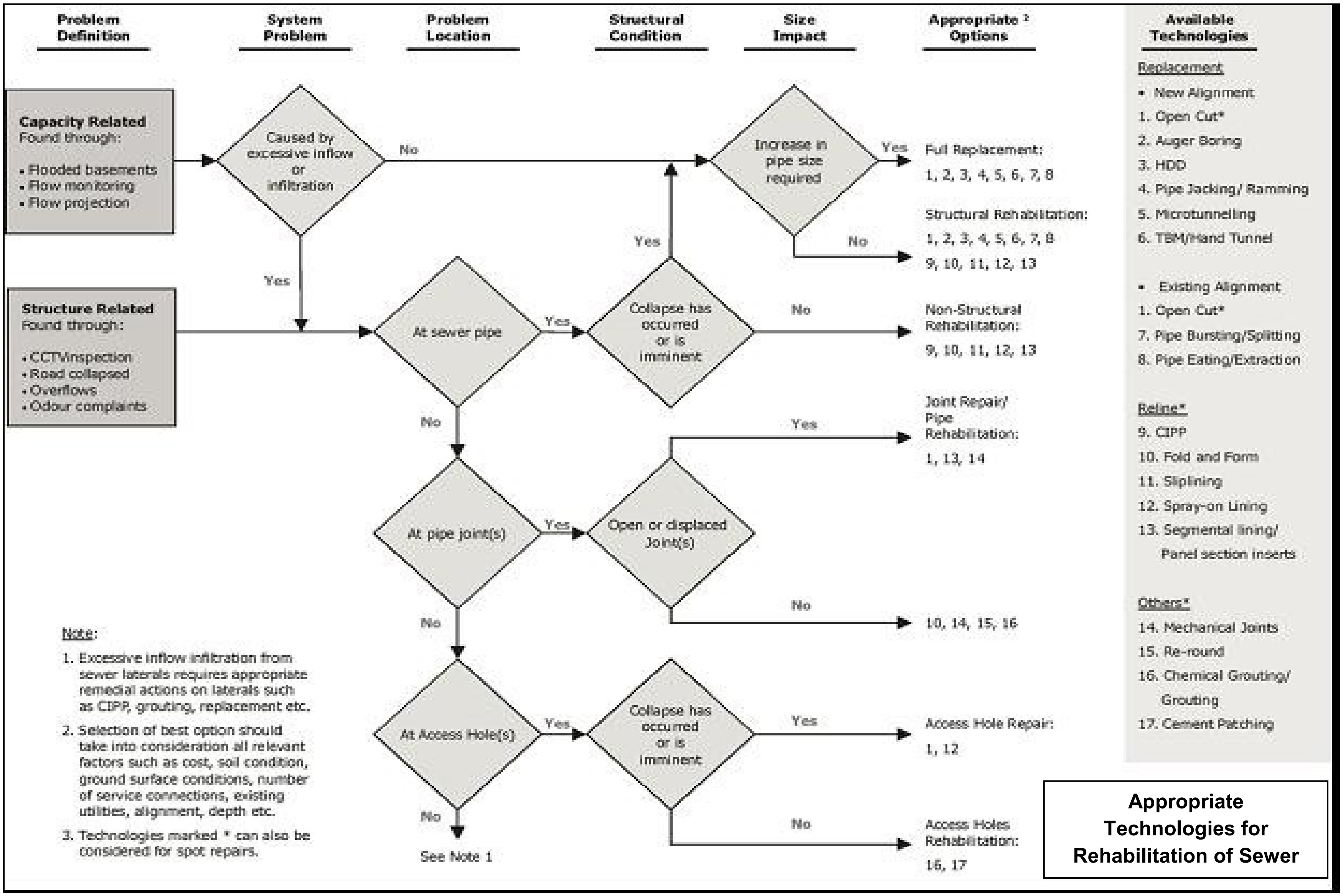
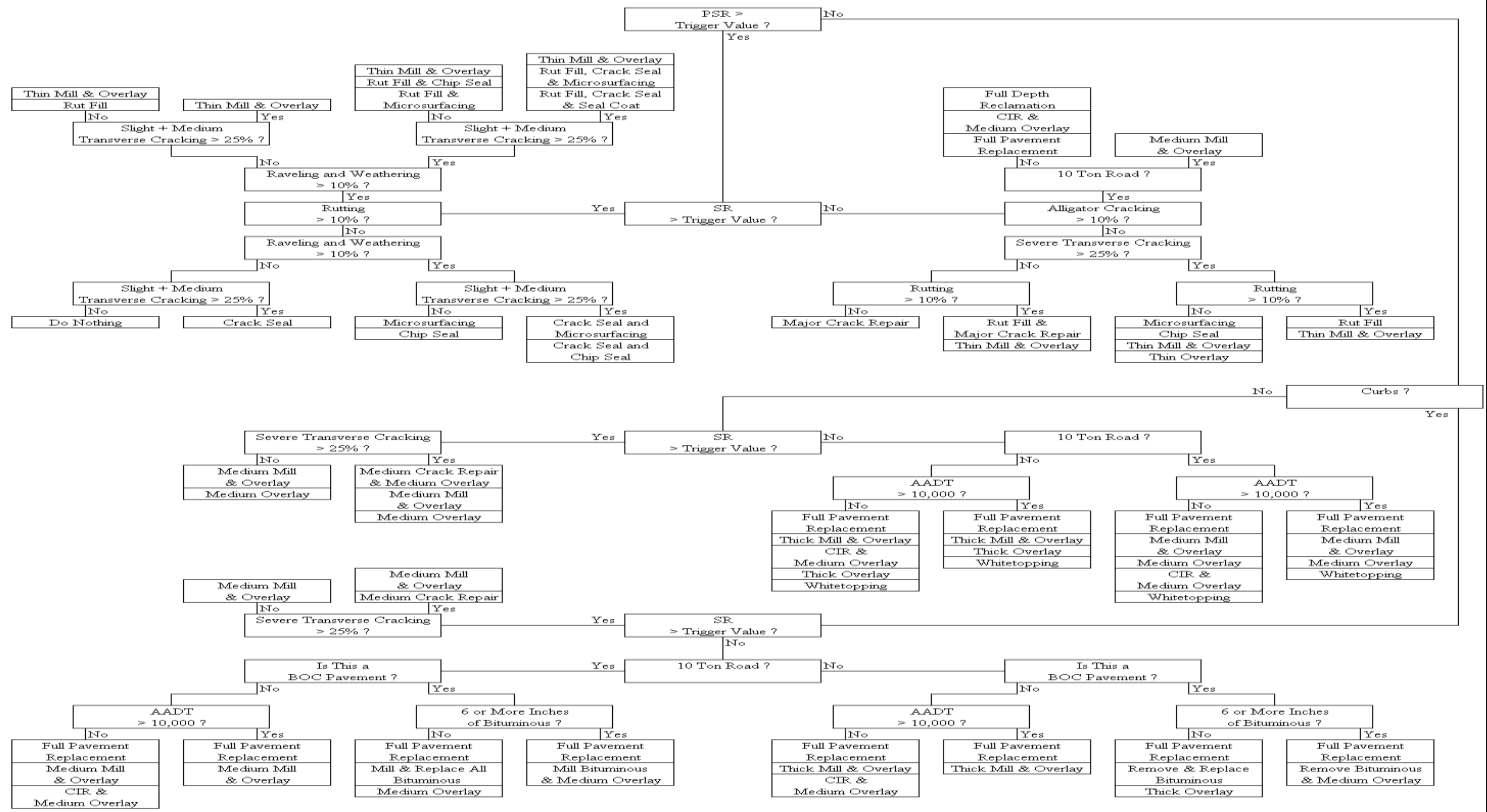


Figure 2.19: Appropriate Technologies for Rehabilitation of Sewer



Functional Classifications	Trigger Values PSR	SR	PQI
Rural Principal Interstate	3.0	2.7	3.0
Rural Principal Arterial	3.0	2.7	2.9
Rural Minor Arterial	2.8	2.5	2.8
Rural Major Collector	2.8	2.5	2.6
Rural Minor Collector	2.8	2.5	2.6
Rural Local	2.7	2.4	2.6
Urban Interstate	3.1	2.7	3.0
Urban Principal Arterial Freeway	3.1	2.7	2.9
Urban Principal Arterial	2.8	2.5	2.9
Urban Minor Arterial	2.7	2.4	2.8
Urban Collector	2.6	2.4	2.6
Urban Local	2.5	2.4	2.6

List of Alternative Treatments

- Do Nothing
- Chip Seal
- Microsurfacing
- Crack Sealing
- Major Crack Repair
- Rut Fill

- Thin Overlay (2 in or less)
- Medium Overlay (between 2 and 4 in)
- Thick Overlay (over 4 in)

- Thin Mill and Overlay (2 in or less)
- Medium Mill and Overlay (between 2 and 4 in)
- Thick Mill and Overlay (over 4 in)
- Remove and Replace All Bituminous
- Remove All Bituminous and Medium Overlay

- Crack Seal and Chip Seal
- Crack Seal and Microsurfacing

- Rut Fill and Chip Seal
- Rut Fill and Microsurfacing
- Rut Fill and Major Crack Repair
- Rut Fill, Crack Seal and Chip Seal
- Rut Fill, Crack Seal and Microsurfacing

- Major Crack Repair and Medium Overlay
- Cold In-Place Recycling (CIR) and Medium Overlay
- Full Depth Reclamation
- Whitetopping
- Full Pavement Replacement

Figure 2.20: Network Level Decision Tree for Bituminous Pavements – Minnesota DOT (Hicks et al., 2000)

In the area of automated decision support systems the need to assess the suitability of constantly changing technologies creates the need for a resource capable of evaluation and selection of appropriate methods. To address to that need, the Trenchless Technology Center (TTC),in collaboration with the National Utility Contractors Association (NUCA), Australasian Society of Trenchless Technology (ASTT), and National Association of Sewer Service Companies (NASSCO), has developed an interactive software for the evaluation of more than 70 technologies that can be employed in the installation, replacement, and rehabilitation of buried water and wastewater pipes (i.e., gravity driven and pressurized) or manhole structures. The fully automated decision support system (DSS) can be accessed through a Web-portal named the Trenchless Assessment Guide for Rehabilitation (TAG-R) online. This paper presents the Web-based tool TAG-R and three case studies used as part of the validation of the DSS. Matthews and Allouche (2012) presented a paper that described the TAG-R and discussed three case studies as part of the validation of this DSS.

The DSS however, does not consider pavement segments. Besides, tt is primarily based on the technical attributes data and does not directly take into account the condition of the segment. Gross approximation about pipe condition is done, as only two states are assumed either partially deteriorated or fully deteriorated. The final selection criteria are also mainly based on practicality feasibility assessment of the techniques expressed in terms of a risk score.

2.7 Gaps in the Existing Body of Knowledge

Findings of the thorough review of literature on the topics related to the study presented in the preceding sections are summarised below:

- There is absence of a quantitative method or tool that transforms community expectation and preferences into level of service
- Absence of a quantitative tool or method that maps expected level of service to asset condition.
- There are variations in the interpretation / results of different condition rating protocols leading to different condition ratings for the same set of observations.
- Condition rating involves both qualitative and quantitative observations for which the most suitable approach is to use fuzzy logic based methods which need to be further developed and enhanced.
- Most of the DSS determine rehabilitation alternatives are based on overall condition grade. Rarely any research considers the individual distress measures while selecting the most suitable/optimum option.

It was also highlighted that due to a number of prevailing factors such as aging infrastructure, political priorities towards new constructions, curtailment of maintenance budgets, growing demands, enhanced public expectations and stricter environmental regulations, infrastructure owners in most of the developed countries are facing difficulties in maintaining their asset inventory at a satisfactory condition. It was also observed that this situation has generated certain needs and to fulfil those needs efficient solutions are to be evolved. Figure 2.21 summarises the scenario.

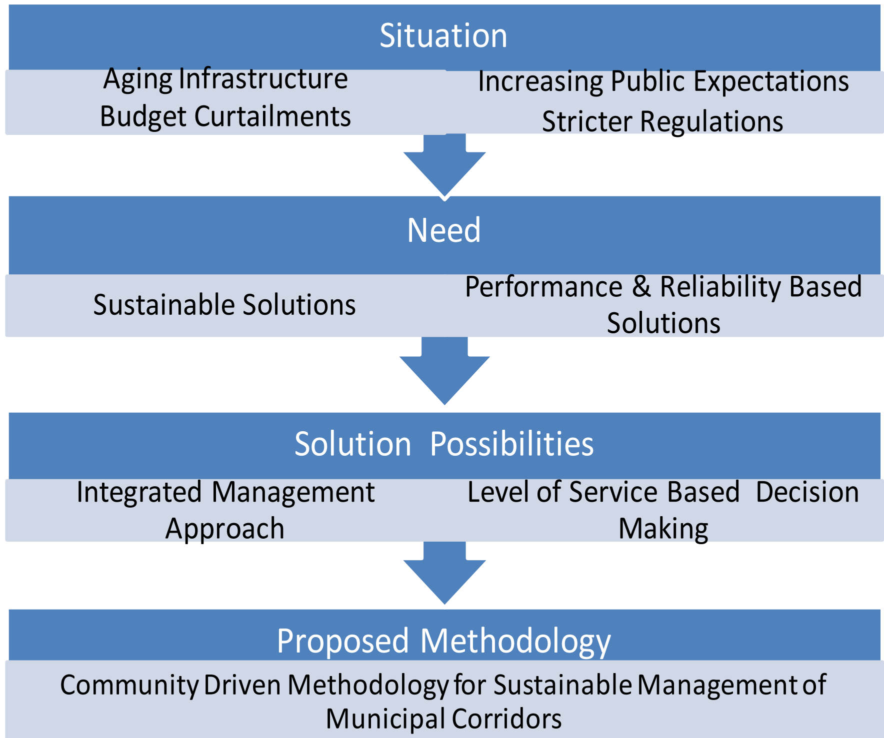


Figure 2.21: Rationale behind the Proposed Methodology

The methodology developed is going to address all the gaps as identified above.

CHAPTER 3: PROPOSED METHODOLOGY

3.1 Introduction

The current critical situation of municipal infrastructure calls for sustainable and performance based solutions. As per common understanding in this research also, "Sustainable Solutions" are defined as those which are technically adequate, cost effective and have the least possible social and environmental impacts. This research introduces level of service based integrated management framework to deal with the situation. The research is organised as shown below:

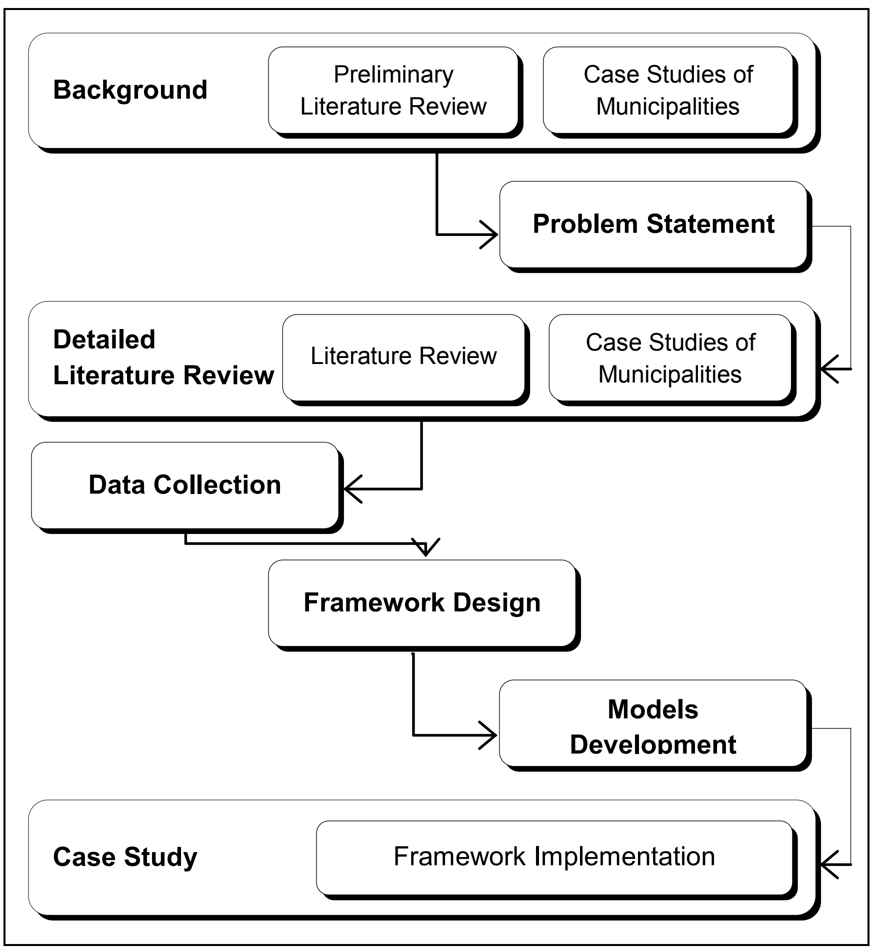


Figure 3.1: Research Organisation

Back ground information and review of relevant literature has already been presented in the preceding sections. Scope and objectives of the research, its conceptual framework, models development and their implementation by a case study are described in following chapters.

3.2 Overview of the Proposed Methodology

The overall research methodology encompasses five distinct parts. These parts are expressed by numbers in the schematic diagram of the methodology presented at Figure 3.2. The legend below identifies these parts of the overall methodology:

Part 1: Back ground knowledge and problem identification

Part 2: Review of related literature / consultation with industry professionals to identify gaps in the body of knowledge and to establish the research scope and objectives

Part 3: Framework development comprising of the following three phases along with their respective models:

Phase I - Performance Modeling and Quantification of Condition Improvement

Phase II - Integrated Need Based Corridor Prioritization

Phase III - Corridor Optimised Work Plan

Part 4: Implementation of the developed methodology utilizing a case study

Part 5: System Outputs - Corridor Work Plan

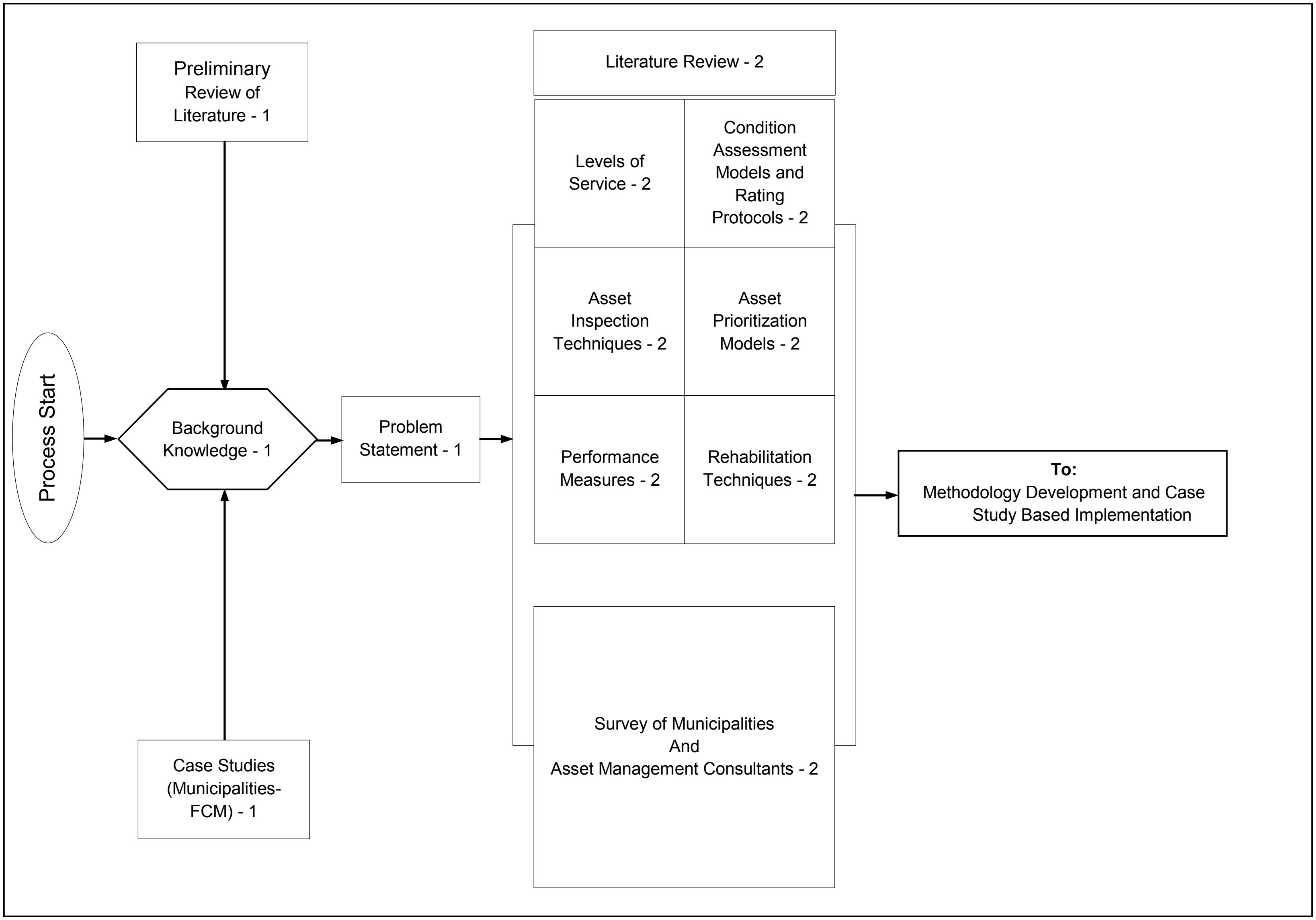


Figure 3.2: Overall Research Methodology (Problem Identification and Theoretical Background)

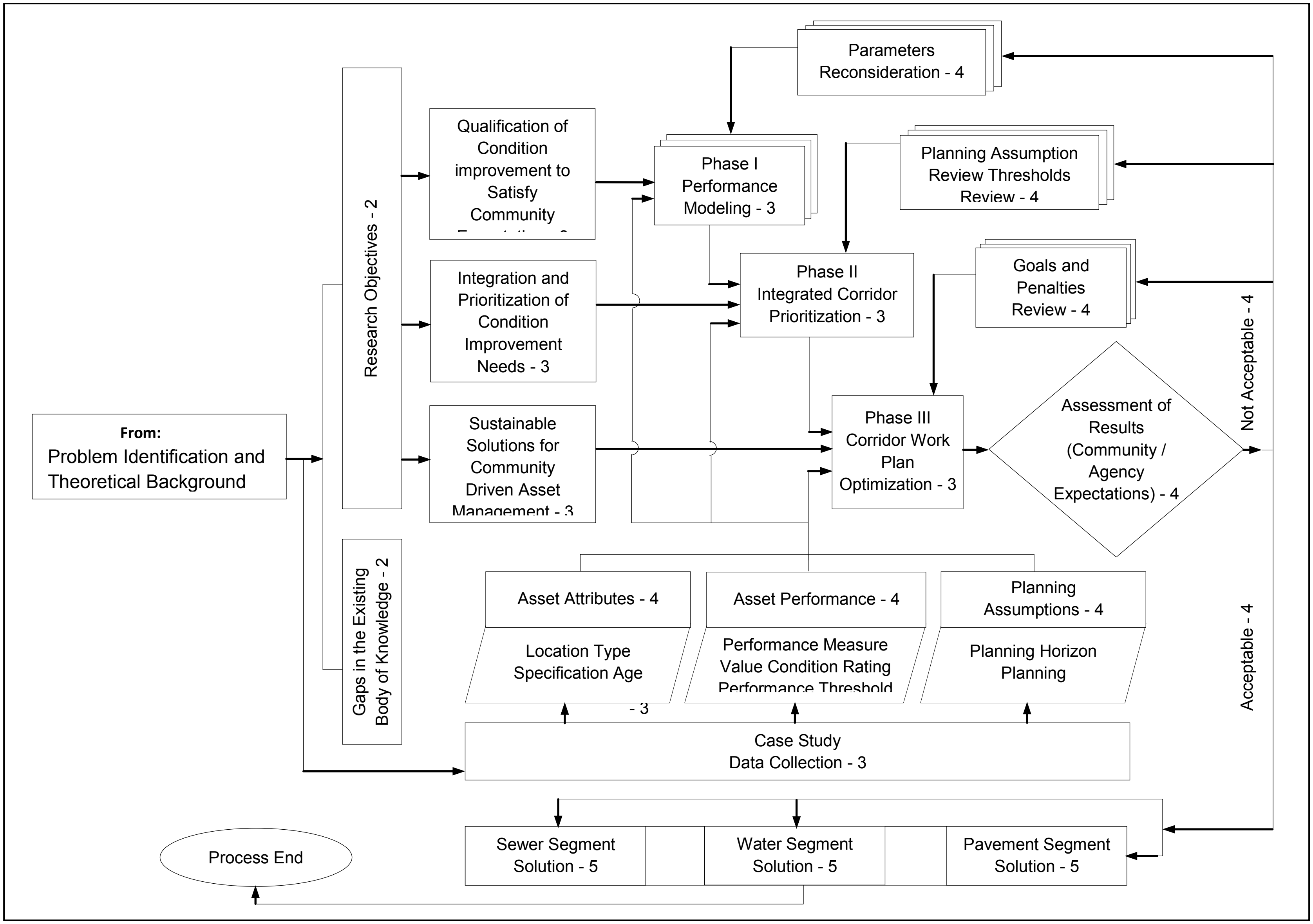


Figure 3.21: Overall Research Methodology (Methodology Development and Case Study Based Implementation)

In the following sections, brief introduction of the concept of each of the three phases of the part 3 and their models are briefly described:

3.3 Phase 1: Performance Modeling and Quantification of Asset Condition Improvement

As briefly mentioned earlier, the models designed and built in this phase are to quantify condition improvement requirements to meet the community desired level of service. The developments are briefly introduced below:

3.3.1 Scaling Asset Condition and Performance

For each of the three asset types, performance indicators and the performance measures under these indicators are identified. Thereafter, the possible distribution of their values for level of service and condition are each graded into five classes. This scaling recommended in the developed methodology is based on extensive review of literature in the domain and the best practices reported by platforms such as InfraGuide Canada and Federation of Canadian Municipalities (FCM). For the practical implementation of the methodology, agencies are suggested to develop their own scaling in consultation with respective communities, keeping in view their preferences and needs.

3.3.2 Quantification of Asset Level of Service (AHP Based Level of Service Model)

In order to express and measure existing and desired level of service rendered by an asset, Analytical Hierarchy Process (AHP) based model of Asset Level of

Service is developed. AHP is considered appropriate for that purpose as it can account for the both the quantitative as well as qualitative measures that are involved in level of service description. AHP is utilized in this research rather than Multi Attribute Utility Theory in view of its simplicity in the development of related utility functions.

The community can be engaged in determining the level of service in a number of ways. Two more direct ones are to conduct town hall meetings in different districts / sectors to assess public expectation on asset performance and its willingness to pay for it. The second is to circulate simple questionnaire, asking them to score their relative preference on different measures of performance. This can be converted to relative weights to perform the analytical hierarchy process to determine the required level of service score.

3.3.3 Quantification of Asset Condition

(Fuzzy weighted average Model of Asset Condition Rating)

To establish condition rating of the assets based on performance measure values, a Fuzzy weighted average Model of Asset Condition Rating is developed. Fuzzy logic based approach is used to account for the subjectivity and uncertainty involved in transforming asset inspection observations into condition assessment.

3.3.4 Mapping Level of Service to Asset Condition

(Fuzzy Alpha Cut Based Condition-LoS Mapping)

In order to map the existing and desired level of service to the corresponding condition of the asset a Fuzzy Alpha Cut based function is utilized. Since the mapping has to relate the level of service scores to a fuzzy weighted average condition rating, the fuzzy logic based 'α' cut theorem is considered most suitable for this purpose. This mapping enables user to quantify the improvement in asset condition, required to raise the level of service of the asset from the existing to the desired one.

The schematic of Phase I of the methodology is given in Figure 3.3:

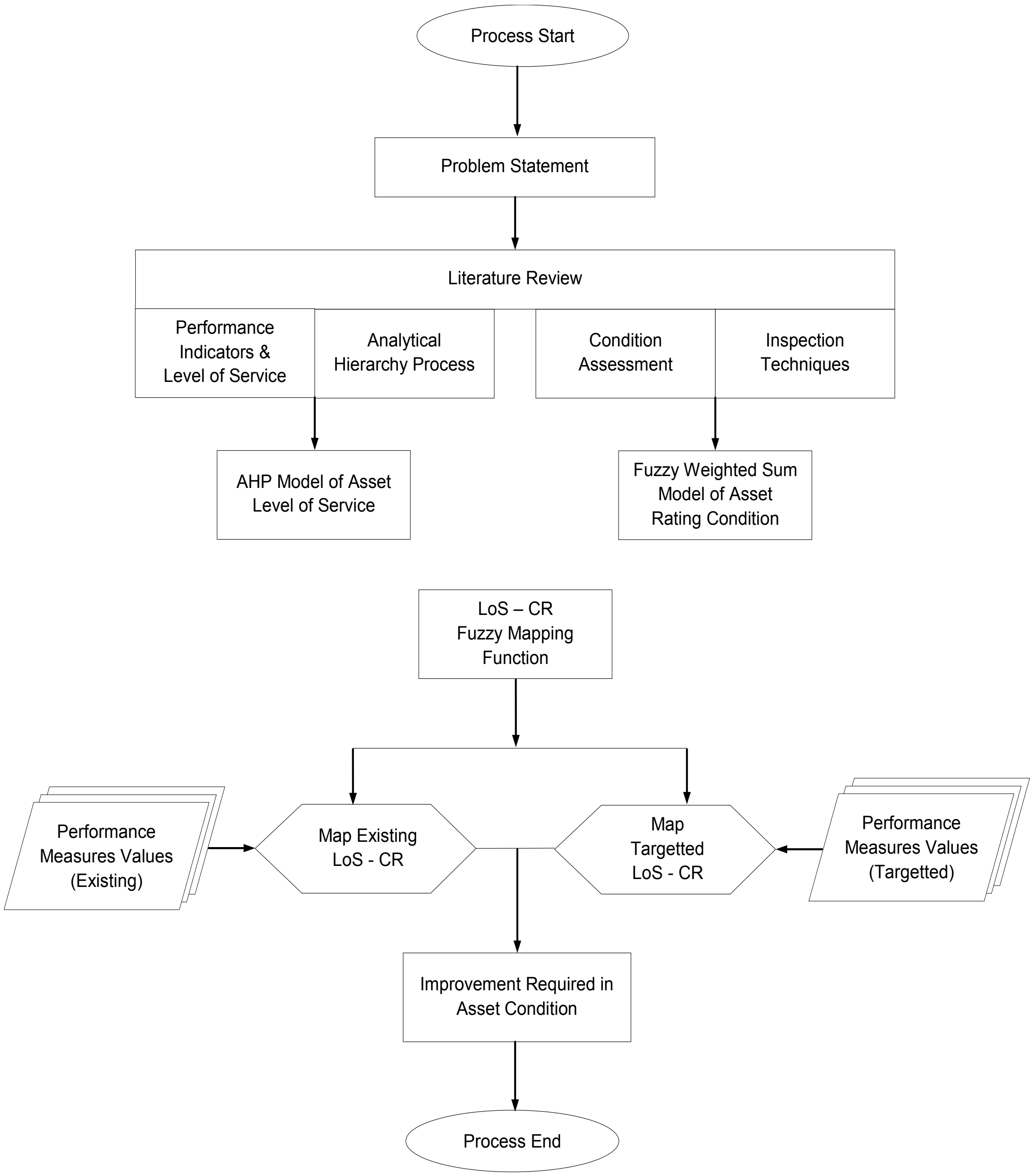


Figure 3.3: Schematic of Phase I - Performance Modeling and Quantification of Condition Improvement

The process starts with the identification of performance measures and setting their desired levels and minimum acceptable thresholds. This is done for all the three asset classes (water, sewer and roads). Based on the selected performance measures, Analytical Hierarchy Process based Model is developed to express and measure level of service / community expectation, in terms of Service Percentile. This is followed by setting a scale from 1 to 10 to express the condition of the assets. A generic Fuzzy weighted average model is designed to establish asset condition rating. Further, by developing a Fuzzy logic based, LoS – CR Mapping Function that uses the same performance measures on both sides of the equation, the desired asset level of service is mapped to the required condition of the asset. This is done for both the existing and targeted situations. All these models provide qualitative as well as quantitative estimation of the different concerns for an asset. The comparison of the output for existing and desired / targeted values, quantifies the improvement required in each asset type of the corridor.

3.4 Phase II: Integrated Need Based Corridor Prioritization

The output of Phase I, in terms of the quantitative values of condition improvements is used as one of the inputs to this phase. The process starts with the identification of corridors, followed by an integrated criticality assessment of corridors which ultimately leads to the determination of the integrated prioritization of corridors for rehabilitation purpose. The following generic rules and models are developed in this Phase II of the methodology:

<u>Identification of Municipal Corridors</u> - Generic rules are suggested for demarcating / identifying the corridors containing the three asset categories of pavement, water and wastewater.

Asset Criticality Model - Parameters pertaining to the criticality of the three asset types are identified and a combined score of the criticality of the corridor as a unit is determined. Since a straight forward scale of criticality could be defined for individual factors so a simple weighted average model serves the purpose of determining the integrated criticality score of the corridor.

Artificial Neural Network Based Model of Corridor Prioritization - Outputs of Phase I (condition improvement requirement) and the output of the criticality model (criticality scores of the corridors), serve as inputs to this model. Artificial neural network model is designed and trained to establish the integrated prioritization rank of each candidate corridor. Unsupervised Neural Networks have the proven capability to cluster given data into desired number of groups (Neuroshell2 1996). This is done based on the weights and values of the governing factors in an adequate number of historic patterns. Kohonen Architecture of Unsupervised Neural Network is used to train a model that clusters the corridors into five priority groups.

Schematic diagram of the process of this phase is presented in Figure 3.4, followed by a brief description of the developments of this phase:

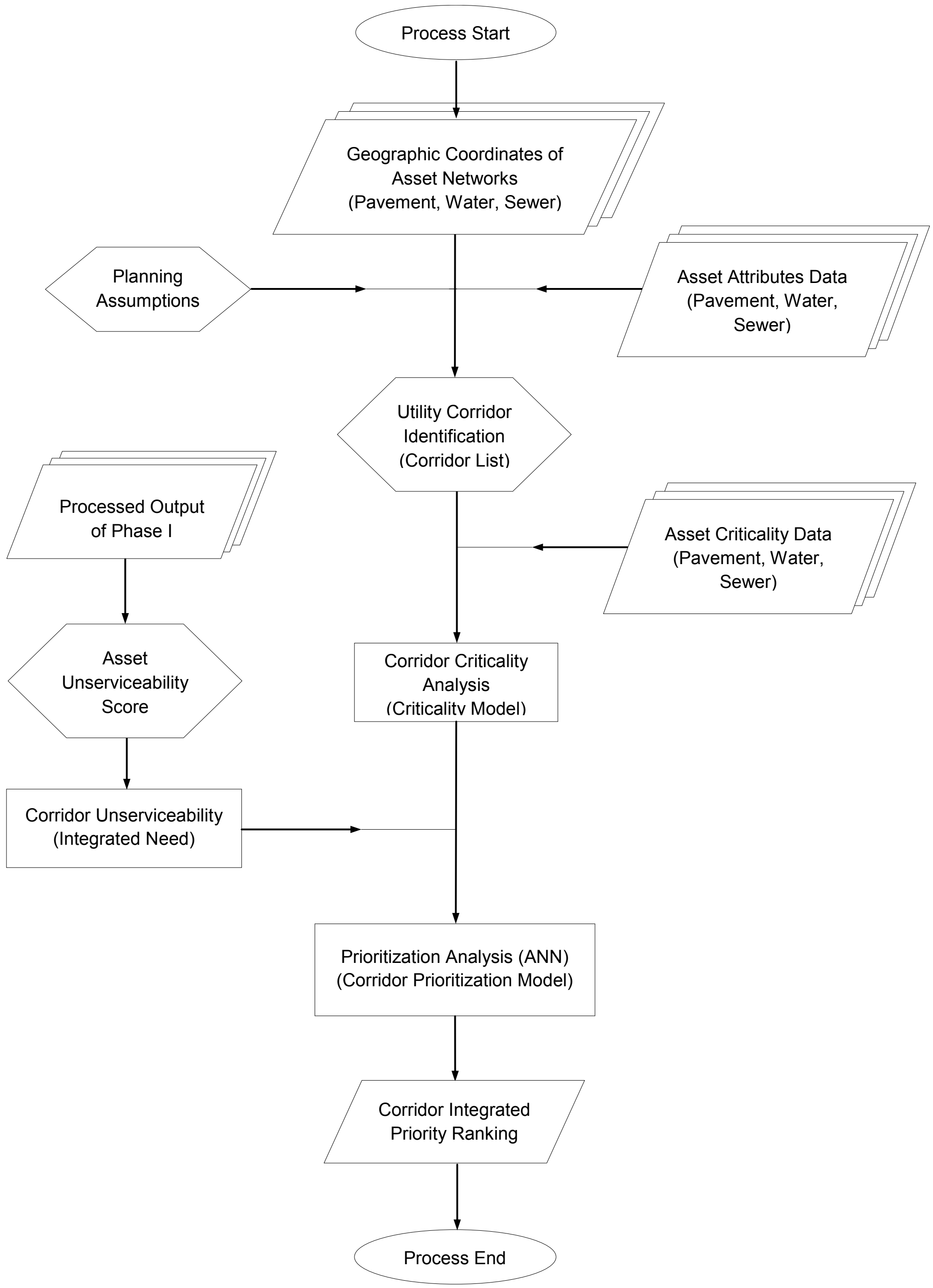


Figure 3.4: Schematic of Phase II - Integrated Need Based Corridor Prioritization

3.4.1 Identification of Integrated Municipal Corridors

Important here is to point out that not every corridor in a network is suitable for integrated management. The primary objective behind integrated management is to take the benefit of avoiding rework and repetition of certain tasks. However, if due to any spatial and/or temporal facts, related to the assets that are co-existing in a corridor, a rework scenario is not generated, there would be no rationale in that case to essentially do integrated management. In order to perform integrated management, it is necessary to assess the coexistence of municipal assets in a municipal corridor, alternatively called as Right of Way (ROW). A photographic depiction of a typical municipal corridor is here in Figure 3.5.

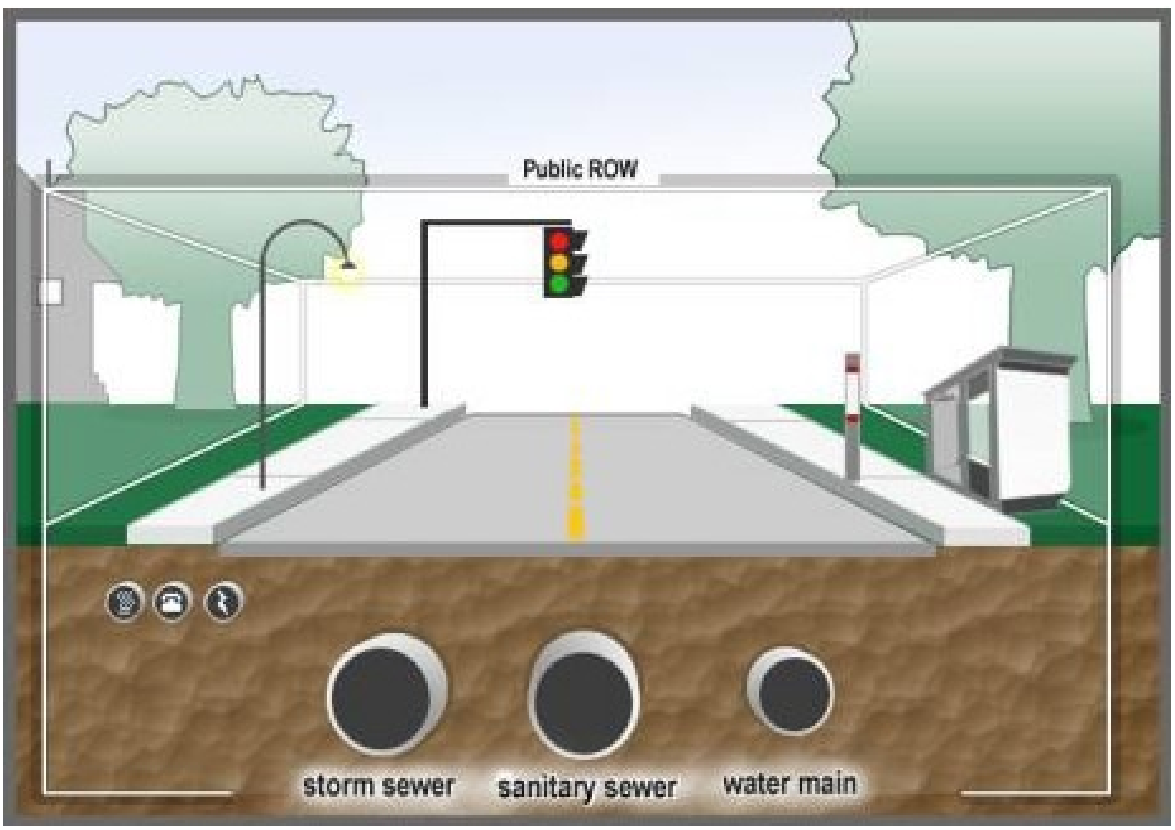


Figure 3.5: Animation of a Typical Municipal Utility Corridor
(InfraGuide E-Learning Tools 2013)

In this research, in order to assess a corridor for integrated management, an analogy is derived from the concept of buffers of linear assets provided in ArcGIS. In GIS terminology, buffer of an asset is the width of its right of way. This width may vary, as in the case of water and sewer mains it depends on asset size i.e. diameter, whereas in case of roads it is the pavement width and its shoulders. Quite often, additional widths may also be required. In case of open cuts for water and sewer, additional allowances may also be provided depending on the soil conditions and the working space, required to execute the intervention. However, for roads the buffer is actually the right of way and it depends upon the type and the category of the road segment. Figure 3.6 below gives an idea of the water main buffer (blue) which is overlapped by the road buffer (grey).

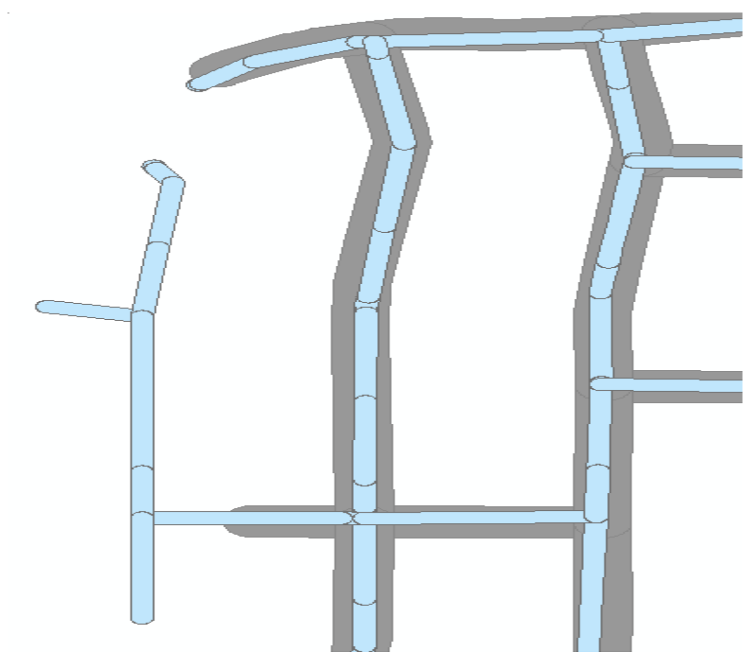


Figure 3.6: Asset Buffers

The impact of the rehabilitation technique of one asset on the selection of the techniques for the other two assets is accounted for to a certain extent in the time space concurrence matrix. Here the corridor is evaluated from the aspect of whether any of the interventions would require corridor excavation. This influences the decision of doing integrated or non-integrated rehabilitation. However, more detailed analysis to identify the technical inter-dependencies of different techniques shall be done and is proposed as a potential future research topic.

For integrated management, the spatial and temporal concurrency of the intervention on road with any of the other two assets needs to be investigated. In this research time concurrence is said to exist if, there is improvement in the condition of two or more assets is required during the year under consideration, irrespective of the magnitude. Spatial co-existence occurs when the buffers of two or more assets, overlap each other. The decision of integrated management for a corridor is suggested to be governed by certain rules, as referred in Figure 3.7 below:

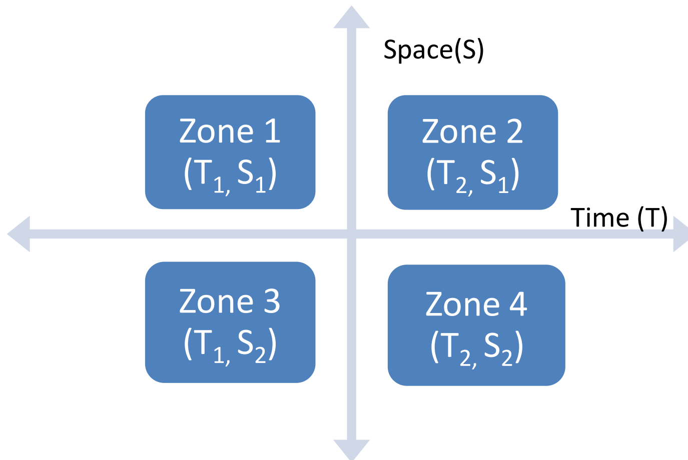


Figure 3.7: Possibilities of Time and Space Concurrence of Interventions

Zone $_k$= (T_i, S_j), where i = 1…….m and j = 1…….n ……………………..Eq. (3.1)

Taking Road = R_d, and Other Utility (Water / Sewer) = W/S

Rule Base 1:

IF

R_d = Zone $_k$= (T_i, S_j) and S/W = Zone $_l$= (T_p, S_q) …. ……………Eq. (3.2)

AND IF

i=p and j=q

THEN

The Corridor a Candidate of Integrated Management

And IF

R_d = Major Rehabilitation

AND (OR)

W/S = Open cut

THEN

<u>Integrated Management</u>

OTHERWISE

Non- Integrated

Establishing a unified criteria for the length of the corridor can be challenging; for it can vary from one municipality to another. The complication arises from the fact that assets of buried networks (water and wastewater) have different lengths and the spatial coordinates of their assemblies / connections (joints) hardly match.

3.4.2 Integrated Assessment of Corridor Criticality

(Weighted Score Model of Corridor Criticality)

The integrated criticality of each corridor is determined here which is the combined criticality score of the three asset types, considered jointly. In all a set of six criticality factors pertaining to network, sub-network, corridor and asset levels is considered. This set comprises of population density, tax base, level of complaint, sub-network type, spatial co-existence and asset size. A simple weighted score approach is used to determine the integrated criticality score of corridors.

3.4.3 Integrated Prioritization of Municipal Corridors

(**Artificial Neural Network Model of Corridor Prioritization)**

The criteria / factors governing corridor integrated prioritization consist of the un-serviceability of the assets in the corridors, and their relative criticality scores. Un-Serviceability is determined from the quantitative value of condition improvement required in each asset type obtained from Phase I, whereas criticality scores is the output of the corridor criticality model. The concept is graphically presented in Figure 3.8.

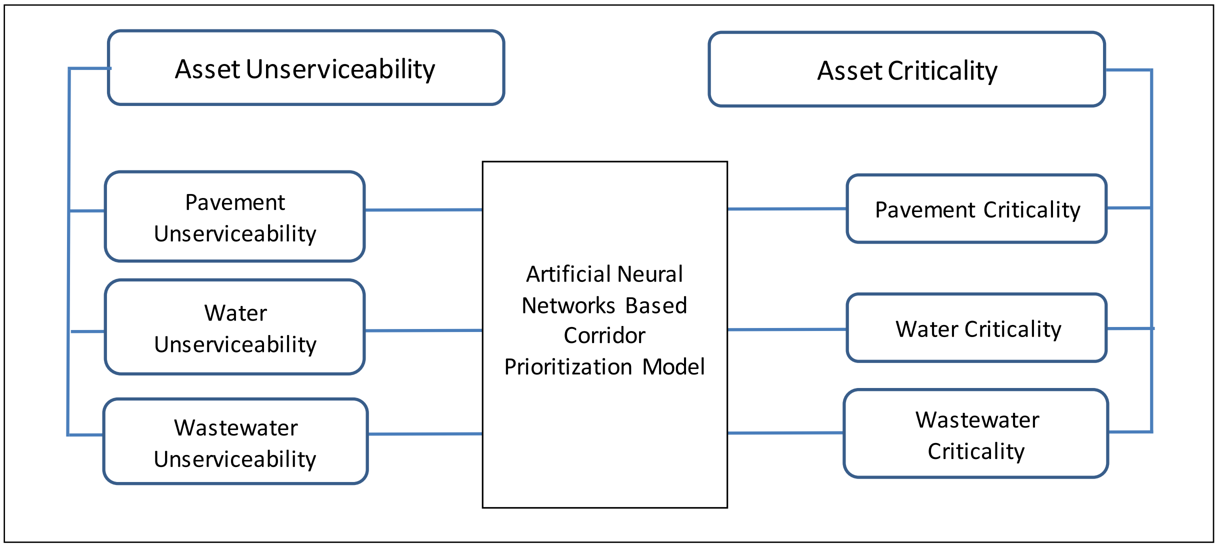


Figure 3.8: Structure of the Corridor Prioritization Model

In this stage of the methodology once again the three assets i.e. water, wastewater and road are jointly processed. In order to reflect on the needs and preferences during prioritization, the same relative weights of the three networks are used as were determined during criticality analysis. Un-serviceability is the complement of the water main level of service and is determined as:

Un-serviceability Percentile = 1 – Serviceability Percentile ……………...Eq. (3.3)

Based on the community and agency preferences, weights of relative importance can be assigned to the two criteria.

3.5 Phase III - Corridor Optimised Intervention Plans

In this phase the outputs of all the previous phases are organized and are augmented with information on asset rehabilitation/ intervention alternatives (IAs) to provide feasible solution space for the developed optimization model. The information sent from phases I and II has already been discussed. Phase III consists of the following two processes:

3.5.1 Identification of Feasible Alternatives for Asset Rehabilitation:

Based on thorough review of literature on municipal asset rehabilitation techniques and the material published by manufacturers and service providers related to maintenance and rehabilitation of pavement, water and waste water assets, ready references in the form of matrices are prepared for identifying feasible options for asset rehabilitation.

3.5.2 Developing the Corridor Optimum Work Plan

A Discrete Non Pre-emptive Goal Programming based optimization model is designed to select the optimum solution for each asset type, thereby constituting the Optimum Work Plan of the Corridor. Since the optimization criteria consider multiple objectives, goal programming is applied to individually select the optimum rehabilitation technique for each asset. The solution approach was customised, as the problem could be solved by simply ranking the alternatives based on their respective penalty scores.

The schematic of Phase III can be referred at Figure 3.9.

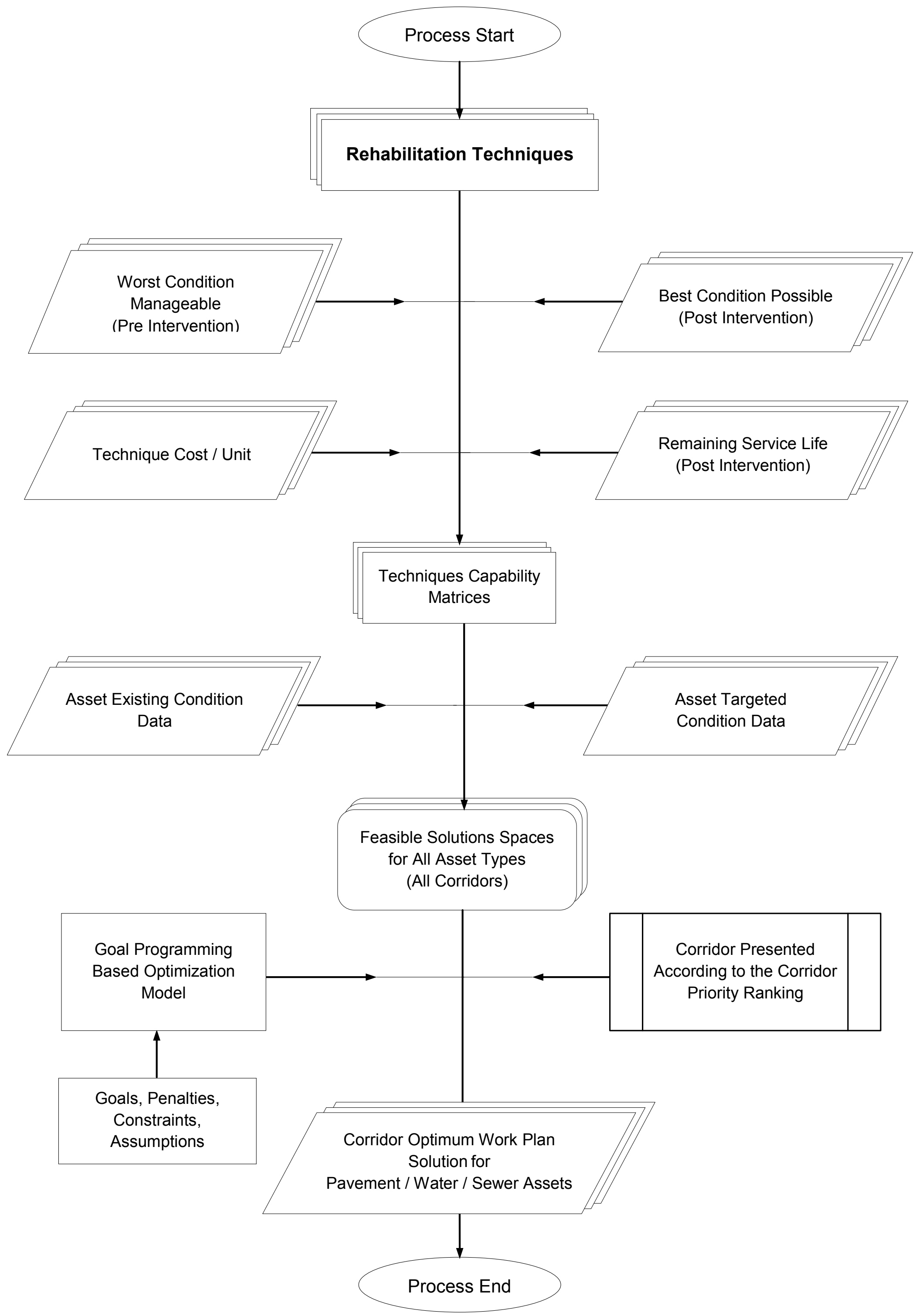


Figure 3.9: Schematic of Phase III -Corridor Optimized Work Plan

In the first process, analysis is done for each of the three asset types. It is a multistage analysis, each stage of which yields a matrix giving certain information about selecting rehabilitation techniques, according to asset requirement. In all three matrices, one of each asset type is composed of rehabilitation techniques versus performance measures. For each asset type, initially the main rehabilitation techniques of all categories (structural, semi structural and maintenance) are listed and the applicability of each technique on each performance measure is checked. This matrix is called “Applicability Matrix”.

In the second stage, the capabilities of all the applicable technique are determined. This gives two values for each technique against each performance measure. The first one represents the worst condition rating value at which the technique can be applied to fix that particular performance measure. The later value represents the best or the post application condition rating of the asset for that performance measure. This matrix is termed as “Technique Capability Matrix”.

Finally the capabilities of the techniques are compared to the actual requirement of condition improvement i.e. the existing asset condition is compared to the technique’s capability to address the worst condition and the asset targeted condition is compared to the techniques post intervention condition. If both cases are satisfied by the techniques for all performance measures only then the technique is included in the set of feasible alternatives. Feasible alternatives are stored in” Feasibility Matrices”

The last process of the developed methodology is the selection of the set of optimum techniques, comprising of the one optimum technique for each asset type. Optimization criteria include asset condition improvement, unit cost of rehabilitation and post intervention remaining service life. All feasible techniques for each of asset type are tested under these criteria and the one with least penalty points is selected as the optimum option. The optimum options of the three asset types leads to the Corridor Optimized Work Plan.

Table 3.1: Types and Level of Analysis of Developed Models

Model / Analysis	**Level of Analysis**			
	Network	**Sub-network**	**Corridor**	**Asset**
Performance Indicators & Measures	Certain	Certain	x	Asset Specific
Level of Service Model	x	x	x	Generic
Condition Rating	x	x	x	Generic
LoS- CR Mapping	x	x	x	Generic
Corridor Identification Rules	x	x	Generic	X
Corridor Criticality	x	x	Generic	x
Corridor Prioritization	x	x	Generic	x
Techniques Feasibility Matrices	x	x	x	Asset Specific
Optimization Model	x	x	Generic	x

It should be noted that the identification of performance measure and rehabilitation techniques are asset specific to logically serve their purpose whereas all models of the developed methodology are generic in nature and can be customised, as needed. They work at asset and/or corridor levels.

3.6 Assumptions and Limitations

The assumptions made in this research pertain to the time units of planning and are given as follows:

- Roads - 5 years
- Water - 15 years
- Wastewater - 15 years

The limitations on the other hand are:

- Considerable pre-processing of collected data. This is because acquisition of data from agencies in the formats that could be used directly is often difficult.
- Consideration of accessories' condition identical to the pipe segments they are connected to.

In cases where the condition of accessories are worse than the pipe itself, there may be practical complications such as unexpected failure or the asset falling short of the required performance levels.

The research was guided by the hypothesis that integration of the three primary utility assets governed by the concept of corridor rehabilitation would lead towards sustainable cost-effective solutions to asset rehabilitation problems. This has been achieved in the case study implementation of the framework in which the results of the methodology met the expectation of the community with lesser agency direct and community indirect costs as compared to the conventional approach. However, more cases need to be analyzed to substantiate the hypothesis.

CHAPTER 4: DATA COLLECTION AND CASE STUDY

This chapter discusses data related details in line with the models described in Section 3.2 of Chapter 3. To organize data collection, the requirements are classified according to certain criteria, such as stakeholder and the frequency of data update/collection. Acquisition of this data for implementation is thereafter discussed. Finally, a case study selected for demonstrating the implementation of the methodology is described. Parts of the data pertaining to the selected case study that is obtained from the municipality of Riyadh, KSA are highlighted.

4.1 System Inputs and Outputs

As described in the earlier chapters, the developed framework has three phases each consisting of various models. Accordingly, each phase has distinct inputs and outputs as shown in Figure 4.1. In most of the cases, the outputs of the preceding phase serve as inputs to the following phase. All developments are implemented in Microsoft Excel environment. Each phase is a standalone application but all of them can be amalgamated into one automated decision support system.

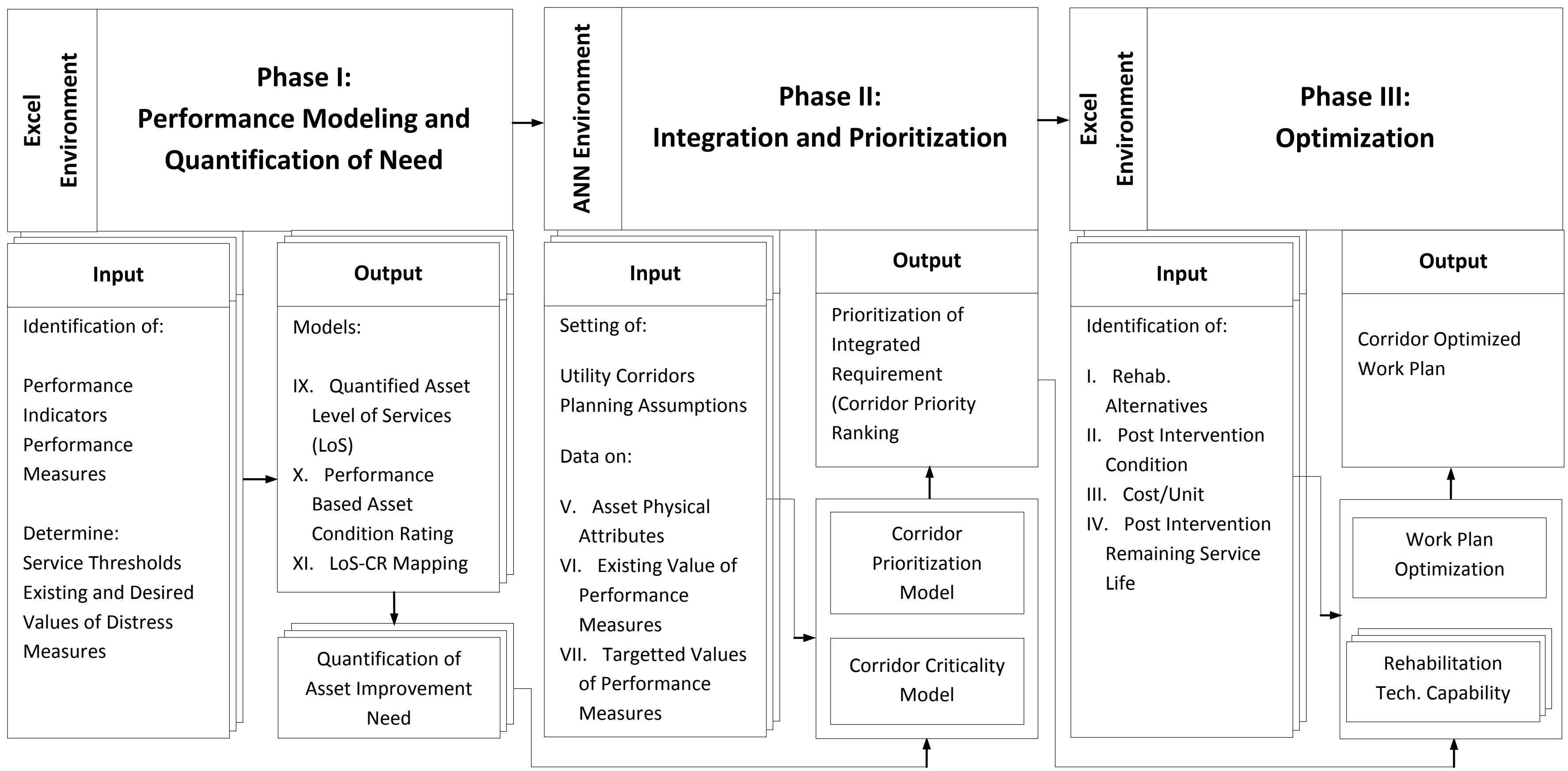


Figure 4.1:Inputs and Outputs of the Three Phases of the Developed Framework

4.2 Framework Data Requirements:

Acquisition of data involves both the municipal agency and the community. The community shall make preference related to levels of service as well as funding / budget decisions. The agency shall conduct inspection and site data collection, do the technical decision making and shall coordinate with community to obtain community related decisions. Explanation of the information organized in Table 4.1 is as under:

Data Item: The items of information needed to setup the framework or to run the subsequent decision cycles.

Methodology Reference: This refers to the specific phase of the developed methodology in which a particular item of information is required.

Data Source: It indicates the source of data or the party responsible to provide it.

Update Frequency: The frequency or the point of time in the asset management routine when the data is to be obtained / updated or decision / selection is to be made.

Item Type: The required data items are of different nature. Some are decisions to be made by the stakeholders; some items are the selection from a range of choices. Some are data to be retrieved from asset inventory and others are data collected by inspection. This column guides on how the data is generated.

Table 4.1: Attributes of Required Data

Data Item	Methodology Reference	Date Source	Update Frequency	Item Type
Identification of Performance Indicators and Performance Measures	Phase I: Performance Modeling and Quantification of Need	Agency/ Community	Once / Initial Setup	Selection/ Choice
Determining Service Thresholds		Community/ Agency	Once / Initial Setup	Decision
Existing Values of Performance Measures		Agency	Repeated / Every Decision Cycle	Inspection
Targeted Values of Performance Measures		Community/ Agency	Once / Initial Setup	Decision
Identification of Municipal Corridors	Phase II Need Based Corridor Prioritization	Agency	Once / Initial Setup	Data/ Decision
Planning Assumptions		Agency	Once / Initial Setup	Selection/ Choice
Data on Asset Physical & Technical Attributes		Agency	Once / Initial Setup	Inspection/ Data
Population Density (Network Level)		Agency	Initial Setup / Repeated In Case of Change	Data
Tax Base (Network Level)		Agency	Initial Setup / Repeated In Case of Change	Data
Level of Complaint (Sub-Network Level)		Agency	Repeated / Every Decision Cycle	Data
Sub-Network Type (Sub-Network Level)		Agency	Once / Initial Setup	Data
Asset Spatial Co-Existence Asset Size		Agency	Once / Initial Setup	Inspection/ Data
Optimization Parameters	Phase III: Optimized Work Plans	Community/ Agency	Initial Setup / Repeated In Case of Change	Decision
Targeted Remaining Service Life		Agency/ Community	Initial Setup / Repeated In Case of Change	Decision
Targeted Unit Cost		Community/ Agency	Initial Setup / Repeated In Case of Change	Decision
Penalty Points Criteria		Agency/ Community	Initial Setup / Repeated In Case of Change	Decision

4.3 Data Acquisition

The acquisition of data to run the system depends on two factors, the source and the type of information needed. There are two sources of data that are the agency and the community, whereas the types of data these sources generate include inspection data, records, selections or choices from a set of options and making decisions based on preferences and needs.

Governed by the preferences and needs a community is required to make broad or strategic level decisions. These include: 1) selecting performance measures 2) deciding the level of service according to which the targeted /desired values of those measures shall be set and the failure thresholds are to be fixed and 3) selecting optimization parameters, deciding limits of their values and penalties for optimised selection of rehabilitation alternatives. On the other hand, the agency has a set of activities and operational level decisions to make. These include: 1) facilitating the community in making its decisions as mentioned above 2) carrying out asset inspections to determine the existing values of performance measures and also the co-existence of assets for integration purpose 3) to collect data related to corridor configuration and asset criticality.

4.4 Case Study

In order to demonstrate the implementation of the methodology a case study is presented in Chapter (6). A sub-network of the Municipality of Riyadh – Saudi Arabia is used for this purpose. As being the capital of a country with abundant resources, the Riyadh municipal authorities are committed more towards performance oriented, level of service based asset management. On a North American scale of city sizes, Riyadh can be placed in the category of mid-size cosmopolitan cities, with its infrastructure easily comparable to any North American city of its size. An aerial view of Riyadh during day time is given at Figure 4.2.

Figure 4.2: Aerial View of Riyadh - KSA

Some salient features of the city of Riyadh are as under:

Table 4.2: Riyadh City Statistics - Year 2013

Population	5.7
No of Households	919,000
No of Housing Units	960,000
Total Urban Development Area	3,114 Sq. Km
City's Drinking Water Consumption	1.8 Million cum / Day
Total Road Network Size	12,850 km
Traffic Volume Counts	7.4 million trips Daily

(Source: High Commission for the Development of Ar-Riyadh KSA)

The Saudi Arabian urban infrastructure sector is booming with new projects but also has a parallel substantial volume of asset maintenance and rehabilitation work, in large cities just as Riyadh, Jeddah and Dammam.

The information needed to demonstrate the use and capabilities of the developed models comprised of a combination of data, opinions and feedback. This was gathered from M/s Zuhair Fayez Partnership (ZFP); leading engineering consultants in the GCC countries. The Asset Management Division of ZFP provides asset management consultancy services to several municipalities in Saudi Arabia. The division has several departments, more important among which are roads, water and wastewater departments. The feedback from these three departments was coordinated by the Divisional Director. In each department, the principal engineer in-charge reviewed the data and feedback provided by the respective municipal engineers, before forwarding it to the

Divisional Director. Geographic data of certain municipal corridors in the capital city of Riyadh was provided by ZFP.

4.4.1 Site Description

The corridors as referred in the above section belonged to four sectors the span and the geometry of which is shown in the Figure 4.3.

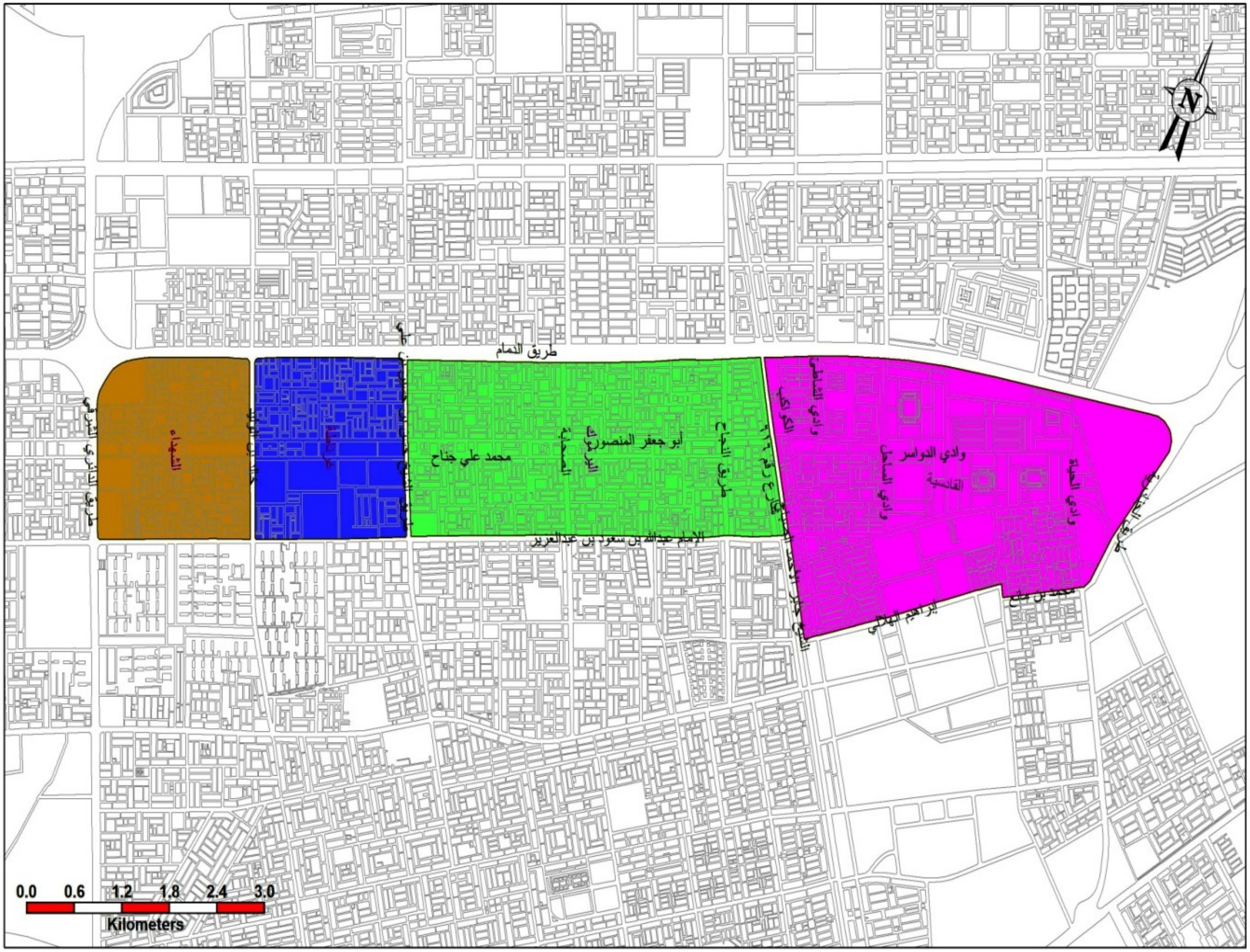


Figure 4.3: Span and Geometry of the Sectors Encompassing the Corridors Suggested for Study

As indicated in the Table 4.3, the four sectors are a mix of residential commercial and amenities services areas with population densities ranging from very high to medium. Area wise the largest sector is around 2.27 sq. kms whereas the smallest one is 0.7 sq. km

Table 4.3: Salient information about Sectors containing the Corridors under consideration

District ID	Sector Name	Area (Sq.m)	Type	Population Density
1	Yarmouk	2,271,826	Residential	Very High
2	Ghernata	782,476	Residential / Amenities	High
3	Qadesya	1,355,822	Commercial / Residential	Medium
4	Shohdaa	708,819	Residential / Commercial	High

4.4.2 Data Collection

The data and feedback required to implement the methodology comprised of the following *sets* of information:

1. As already described above, the first item was the geographic coordinate's information of a set of interconnected segments / corridors of a part of any municipal asset network. In this case, as referred in the previous section, data of a total of 95 corridors in the municipality of Riyadh, KSA was obtained. Out of that sample 30 had errors and / or were incomplete and 65 corridors were considered. Corridor ID No: 440249758M, with

geographic coordinators E680844.52 and N274138.35 was selected as the case study because it had all the representative attributes needed to demonstrate the implementation of the developed methodology in a detailed manner.

2. The second set of needed information pertained to the selection of performance measures that constitute the level of service and condition rating, the distribution of their values in different grades, their thresholds and the existing and targeted values of these measures for the assets of the selected segment.
3. The last set of information related to asset criticality and segment (corridor) prioritization.

The information required in first item was provided by the agency from their GIS data base. MS Access format files containing the geographic and physical attributes were provided. A snapshot of this file is placed in Appendix “C”. To obtain the second and third set of data / feedback, customised forms were prepared as shown in Tables 4.4 to 4.11. The agency was requested to do the following:

a. Give opinion about the suitability of suggested performance measures in measuring and quantifying level of service and condition rating (see columns 1 and 2 in Tables 4.4, 4.5, and 4.6).
b. Give opinion on the suggested distribution of these values into five different grades of service and condition as shown in columns 3 to 7 of Tables 4.4 to 4.9.

c. To suggest the threshold values of these measures. The values suggested by the municipality are shown in column 8 of Tables 4.4 to 4.9.
d. To provide actual or estimated values and suggested targeted values for the set of assets of the selected segment (corridor). This information provided by the agency is tabulated in columns 9 and 10 of Tables 4.4 to 4.9.
e. To suggest weights of factors and sub-factors for use in the developed criticality model (see rows 1, 2 and 3 of Table 4.10). Also to estimate values of the criticality parameters for the assets of the selected corridor, as shown in row 4 of Table 4.10.
f. To give suggestions on the developed optimization criteria for selecting the optimum technique of rehabilitation (see columns 1 to 6 in Table 4.11).

All collected data and feedback provided by the agency are highlighted as yellow shaded cells in the tables referred above. The collected data is used to develop the models presented in Chapter 5 and also to demonstrate the implementation of these models in Chapter 6.

This is to note in the level of service calculations, normalization of the values of Roughness Co-efficient (in water asset) and that of Pavement Marking and Skid Resistance (in pavement asset) is done in two steps. The value of the usual normalisation done on a scale of 0-1 in the first step is deducted from 1.0 in the second step. This is to reverse the scale, as for these performance (distress) measures, contrary to all other measures; a larger number implies better condition.

Table 4.4: Water Segment Performance Measures and Distribution of its Values in Different Levels of Service

Performance Indicator	Performance Measure	Range of Performance Measure for Different Levels of Service (LoS)					Service Thresholds	Existing Value	Targeted Value
		LoS 1	LoS 2	LoS 3	LoS 4	LoS 5			
1	2	3	4	5	6	7	8	9	10
Structural	Fracture / Crack Width (mm)	0.0 - 0.10	0.11-0.25	0.26-0.75	0.76-1.25	1.26 -1.75	1.0	1.0	0.0
	Sag (≤ 0.1 D mm)	0-5	6 - 10	11-20	21-25	26-30	20	10	10
	Corrosion (% Pipe Thickness Reduction)	0-0	1-10	11-35	36-60	61-85	60	60	10
Operational	Leakage Volume (Litres/Day/Km/in-dia)	0-5	6-50	51-100	101-200	201-300	150	150	10
	Roughness Coefficient (C-Factor) Range= (175 - 25)	175 - 126	125 - 101	100 - 76	75 -51	50 - 25	65	65	105
	Loss in Water Pressure (Psi) Household Supply Standard = 60 psi	0-5	6-10	11-15	16-20	21-25	25	25	15
Water Quality	Lead Concentration (% Threshold) (Action Level at 10 % + ve Sample for 0.015 mg/l) Range= (0 - 100)	0.0-0.002	0.003-0.005	0.006-0.008	0.009-0.010	0.011-0.015	0.009	0.009	0.006
	Iron Concentration (% Threshold) (Action Level at 10 % + ve Sample for 0.3 mg/l) Range= (0 - 100)	0-0.1	0.11-0.15	0.16-0.2	0.21-0.30	0.31-0.5	0.25	0.3	0.15
	Total Coliform Bacteria (% positive samples in a month)	0.0-1.0	1.1-2.0	2.1-3.0	3.1-4.0	4.1-5.0	1	2	0

Table 4.5: Wastewater Segment Performance Measures and Distribution of its Values in Different Levels of Service

Performance Indicator	Performance Measure	Range of Performance Measure for Different Levels of Service (LoS)					Service Thresholds	Existing Value	Targeted Value
		LoS 1	LoS 2	LoS 3	LoS 4	LoS 5			
1	2	3	4	5	6	7	8	9	10
Structural Reliability	Cracks / Missing Bricks (No. per meter of pipe segment)	0.0 - 1.0	1.1 - 3.0	3.1 - 4.0	4.1-5.0	5.1-7.0	4.1-5.0	5	2
	Open Joints (No per segment)	0-0	1-1	2-2	3-3	4-4	3-3	0	0
	Sag Depth (mm) (Per Segment)	0-50	51-75	76-125	126-150	151-200	126-150	50	75
Operational	Debris and Encrustation (% Reduction in Diameter)	0-5	6-10	11-15	16-20	21-30	16-20	20	10
	Root Intrusion (% Reduction in Diameter)	0-5	6-10	11-15	16-20	21-30	16-20	20	10
	Protuding Joints (% Reduction in Diameter)	0-5	6-10	11-15	16-20	21-25	16-20	5	10
Environmental	Infiltration (Intensity Scale)	0-0	1-1	2-3	4-5	6-10	2 - 3	10	2
	Exfiltration (Intensity Scale)	0-0	1-1	2-3	4-5	6-10	2 - 3	10	2
	No. of Pollution Incident	0-0	1-1	1-1	2-2	3-3	1 - 1	2	1

Table 4.6: Pavement Segment Performance Measures and Distribution of its Values in Different Levels of Service

Performance Indicator	**Performance Measure**	**Range of Performance Measure for Different Levels of Service (LoS)**					**Service Thresholds**	**Existing Value**	**Targeted Value**
		LoS 1	**LoS 2**	**LoS 3**	**LoS 4**	**LoS 5**			
1	2	3	4	5	6	7	8	9	10
Surface Related Comfort	Ravelling (Percent Surface Area) (Moderately rough surface texture, pitted)	0	≤ 5	≤ 15	≤ 25	≤ 40	≤ 30	≤ 40	0
	Longitudinal & Center line Cracking (Linear Meter / 100 Sqm) (Non-Filled crack width b/w 3/8 to 3 in)	≤ 0.5	≤ 1	≤ 2	≤ 3	≤ 4	≤ 3	≤ 3	≤ 0.5
	Pavement Edge Cracking (Linear Meter / 100 Sqm) (Non-Filled crack width b/w 3/8 to 3 in)	≤ 0.5	≤ 1	≤ 2	≤ 3	≤ 4	≤ 4	≤ 1	≤ 1
	Transverse Cracking (Linear meter / 100 sqm) (Non-Filled crack width b/w 3/8 to 3 in)	≤ 0	≤ 0.5	≤ 1	≤ 1.5	≤ 2	≤ 1.5	≤ 1.5	≤ 0
Structure Related Comfort	Alligator and Block Cracking (Percent Surface Area) (Network of Cracks)	≤ 1	≤ 4	≤ 8	≤ 15	≤ 25	≤ 18	≤ 1	≤ 1
	Corrugation (Percent Surface Area) (Vehicle Vibration, Speed Reduction)	≤ 0	≤ 0.5	≤ 1	≤ 3	≤ 10	≤ 3	≤ 3	≤ 0.5
	Rutting (Percent Surface Area) (1 to < 2 in)	≤ 0	≤ 0.5	≤ 2	≤ 5	≤ 10	≤ 3	≤ 3	≤ 0.5
	Pothole Density (Percent Surface Area) Min Plan Dimension = 6in, Min Depth = 2 in	≤ 0	≤ 1	≤ 3	≤ 5	≤ 10	≤ 6	≤ 0	≤ 0
Safety Concerns	Water Ponding (Percent Surface Area)	≤ 0	≤ 3	≤ 8	≤ 15	≤ 35	≤ 20	≤ 4	≤ 4
	Pavement Marking (White) (Retro Reflectivity Value)	≥300	≥ 275	≥225	≥ 150	≥ 100	≥ 150	≥ 150	≥ 275
	Skid Resistance (Skid No)	≥1.95	≥ 1.85	≥ 1.65	≥ 1.40	≥ 1.0	≥ 1.55	≥ 1.0	≥ 1.75

* -- The Normalized values are subtracted from 1 to change the order so that increase in normalized value implies increase in LoS

Table 4.7: Water Segment Performance Measures and Distribution of its Values in Different Condition Ratings

Performance Indicator	Performance Measure	Value Type	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
			A	B	C	D	E			
1	2	3	4	5	6	7	8	9	10	11
Structural	Fracture / Crack Depth (mm)	Description	None	Negligible	Slight	Moderate	Extensive	Moderate	Moderate	None
		Value	≤ 0.0	≤ 0.15	≤ 0.50	≤ 1.0	≤ 1.5	≤ 1.0	≤ 1.0	≤ 0.0
	Sag (≤ 0.1 D mm) For 6" Ductile Pipe	Description	Nil	Very Slight	Slight	Moderate	Extensive	Extensive	Slight	Slight
		Value	≤ 0.0	≤ 5	≤ 10	≤ 15	≤ 20	≤ 20	≤ 10	≤ 10
	Corrosion (% Pipe Thickness Reduction)	Description	Nil	Slight	Moderate	Extensive	Severe	Extensive	Extensive	Slight
		Value	≤ 0.0	≤ 10	≤ 35	≤ 60	≤ 85	≤ 60	≤ 60	≤ 10
Operational	Leakage Volume (Litres/Day/Km/in-dia)	Description	Very Slight	Slight	Moderate	Extensive	Severe	Extensive	Extensive	Very Slight
		Value	≤ 10	≤ 50	≤ 75	≤ 150	≤ 250	≤ 150	≤ 150	≤ 10
	Roughness Coefficient (C-Factor) Range= (125 - 50)	Description	Very High	High	Moderate	Low	Very Low	Low	Low	High
		Value	≥ 125	≥ 105	≥ 85	≥ 65	≥ 50	≥ 65	≥ 65	≥ 105
	Loss in Water Pressure (Psi) Household Supply Standard = 60 psi	Description	Very Low	Low	Moderate	High	Very High	High	High	Low
		Value	≤ 10	≤ 15	≤ 20	≤ 25	≤ 30	≤ 25	≤ 25	≤ 15
Water Quality	Lead Concentration (Action Level at 10 % + ve Sample for 0.015 mg/l) Range= (0 - 100)	Description	Very Low	Low	Moderate	High	Very High	Moderate	Moderate	Low
		Value	≤ 0.003	≤ 0.006	≤ 0.009	≤ 0.012	≤ 0.015	≤ 0.009	≤ 0.009	≤ 0.006
	Iron Concentration (Action Level at 10 % + ve Sample for 0.3 mg/l Range= (0 - 100)	Description	Very Low	Low	Moderate	High	Very High	High	Very High	Low
		Value	≤ 0.1	≤ 0.15	≤ 0.20	≤ 0.25	≤ 0.3	≤ 0.25	≤ 0.3	≤ 0.15
	Total Coliform Bacteria (% positive samples in a month)	Description	None	Rare	Few	Occasional	Often	Rare	Few	None
		Value	0	≤ 1	≤ 2	≤ 4	≤ 5	≤ 1	≤ 2	0

* -- A value of 1.0 is subtracted from the normalized value change the order so that lower normalized value corresponds to lower number of condition rating implying better condition

Table 4.8: Wastewater Segment Performance Measures and Distribution of its Values in Different Condition Ratings

Category	Performance Measure	Value Type	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
			A	B	C	D	E			
1	2	3	4	5	6	7	8	9	10	11
Structural	Cracks / Missing Bricks (No. per meter of pipe segment)	Description	None	Negligible	Slight	Moderate	Extensive	Moderate	Moderate	Negligible
		Value	≤ 1	≤ 2	≤3	≤ 5	≤ 7	≤ 1.0	≤ 5	≤ 2
	Open Joints (No per segment)	Description	Nil	Very Slight	Slight	Moderate	Extensive	Extensive	Nil	Nil
		Value	≤ 0.0	≤ 1	≤ 2	≤ 3	≤ 4	≤ 20	≤ 0	≤ 0
	Sag Depth (mm) (Per Segment)	Description	Nil	Slight	Moderate	Extensive	Severe	Extensive	Slight	Moderate
		Value	≤ 25	≤ 50	≤ 100	≤ 150	≤ 200	≤ 60	≤ 50	≤ 75
Operational	Debris and Encrustation (% Reduction in Diameter)	Description	Very Slight	Slight	Moderate	Extensive	Severe	Extensive	Extensive	Slight
		Value	≤ 5	≤ 10	≤ 15	≤ 20	≤ 30	≤ 150	≤ 20	≤ 10
	Root Intrusion (% Reduction in Diameter)	Description	Very High	High	Moderate	Low	Very Low	Low	Low	High
		Value	≤ 5	≤ 10	≤ 15	≤ 20	≤ 30	≤ 150	≤ 20	≤ 10
	Protuding Joints (% Reduction in Diameter)	Description	Very Low	Low	Moderate	High	Very High	High	Very Low	Low
		Value	≤ 5	≤ 10	≤ 15	≤ 20	≤ 25	≤ 25	≤ 5	≤ 10
Environmental	Infiltration (Intensity Scale)	Description	Very Low	Low	Moderate	High	Very High	Moderate	Very High	Low
		Value	≤ 0	≤ 2	≤ 5	≤ 8	≤ 10	≤ 0.009	≤ 10	≤ 2
	Exfiltration (Intensity Scale)	Description	Very Low	Low	Moderate	High	Very High	High	Very High	Low
		Value	≤ 0	≤ 2	≤ 5	≤ 8	≤ 10	≤ 0.25	≤ 10	≤ 2
	No. of Pollution Incident	Description	None	Rare	Few	Occasional	Often	Rare	Few	Rare
		Value	0	≤ 1	≤ 2	≤ 2	≤ 3	≤ 1	≤ 2	≤ 1

Table 4.9: Pavement Segment Performance Measures and Distribution of its Values in Different Condition Ratings

Category	**Performance Measure**	**Value Type**	**Values of Performance Measures in Fuzzy Grades for Condition Rating**					**Service Thresholds**	**Existing**	**Target**
			A	**B**	**C**	**D**	**E**			
1	2	3	4	5	6	7	8	9	10	11
Surface Related Ride Quality	Ravelling (Percent Surface Area) (Moderately rough surface texture, pitted)	Description	Nil	Very Slight	Slight	Moderate	Extensive	Moderate	Extensive	Nil
		Value	0	≤ 10	≤ 20	≤ 30	≤ 40	≤ 30	≤ 40	0
	Longitudinal & Center line Cracking (Linear Meter / 100 Sqm) (Non-Filled crack width b/w 3/8 to 3 in)	Description	Rare	Very few	Occasional	Often	Frequent	Often	Often	Rare
		Value	≤ 0.5	≤ 1	≤ 2	≤ 3	≤ 4	≤ 3	≤ 3	≤ 0.5
	Pavement Edge Cracking (Linear Meter / 100 Sqm) (Non-Filled crack width b/w 3/8 to 3 in)	Description	Rare	Very few	Occasional	Often	Frequent	Frequent	Very few	Very few
		Value	≤ 0.5	≤ 1	≤ 2	≤ 3	≤ 4	≤ 4	≤ 1	≤ 1
	Transverse Cracking (Linear meter / 100 sqm) (Non-Filled crack width b/w 3/8 to 3 in)	Description	None	Rare	Few	Occasional	Often	Occasional	Occasional	None
		Value	≤ 0	≤ 0.5	≤ 1	≤ 1.5	≤ 2	≤ 1.5	≤ 1.5	≤ 0
Structure Related Ride Quality	Alligator and Block Cracking (Percent Surface Area) (Network of Cracks)	Description	None	Rare	Few	Occasional	Often	High	None	None
		Value	≤ 1	≤ 6	≤ 12	≤ 18	≤ 25	≤ 18	≤ 1	≤ 1
	Corrugation (Percent Surface Area) (Vehicle Vibration, Speed Reduction)	Description	Nil	Very Slight	Slight	Moderate	Extensive	Moderate	Moderate	Very Slight
		Value	≤ 0	≤ 0.5	≤ 1	≤ 3	≤ 10	≤ 3	≤ 3	≤ 0.5
	Rutting (Percent Surface Area) (1 to < 2 in)	Description	Nil	Very Slight	Slight	Moderate	Extensive	Moderate	Moderate	Very Slight
		Value	≤ 0	≤ 0.5	≤ 1	≤ 3	≤ 10	≤ 3	≤ 3	≤ 0.5
	Pothole Density (Percent Surface Area) Min Plan Dimension = 6in, Min Depth = 2 in	Description	Nil	Very Slight	Slight	Moderate	Extensive	Moderate	Nil	Nil
		Value	≤ 0	≤ 1	≤ 3	≤ 6	≤ 10	≤ 6	≤ 0	≤ 0
Safety Concerns	Water Ponding (Percent Surface Area)	Description	Nil	Very Slight	Slight	Moderate	Extensive	Moderate	Very Slight	Very Slight
		Value	≤ 0	≤ 4	≤ 10	≤ 20	≤ 35	≤ 20	≤ 4	≤ 4
	Pavement Marking (White) (Retro Reflectivity Value)	Description	Very High	High	Adequate	Low	Very Low	Low	Low	High
		Value	≥300	≥ 275	≥225	≥ 150	≥ 100	≥ 150	≥ 150	≥ 275
	Skid Resistance (Skid No)	Description	Very High	High	Adequate	Low	Very Low	Adequate	Very Low	High
		Value	≥1.95	≥ 1.75	≥ 1.55	≥ 1.20	≥ 1.0	≥ 1.55	≥ 1.0	≥ 1.75

Table 4.10: Asset Criticality Data for Corridor Integrated Criticality Score

Row No.	Asset Criticality Data										
	Level of Analysis	**Network Level Score (NLS)**		**Sub-Network Level Scores (SNLS)**				**Corridor Level Score (CLS)**	**Asset Level Score (ALS)**		
1	Level Weight	20%		30%				20%	30%		
	Criticality Parameter	Population Density	Tax Base	Sub-Network Type (snt)	Level of Complaint (loc)			Asset Spatial Co-Existence (asce)	Pavement Asset Size	**Water Asset Size**	**Sewer Asset Size**
2	Parameter Weight	60%	40%	50%	50%			100%	35%	35%	30%
3	Asset Type	S(pd)	S(tx)	S(t)	35%	35%	30%	S(ce)	S(Pas)	S(Was)	S(Sas)
	Asset Type Weight				S(Ploc)	S(Wloc)	S(Sloc)				
	Corridor No.										
4	440249758M	5	NA	5	7	9	3	7	5	6	4

Table 4.11: Optimization Parameters Suggested Penalty Points

Asset Type	Penalty Points for the Optimization Parameters					
	Cost (x 100 $) (Overrun)	Cost (x 100 $) (Saving)	Condition (Over Achieved)	Condition (Under Achieved)	RSL (x10 Yrs) (Over Achieved)	RSL (x10 Yrs) (Under Achieved)
	1	2	3	4	5	6
Water	4	0	(20)	50	(3)	3
Sewer	4	(4)	20	50	3	2
Pavement	4	(4)	20	50	2	3

The developed methodology is generic. Its models can be customized and reset according to different preferences and requirements and so there is no need of any quantitative validation. The methodology was checked by applying it on the case study in the city of Riyadh, KSA and later assessing the suitability of results. The results were found to meet the community's required level of asset performance. In case, the results do not meet the community expectation, the three step process of adjustment and fine tuning shown in Figure 3.21 can be applied.

CHAPTER 5: MODELS DEVELOPMENT

This chapter describes the theoretical basis and mathematical formulation of the models and rules developed in the methodology. The performance indicators and their corresponding measures on which this performance oriented framework is based are different for each asset class. Table 5.1 below provides the performance measures for water, wastewater and pavement segments that are identified based on literature review, recommendations of the best practices (InfraGuide 2003d) and consultation with asset managers.

Table 5.1: Performance Measures & their Units for Water, Wastewater & Pavement Asset Classes

Performance Measures (Water Mains)	**Performance Measures (Wastewater Mains)**	**Performance Measures (Pavement Segment)**
Fracture / Crack Depth (mm)	Cracks / Missing Bricks (No. per meter of pipe segment)	Ravelling (Percent Surface Area) (Moderately rough surface texture, pitted)
Sag (≤ 0.1 D mm) For 12" Ductile Pipe	Open Joints (No per segment)	Flushing (Percentage Surface Area) (Moderate)
Corrosion (% Pipe Thickness Reduction)	Sag Depth (mm) (Per Segment)	Longitudinal & Center line Cracking (Linear Meter / 100 Sqm) (Non-Filled crack width b/w 3/8 to 3 in)
Leakage Volume (Litres/Day/Km/in-dia)	Debris and Encrustation (% Reduction in Diameter)	Pavement Edge Cracking (Linear Meter / 100 Sqm) (Non-Filled crack width b/w 3/8 to 3 in)
Roughness Coefficient (C-Factor) Range= (125 - 50)	Root Intrusion (% Reduction in Diameter)	Transverse Cracking (Linear meter / 100 sqm) (Non-Filled crack width b/w 3/8 to 3 in)
Loss in Water Pressure (Psi) Household Supply Standard = 60 psi	Protuding Joints (% Reduction in Diameter)	Alligator and Block Cracking (Percent Surface Area) (Network of Cracks)
Lead Concentration (Action Level @ 10 % + ve sample for 0.015 mg/l) Range= (0 - 100)	Infiltration (Intensity Scale)	Corrugation (Percent Surface Area) (Vehicle Vibration, Speed Reduction)
Iron Concentration (Action Level at 10 % + ve sample for 0.3 mg/l) Range= (0 - 100)	Exfiltration (Intensity Scale)	Rutting (Percent Surface Area) (1 to < 2 in)
Total Coliform Bacteria (% positive samples in a month)	No. of Pollution Incident (No per segment per year)	Pothole Density (Percent Surface Area) Min Plan Dimension = 6in, Min Depth = 2 in
		Water Ponding (Percent Surface Area)
		Pavement Marking (White) (Retro Reflectivity Value)
		Skid Resistance (Skid No)

Water distribution mains are buried assets that work under hydraulic pressure and this makes their management most challenging among the three asset types considered in this research. Therefore, water mains are selected to illustrate the working of all the models in all the phases.

The unit of analysis adopted in this study is the length between two intersections termed as “Segment”. This is considered to be adaptable with integrated approaches such as municipal corridor rehabilitation. To analyze the performance and express level of service of water mains, nine operational level performance measures are selected. The performance measures and their values for the three asset classes, described earlier, were reviewed and recommended by the asset management consultant of Riyadh city.

5.1 Analytical Hierarchy Process Based Model of Level of Service

The performance measures of water, wastewater and pavement assets used to develop the level of service models, along with the required data are respectively presented in Table 5.2, 5.3 and 5.4. Failure thresholds are the minimum acceptable values of a performance measure. For any performance measure, a value beyond threshold would imply an overall performance failure of that asset. In order to use the performance measure values in AHP analysis, their

Table 5.2: Ranges and Thresholds of Performance Measures for Different LoS of Water Mains

Performance Indicator	Performance Measure	Value Description	Range of Performance Measure for Different Levels of Service (LoS)					Service Thresholds	Existing Value	Targeted Value
			LoS 1	LoS 2	LoS 3	LoS 4	LoS 5			
Structural	Fracture / Crack Width (mm)	Actual	0.0 - 0.10	0.11-0.25	0.26-0.75	0.76-1.25	1.26 -1.75	1.0	1.0	0.0
		Normalized	(1.0 - 0.94)	(0.93-0.86)	(0.850-0.57)	(0.56-0.29)	(0.280-0.0)	≤ 0.67	≤ 0.67	≤ 0.0
		Attribute Effcet	100	75	50	25	0		63	100
	Sag (≤ 0.1 D mm) For 6" Ductile Pipe	Actual	0-5	6 - 10	11-20	21-25	26-30	20	10	10
		Normalized	(1.0 - 0.83)	(0.80 - 0.67)	(0.66 - 0.33)	(0.3 - 0.17)	(0.16- 0.0)	(0.0)		
		Attribute Effcet	100	70	50	25	5		38	75
	Corrosion (% Pipe Thickness Reduction)	Actual	0-0	1-10	11-35	36-60	61-85	60	60	10
		Normalized	(1.0 - 1.0)	(0.99 - 0.88)	(0.87 - 0.59)	(0.58 - 0.29)	(0.28 - 0.0)	≤ 0.70	≤ 0.70	≤ 0.10
		Attribute Effcet	100	70	50	30	10		50	78
Operational	Leakage Volume (Litres/Day/Km/in-dia)	Actual	0-5	6-50	51-100	101-200	201-300	150	150	10
		Normalized	(1.0-0.98)	(0.97-0.833)	(0.80-0.67)	(0.66-0.33)	(0.32-0.0)	≤ 0.85	≤ 0.85	≤ 0.35
		Attribute Effcet	100	90	65	50	16		50	95
	Roughness Coefficient (C-Factor) Range= (175 - 25)	Actual	175 - 126	125 - 101	100 - 76	75 -51	50 - 25	65	65	105
		Normalized	(1.0 - 0.67)	(0.66 - 0.51)	(0.50 - 0.34)	(0.33-0.17)	(0.16-0.0)	≤ 0.80	≤ 0.80	≤ 0.25
		Attribute Effcet	100	55	40	25	10		77	92
	Loss in Water Pressure (Psi) Household Supply Standard = 60 psi	Actual	0-5	6-10	11-15	16-20	21-25	25	25	15
		Normalized	(1.0 - 0.8)	(0.76 - 0.60)	(0.59 - 0.4)	(0.39 - 0.2)	(0.19 - 0.0)	≤ 0.75	≤ 0.75	≤ 0.25
		Attribute Effcet	100	70	50	30	10		60	76
Water Quality	Lead Concentration (% Threshold) (Action Level at 10 % + ve Sample for 0.015 mg/l) Range= (0 - 100)	Actual	0.0-0.002	0.003-0.005	0.006-0.008	0.009-0.010	0.011-0.015	0.009	0.009	0.006
		Normalized	(1.0 - 0.83)	(0.8-0.58)	(0.57-0.33)	(0.30 - 0.16)	(0.15 - 0.0)	≤ 0.50	≤ 0.50	≤ 0.25
		Attribute Effcet	100	80	65	40	15		50	95
	Iron Concentration (% Threshold) (Action Level at 10 % + ve Sample for 0.3 mg/l) Range= (0 - 100)	Actual	0-0.1	0.11-0.15	0.16-0.2	0.21-0.30	0.31-0.5	0.25	0.3	0.15
		Normalized	(1.0 - 0.8)	(0.79 - 0.70)	(0.69 -0.60)	(0.59 - 0.4)	(0.39 - 0.0)	≤ 0.75	≤ 1.0	≤ 0.25
		Attribute Effcet	100	80	65	40	15		45	95
	Total Coliform Bacteria (% positive samples in a month)	Actual	0.0-1.0	1.1-2.0	2.1-3.0	3.1-4.0	4.1-5.0	1	2	0
		Normalized	(1.00.8)	(0.79-0.6)	(0.59 - 0.41)	(0.4 - 0.21)	(0.2 - 0.0)	≤ 0.20	≤ 0.40	≤ 0.0
		Attribute Effcet	100	70	50	30	10		40	80

* -- The normalized values are subtracted from 1 so that increase in normalized value results in increase in LoS

Table 5.3: Ranges and Thresholds of Performance Measure for Different LoS of Wastewater Mains

Performance Indicator	Performance Measure	Range of Performance Measure for Different Levels of Service (LoS)					Service Thresholds	Existing Value	Targeted Value
		LoS 1	LoS 2	LoS 3	LoS 4	LoS 5			
Structural Reliability	Cracks / Missing Bricks (No. per meter of pipe segment)	0.0 - 1.0	1.1 - 3.0	3.1 - 4.0	4.1-5.0	5.1-7.0	LoS 4	LoS 3	LoS 2
		(1.0 - 0.86)	(0.85-0.57)	(0.56-0.43)	(0.42 - 0.29)	(0.28 - 0.0)	4.1-5.0	4	2
	Open Joints (No per segment)	0-0	1-1	2-2	3-3	4-4	LoS 4	LoS 2	LoS 2
		(1.0 - 1.0)	(0.75 - 0.75)	(0.50 - 0.50)	(0.25 - 0.25)	(0.0 - 0.0)	3-3	1	1
	Sag Depth (mm) (Per Segment)	0-50	51-75	76-125	126-150	151-200	LoS 4	LoS 3	LoS 3
		(1.0 - 0.75)	(0.74 - 0.63)	(0.62 - 0.38)	(0.37 - 0.25)	(0.24- 0.0)	126-150	100	100
Operational	Debris and Encrustation (% Reduction in Diameter)	0-5	6-10	11-15	16-20	21-30	LoS 4	LoS 5	LoS 2
		(1.0-0.83)	(0.82-0.67)	(0.66-0.50)	(0.49-0.33)	(0.32-0.0)	16-20	25	10
	Root Intrusion (% Reduction in Diameter)	0-5	6-10	11-15	16-20	21-30	LoS 4	LoS 5	LoS 2
		(1.0-0.83)	(0.82-0.67)	(0.66-0.50)	(0.49-0.33)	(0.32-0.0)	16-20	30	10
	Protuding Joints (% Reduction in Diameter)	0-5	6-10	11-15	16-20	21-25	LoS 4	LoS 2	LoS 2
		(1.0-0.83)	(0.82-0.67)	(0.66-0.50)	(0.49-0.33)	(0.32-0.0)	16-20	10	10
Environmental	Infiltration (Intensity Scale)	0-0	1-1	2-3	4-5	6-10	LoS 3	LoS 5	LoS 3
		(1.0 - 1.0)	(0.90-0.90)	(0.80-0.70)	(0.60 - 0.50)	(0.4 - 0.0)	2 - 3	10	3
	Exfiltration (Intensity Scale)	0-0	1-1	2-3	4-5	6-10	LoS 3	LoS 5	LoS 2
		(1.0 - 1.0)	(0.90-0.90)	(0.80-0.70)	(0.60 - 0.50)	(0.4 - 0.0)	2 - 3	10	3
	No. of Pollution Incident (No per segment per year)	0-0	1-1	1-1	2-2	3-3	LoS 3	LoS 4	LoS 3
		(1 - 1)	(0.67 - 0.67)	(0.67 - 0.67)	(0.33 - 0.33)	(0.0- 0.0)	1 - 1	2	1

* -- The normalized values are subtracted from 1 so that increase in normalized value results in increase in LoS

Infiltration and Exfiltration Intensity Scale:

0-1 Seeping 2-3 Dripping 4-5 Running 6-8 Spurting 9-10 Gushing

Table 5.4: Ranges and Thresholds of Performance Measure for Different LoS of Pavement Segment

Performance Indicator	Performance Measure	Range of Performance Measure for Different Levels of Service (LoS)					Service Thresholds	Existing Value	Targeted Value
		LoS 1	LoS 2	LoS 3	LoS 4	LoS 5			
Surface Related Comfort	Ravelling (Percent Surface Area) Moderately rough surface texture, pitted)	0	≤ 5	≤ 15	≤ 25	≤ 40	LoS 3	LoS 4	LoS 1
		0	≤ 0.125	≤ 0.375	≤ 0.625	≤ 1	15	25	0
	Longitudinal & Center line Cracking (Linear Meter / 100 Sqm) (Non-Filled crack width b/w 3/8 to 3 in)	≤ 0.5	≤ 1	≤ 2	≤ 3	≤ 4	LoS 3	LoS 4	LoS 1
		≤ 0.125	≤ 0.25	≤ 0.5	≤ 0.75	≤ 1.0	2	3	0.5
	Pavement Edge Cracking (Linear Meter / 100 Sqm) (Non-Filled crack width b/w 3/8 to 3 in)	≤ 0.5	≤ 1	≤ 2	≤ 3	≤ 4	LoS 4	LoS 2	LoS 2
		≤ 0.125	≤ 0.25	≤ 0.5	≤ 0.75	≤ 1.0	3	1	1
	Transverse Cracking (Linear meter / 100 sqm) (Non-Filled crack width b/w 3/8 to 3 in)	≤ 0	≤ 0.5	≤ 1	≤ 1.5	≤ 2	LoS 3	LoS 4	LoS 1
		≤ 0	≤ 0.25	≤ 0.5	≤ 0.75	≤ 1.0	1	1.5	0
Structure Related Comfort	Alligator and Block Cracking (Percent Surface Area) (Network of Cracks)	≤ 1	≤ 4	≤ 8	≤ 15	≤ 25	LoS 3	LoS 1	LoS 1
		≤ 0.04	≤ 0.16	≤ 0.32	≤ 0.60	≤ 1.0	8	1	1
	Corrugation (Percent Surface Area) (Vehicle Vibration, Speed Reduction)	≤ 0	≤ 0.5	≤ 1	≤ 3	≤ 10	LoS 3	LoS 2	LoS 2
		≤ 0	≤ 0.05	≤ 0.1	≤ 0.3	≤ 1.0	1	0.5	0.5
	Rutting (Percent Surface Area) (1 to < 2 in)	≤ 0	≤ 0.5	≤ 2	≤ 5	≤ 10	LoS 4	LoS 3	LoS 1
		≤ 0.1	≤ 0.05	≤ 0.2	≤ 0.5	≤ 1.0	5	2	0
	Pothole Density (Percent Surface Area) Min Plan Dimension = 6in, Min Depth = 2 in	≤ 0	≤ 1	≤ 3	≤ 5	≤ 10	LoS 3	LoS 1	LoS 1
		≤ 0.0	≤ 0.1	≤ 0.3	≤ 0.5	≤ 1.0	3	0	0
Safety Concerns	Water Ponding (Percent Surface Area)	≤ 0	≤ 3	≤ 8	≤ 15	≤ 35	LoS 4	LoS 2	LoS 2
		≤ 0	≤ 0.09	≤ 0.23	≤ 0.43	≤ 1.0	15	3	3
	Pavement Marking (White) (Retro Reflectivity Value)	≥300	≥ 275	≥225	≥ 150	≥ 100	LoS 3	LoS 1	LoS 1
		≤ 0	≤ 0.083	≤ 0.25	≤ 0.50	≤ 0.67	225	300	300
	Skid Resistance (Skid No)	≥1.95	≥ 1.85	≥ 1.65	≥ 1.40	≥ 1.0	LoS 3	LoS 3	LoS 1
		≤ 0.0	≤ 0.05	≤ 0.15	≤ 0.28	≤ 0.49	1.65	1.65	1.95

* -- The normalized values are subtracted from 1 so that increase in normalized value results in increase in LoS

existing and targeted values, desired ranges and threshold values, are normalized to a scale of 0-1.

The AHP technique assists decision makers in solving complex problems by organizing thoughts, experiences, knowledge, and judgments into a hierarchical framework, and guiding them through a sequence of pair-wise comparison judgments (Saaty 1991). The AHP theory has been widely used and applied in different fields. It has been applied in multi-criteria decision making, planning and resource allocation, conflict resolutions, and prediction problems (Saaty 2001). Dey (2003) developed a risk-based model using the AHP technique to identify the factors that influence failure of specific portions of petroleum pipelines. Tran et al. (2003) combined AHP technique with the expected maximum utility to evaluate renewal priorities of irrigation assets that were grouped by types and location within a hydraulic system. While dealing with LoS, asset managers should have clear and definite target values of performance measures that would define the LoS. Normally, these inputs are deterministic and quantitative in nature. Analytical hierarchy process was therefore deemed appropriate to develop the intended LoS model. An overview of the model building process is presented in Figure 5.1. This research encompasses the tactical level indicators and operational level performance measures to establish the LoS of a water main.

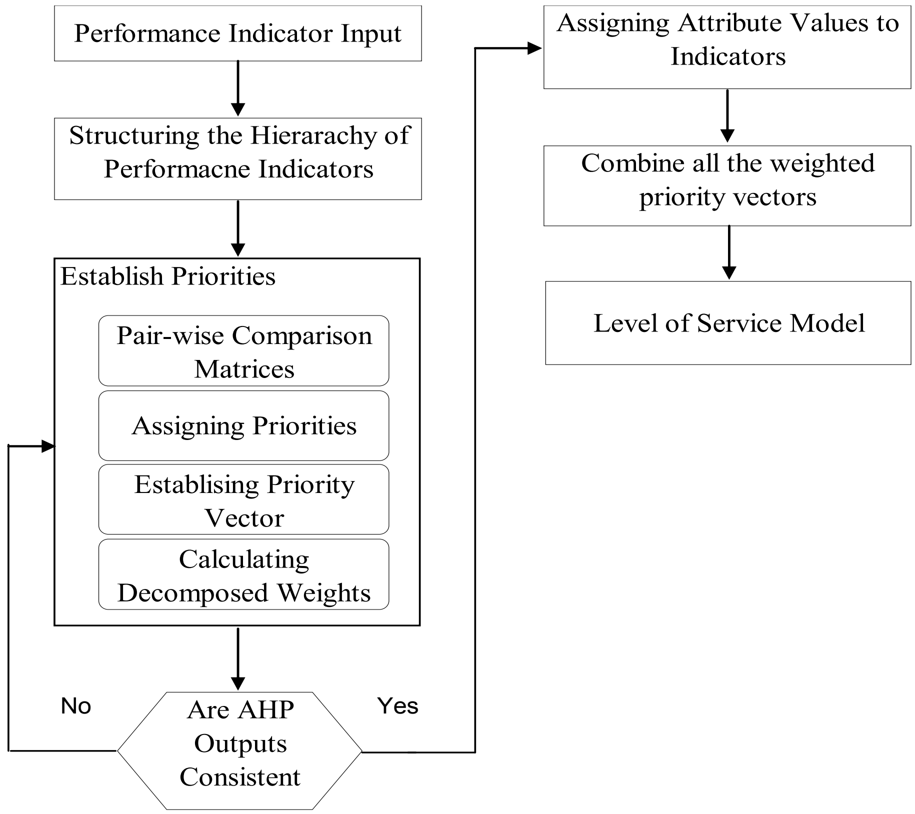


Figure 5.1: Process of AHP Model Development of LoS of Water Mains

In order to apply AHP technique the problem should undergo the following six steps:

Step 1: Setting up the Decision Hierarchy

There are two levels of hierarchy: 1) performance indicators which comprise of structural reliability, operational performance and water quality 2) the corresponding performance measures defining these indicators (see Figure 5.2). The final outcome of this process is the level of service of water main expressed in terms of Service Percentile (scale of 0-100). Increasing number implies increasing level of service.

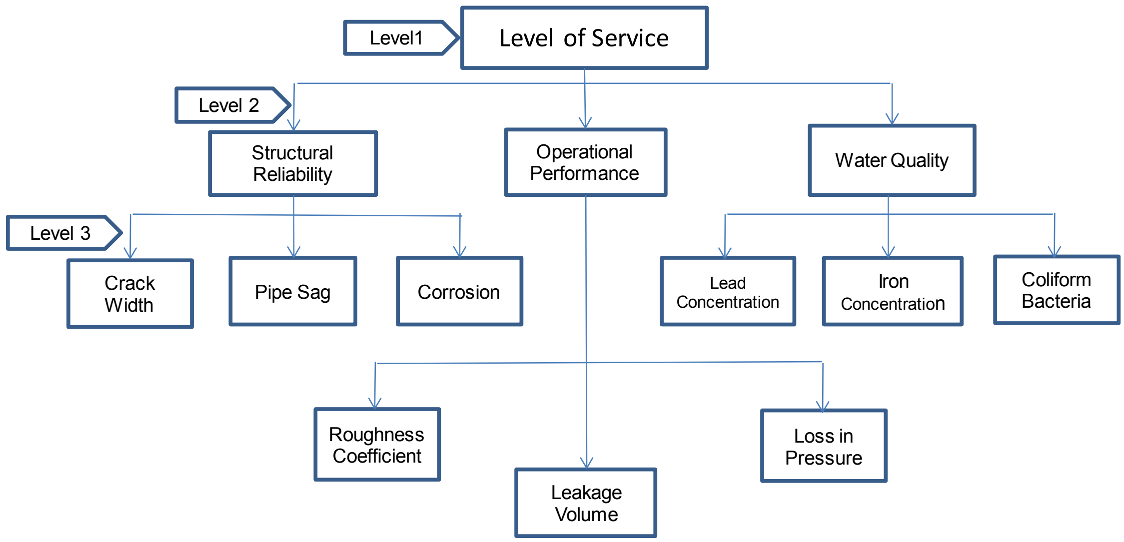


Figure 5.2: Hierarchy of Performance Indicators and Measures in LoS of Water Mains

Step 2: Assigning Priorities and Establish Priority Vector

In this step, decision makers provide pair-wise comparison matrices for the main factors and sub-factors. AHP methodology is applied to these matrices in order to determine the relative weight of each measure. For details on how to calculate the factor and sub-factor weights readers may refer to Saaty (1991). The pair-wise comparison matrix for the main indicators of the numerical example is presented in Table 5.5.

Table 5.5: Pair-wise comparison and priority vectors for main indicators

Perfromance Indicator	Structure	Operational	Water Quality	Normalized Vectors Structure	Normalized Vectors Operational	Normalized Vectors Water Quality	Weight Vectors
Structure	1	1.5	1.25	0.4048583	0.4054054	0.405844156	$W_s = 0.4054$
Operational	0.67	1	0.833	0.2712551	0.2702703	0.270454545	$W_{op} = 0.2707$
Water Quality	0.8	1.2	1	0.3238866	0.3243243	0.324675325	$W_{wq} = 0.3243$
Column Sum	2.47	3.7	3.08				

Step 3: Consistency Analysis

This step verifies the consistency of pair-wise comparisons using Equations 5.1 and 5.2 for the consistency index (CI) and consistency ratio (C.R.), as described by (Saaty 1982):

$$CI = \frac{\lambda \max - m}{m - 1} \quad \text{...Eq. (5.1)}$$

$$C.R. = CI / RI \quad \text{...Eq. (5.2)}$$

where

CI = Consistency Index; m = matrix size; λ_{max} = Maximum Eigen Value;

RI = Average Random Index which depends on matrix size (Saaty 1982)

Step 4: Decomposed Priority Weights

After verifying the consistency of all matrices, priority weights 'W_i' are considered valid for further processing. Subsequently, decomposed weight of each measure will be calculated by multiplying the indicator weight by its measure weight. This decomposed weight will represent the overall weight of that specific sub-factor. Accordingly, priority can be established based on the overall weights using Eq. 5.3.

Overall performance measure decomposed weight = $W_i * V_{ij}$ ....Eq. (5.3)

= $SDW_{ij} = W_i * V_{ij}$ ....Eq. (5.4)

where W_i = weight of indicator "i" and V_{ij} = weight of measure "j" within the indicator "i".

Step 5: Attributes Effect AE*ij*.

The decomposed weights represent a generic weight for indicators and performance measures. As such, each measure has range of values corresponding to different LoS. Therefore, the effect of each performance measure on the LoS of water mains is considered through the attributes effect term AE_{ij}. The user is required to assign the AE_{ij} for each measure, using a scale from 0 to 100, where "0" represents the lowest attribute value and "100" represents the highest attribute value.

Step 6: Water Main Level of Service Model

The overall service percentile value that represents the LoS is then calculated using Eq.5.5:

Water Main Service Percentile = WMSP = $\sum_{i=1}^{n}\sum_{j=1}^{m}(SDWij)*(AEij)$ ……… Eq. (5.5)

This quantification of the improvements required in asset performance can assist asset managers in integrating technical plans with financial plans and to thereby make more sustainable asset management decisions.

5.2 Fuzzy weighted average Model of Performance Based Asset Condition

The community perspective of the performance of an asset from service point of view may be quite different from the municipality perspective of the performance of the same asset from a condition point of view. This section presents a methodology that consists of: 1) Scaling a performance measures based condition assessment protocol and 2) Fuzzy weighted average model of water main condition rating. The performance measures of water, wastewater and pavement assets used to develop the condition rating models along with their required data are presented in Table 5.6, 5.7 and 5.8.

Table 5.6: Ranges and Thresholds of Performance Measure for Different Condition of Water Segment

Performance Indicator	Performance Measure	Value Type	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
			A	B	C	D	E			
Structural	Fracture / Crack Depth (mm)	Description	None	Negligible	Slight	Moderate	Extensive	Moderate	Moderate	None
		Value	≤ 0.0	≤ 0.15	≤ 0.50	≤ 1.0	≤ 1.5	≤ 1.0	≤ 1.0	≤ 0.0
		Normalized Value	≤ 0.0	≤ 0.10	≤ 0.33	≤ 0.67	≤ 1.0	≤ 0.67	≤ 0.67	≤ 0.0
	Sag (≤ 0.1 D mm) For 6" Ductile Pipe	Description	Nil	Very Slight	Slight	Moderate	Extensive	Extensive	Slight	Slight
		Value	≤ 0.0	≤ 5	≤ 10	≤ 15	≤ 20	≤ 20	≤ 10	≤ 10
		Normalized Value	≤ 0.0	≤ 0.25	≤ 0.50	≤ 0.75	≤ 1.0	≤ 1.0	≤ 0.50	≤ 0.50
	Corrosion (% Pipe Thickness Reduction)	Description	Nil	Slight	Moderate	Extensive	Severe	Extensive	Extensive	Slight
		Value	≤ 0.0	≤ 10	≤ 35	≤ 60	≤ 85	≤ 60	≤ 60	≤ 10
		Normalized Value	≤ 0.0	≤ 0.10	≤ 0.40	≤ 0.70	≤ 1.0	≤ 0.70	≤ 0.70	≤ 0.10
Operational	Leakage Volume (Litres/Day/Km/in-dia)	Description	Very Slight	Slight	Moderate	Extensive	Severe	Extensive	Extensive	Very Slight
		Value	≤ 10	≤ 50	≤ 75	≤ 150	≤ 250	≤ 150	≤ 150	≤ 10
		Normalized Value	≤ 0.35	≤ 0.50	≤ 0.70	≤ 0.85	≤ 1.0	≤ 0.85	≤ 0.85	≤ 0.35
	Roughness Coefficient (C-Factor) Range= (125 - 50)	Description	Very High	High	Moderate	Low	Very Low	Low	Low	High
		Value	≥ 125	≥ 105	≥ 85	≥ 65	≥ 50	≥ 65	≥ 65	≥ 105
		Normalized Value *	≤ 0.0	≤ 0.25	≤ 0.55	≤ 0.80	≤ 1.0	≤ 0.80	≤ 0.80	≤ 0.25
	Loss in Water Pressure (Psi) Household Supply Standard = 60 psi	Description	Very Low	Low	Moderate	High	Very High	High	High	Low
		Value	≤ 10	≤ 15	≤ 20	≤ 25	≤ 30	≤ 25	≤ 25	≤ 15
		Normalized Value	≤ 0.0	≤ 0.25	≤ 0.50	≤ 0.75	≤ 1.0	≤ 0.75	≤ 0.75	≤ 0.25
Water Quality	Lead Concentration (Action Level at 10 % + ve Sample for 0.015 mg/l) Range= (0 - 100)	Description	Very Low	Low	Moderate	High	Very High	Moderate	Moderate	Low
		Value	≤ 0.003	≤ 0.006	≤ 0.009	≤ 0.012	≤ 0.015	≤ 0.009	≤ 0.009	≤ 0.006
		Normalized Value	≤ 0.0	≤ 0.25	≤ 0.50	≤ 0.75	≤ 1.0	≤ 0.50	≤ 0.50	≤ 0.25
	Iron Concentration (Action Level at 10 % + ve Sample for 0.3 mg/l) Range= (0 - 100)	Description	Very Low	Low	Moderate	High	Very High	High	Very High	Low
		Value	≤ 0.1	≤ 0.15	≤ 0.20	≤ 0.25	≤ 0.3	≤ 0.25	≤ 0.3	≤ 0.15
		Normalized Value	≤ 0.0	≤ 0.25	≤ 0.50	≤ 0.75	≤ 1.0	≤ 0.75	≤ 1.0	≤ 0.25
	Total Coliform Bacteria (% positive samples in a month)	Description	None	Rare	Few	Occasional	Often	Rare	Few	None
		Value	0	≤ 1	≤ 2	≤ 4	≤ 5	≤ 1	≤ 2	0
		Normalized Value	≤ 0.0	≤ 0.20	≤ 0.40	≤ 0.80	≤ 1.0	≤ 0.20	≤ 0.40	≤ 0.0

*-- A value of 1.0 is subtracted from the normalized value to change the order so that lower normalized value corresponds to lower number of condition rating implying better condition

Table 5.7: Ranges and Thresholds of Performance Measure for Different Condition of Wastewater Segment

Category	Performance Measure	Value Type	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
			A	B	C	D	E			
Structural	Cracks / Missing Bricks (No. per meter of pipe segment)	Description	None	Negligible	Slight	Moderate	Extensive	Moderate	Moderate	Negligible
		Value	≤ 1	≤ 2	≤3	≤ 5	≤ 7	≤ 1.0	≤ 5	≤ 2
		Normalized Value	≤ 0.0	≤ 0.10	≤ 0.33	≤ 0.67	≤ 1.0	≤ 0.67	≤ 0.67	≤ 0.0
	Open Joints (No per segment)	Description	Nil	Very Slight	Slight	Moderate	Extensive	Extensive	Nil	Nil
		Value	≤ 0.0	≤ 1	≤ 2	≤ 3	≤ 4	≤ 20	≤ 0	≤ 0
		Normalized Value	≤ 0.0	≤ 0.25	≤ 0.50	≤ 0.75	≤ 1.0	≤ 1.0	≤ 0.50	≤ 0.50
	Sag Depth (mm) (Per Segment)	Description	Nil	Slight	Moderate	Extensive	Severe	Extensive	Slight	Moderate
		Value	≤ 25	≤ 50	≤ 100	≤ 150	≤ 200	≤ 60	≤ 50	≤ 75
		Normalized Value	≤ 0.0	≤ 0.10	≤ 0.40	≤ 0.70	≤ 1.0	≤ 0.70	≤ 0.70	≤ 0.10
Operational	Debris and Encrustation (% Reduction in Diameter)	Description	Very Slight	Slight	Moderate	Extensive	Severe	Extensive	Extensive	Slight
		Value	≤ 5	≤ 10	≤ 15	≤ 20	≤ 30	≤ 150	≤ 20	≤ 10
		Normalized Value	≤ 0.35	≤ 0.50	≤ 0.70	≤ 0.85	≤ 1.0	≤ 0.85	≤ 0.85	≤ 0.35
	Root Intrusion (% Reduction in Diameter)	Description	Very High	High	Moderate	Low	Very Low	Low	Low	High
		Value	≤ 5	≤ 10	≤ 15	≤ 20	≤ 30	≤ 150	≤ 20	≤ 10
		Normalized Value *	≤ 0.35	≤ 0.50	≤ 0.70	≤ 0.85	≤ 1.0	≤ 0.85	≤ 0.85	≤ 0.35
	Protuding Joints (% Reduction in Diameter)	Description	Very Low	Low	Moderate	High	Very High	High	Very Low	Low
		Value	≤ 5	≤ 10	≤ 15	≤ 20	≤ 25	≤ 25	≤ 5	≤ 10
		Normalized Value	≤ 0.35	≤ 0.50	≤ 0.70	≤ 0.85	≤ 1.0	≤ 0.75	≤ 0.75	≤ 0.25
Environmental	Infiltration (Intensity Scale)	Description	Very Low	Low	Moderate	High	Very High	Moderate	Very High	Low
		Value	≤ 0	≤ 2	≤ 5	≤ 8	≤ 10	≤ 0.009	≤ 10	≤ 2
		Normalized Value	≤ 0.0	≤ 0.25	≤ 0.50	≤ 0.75	≤ 1.0	≤ 0.50	≤ 0.50	≤ 0.25
	Exfiltration (Intensity Scale)	Description	Very Low	Low	Moderate	High	Very High	High	Very High	Low
		Value	≤ 0	≤ 2	≤ 5	≤ 8	≤ 10	≤ 0.25	≤ 10	≤ 2
		Normalized Value	≤ 0.0	≤ 0.25	≤ 0.50	≤ 0.75	≤ 1.0	≤ 0.75	≤ 1.0	≤ 0.25
	No. of Pollution Incident (No per segment per year)	Description	None	Rare	Few	Occasional	Often	Rare	Few	Rare
		Value	0	≤ 1	≤ 2	≤ 2	≤ 3	≤ 1	≤ 2	≤ 1
		Normalized Value	≤ 0.0	≤ 0.20	≤ 0.40	≤ 0.80	≤ 1.0	≤ 0.20	≤ 0.40	≤ 0.0

*-- A value of 1.0 is subtracted from the normalized value to change the order so that lower normalized value corresponds to lower number of condition rating implying better condition

Table 5.8: Ranges and Thresholds of Performance Measure for Different Condition of Pavement

Category	Performance Measure	Value Type	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
			A	B	C	D	E			
Surface Related Ride Quality	Ravelling (Percent Surface Area) (Moderately rough surface texture, pitted)	Description	Nil	Very Slight	Slight	Moderate	Extensive	Moderate	Extensive	Nil
		Value	0	≤ 10	≤ 20	≤ 30	≤ 40	≤ 30	≤ 40	0
		Normalized Value	0	≤ 0.25	≤ 0.5	≤0 .75	≤ 1	≤ .75	≤ 1	0
	Longitudinal & Center line Cracking (Linear Meter / 100 Sqm) (Non-Filled crack width b/w 3/8 to 3 in)	Description	Rare	Very few	Occasional	Often	Frequent	Often	Often	Rare
		Value	≤ 0.5	≤ 1	≤ 2	≤ 3	≤ 4	≤ 3	≤ 3	≤ 0.5
		Normalized Value	≤ 0.125	≤ 0.25	≤ 0.5	≤ 0.75	≤ 1.0	≤ 0.75	≤ 0.75	≤ 0.25
	Pavement Edge Cracking (Linear Meter / 100 Sqm) (Non-Filled crack width b/w 3/8 to 3 in)	Description	Rare	Very few	Occasional	Often	Frequent	Frequent	Very few	Very few
		Value	≤ 0.5	≤ 1	≤ 2	≤ 3	≤ 4	≤ 4	≤ 1	≤ 1
		Normalized Value	≤ 0.125	≤ 0.25	≤ 0.5	≤ 0.75	≤ 1.0	≤ 1.0	≤ 0.25	≤ 0.25
	Transverse Cracking (Linear meter / 100 sqm) (Non-Filled crack width b/w 3/8 to 3 in)	Description	None	Rare	Few	Occasional	Often	Occasional	Occasional	None
		Value	≤ 0	≤ 0.5	≤ 1	≤ 1.5	≤ 2	≤ 1.5	≤ 1.5	≤ 0
		Normalized Value *	≤ 0	≤ 0.25	≤ 0.5	≤ 0.75	≤ 1.0	≤ 0.75	≤ 0.75	≤ 0.22
Structure Related Ride Quality	Alligator and Block Cracking (Percent Surface Area) (Network of Cracks)	Description	None	Rare	Few	Occasional	Often	High	None	None
		Value	≤ 1	≤ 6	≤ 12	≤ 18	≤ 25	≤ 18	≤ 1	≤ 1
		Normalized Value	≤ 0.04	≤ 0.24	≤ 0.48	≤ 0.72	≤ 1.0	≤ 0.72	≤ 0.04	≤ 0.12
	Corrugation (Percent Surface Area) (Vehicle Vibration, Speed Reduction)	Description	Nil	Very Slight	Slight	Moderate	Extensive	Moderate	Moderate	Very Slight
		Value	≤ 0	≤ 0.5	≤ 1	≤ 3	≤ 10	≤ 3	≤ 3	≤ 0.5
		Normalized Value	≤ 0	≤ 0.05	≤ 0.1	≤ 0.3	≤ 1.0	≤ 0.3	≤ 0.3	≤ 0.2
	Rutting (Percent Surface Area) (1 to < 2 in)	Description	Nil	Very Slight	Slight	Moderate	Extensive	Moderate	Moderate	Very Slight
		Value	≤ 0	≤ 0.5	≤ 1	≤ 3	≤ 10	≤ 3	≤ 3	≤ 0.5
		Normalized Value	≤ 0.1	≤ 0.05	≤ 0.1	≤ 0.3	≤ 1.0	≤ 0.3	≤ 0.3	≤ 0.2
	Pothole Density (Percent Surface Area) Min Plan Dimension = 6in, Min Depth = 2 in	Description	Nil	Very Slight	Slight	Moderate	Extensive	Moderate	Nil	Nil
		Value	≤ 0	≤ 1	≤ 3	≤ 6	≤ 10	≤ 6	≤ 0	≤ 0
		Normalized Value *	≤ 0.0	≤ 0.1	≤ 0.3	≤ 0.6	≤ 1.0	≤ 0.6	≤ 0.0	≤ 0.0
Safety Concerns	Water Ponding (Percent Surface Area)	Description	Nil	Very Slight	Slight	Moderate	Extensive	Moderate	Very Slight	Very Slight
		Value	≤ 0	≤ 4	≤ 10	≤ 20	≤ 35	≤ 20	≤ 4	≤ 4
		Normalized Value	≤ 0.0	≤ 0.11	≤ 0.29	≤ 0.57	≤ 1.0	≤ 0.57	≤ 0.11	≤ 0.11
	Pavement Marking (White) (Retro Reflectivity Value)	Description	Very High	High	Adequate	Low	Very Low	Low	Low	High
		Value	≥300	≥ 275	≥225	≥ 150	≥ 100	≥ 150	≥ 150	≥ 275
		Normalized Value	≤ 0	≤ 0.125	≤ 0.375	≤ 0.75	≤ 1.0	≤ 0.75	≤ 0.75	≤ 0.125
	Skid Resistance (Skid No)	Description	Very High	High	Adequate	Low	Very Low	Adequate	Very Low	High
		Value	≥1.95	≥ 1.75	≥ 1.55	≥ 1.20	≥ 1.0	≥ 1.55	≥ 1.0	≥ 1.75
		Normalized Value *	≤ 0.0	≤ 0.22	≤ 0.42	≤ 0.789	≤ 1.0	≤ 0.42	≤ 1.0	≤ 0.22

*-- A value of 1.0 is subtracted from the normalized value to change the order so that lower normalized value corresponds to lower number of condition rating implying better condition

A review of a number of water main condition assessment models indicates that, most of the models do not determine pipe condition as a function of performance distress indicators. The model developed by Yan et al (2003)], which used fuzzy composite programming (FCP), is the closest to the concern mentioned here. Yet the hierarchy mostly comprised of physical attributes of pipes. To achieve the objective of developing a water main condition assessment model that is based on performance distresses and also deals with the qualitative nature of inspection data, described earlier, an analogy with the method developed by Schumker (1984) was made. Based on Schumker's relation a Fuzzy weighted average model of water mains condition assessment is formulated.

The condition rating and weight of measures are expressed in linguistic grades. The advantages of using linguistic grades in a predominately qualitative engineering evaluation are well documented (Elton et al. 1998, Juang 1990, Murthy et al. 1990, Zadeh 1983). However, it demands an effective method for processing and combining the qualitative information. One such method is that of Schmucker (1984):

$$R = \Sigma (Ri \times Wi) / \Sigma Wi \qquad \text{Eq. (5.6)}$$

where R = the overall rating of the water main condition; Ri, = the rating of the water main condition with respect to a particular performance measure 'i'; and Wi, = the weight of that measure 'i'. Each term in the right-hand side of Eq. 5.6 is a linguistic grade or, simply, a letter grade - A, B, C, D, or E. A rational approach to evaluate Eq. 5.6 is to represent these letter grades using fuzzy sets (Zayed and Halpin 2004). A fuzzy set is a set of paired numbers that describe the degree of support / association to each value of performance measure. For example, in describing the iron concentration in the water supplied by the water main, a type of measure used in the study, a letter grade of ‘D’ means that water has high percentage of iron contamination which implies that the water main is in an alarming state of internal corrosion. This letter grade ‘D’ further means that this stress is likely to be in the range from 41% to 70% of the maximum allowable limit (See Table 5.6).

Fuzzy sets can account for uncertainty associated with the quantification of linguistic or letter grade. In other words, these letter grades, when used along with the fuzzy sets in a qualitative evaluation, can form a comprehensive rating scale. For simplicity, a linear (triangular) membership function is assumed to illustrate the proposed method. Although this assumption is deemed to be appropriate in this study and many others (Juang 1990, Dong and Wong 1987). Other membership functions can be used. The fuzzy sets of the condition rating grades and weights of performance measures associated with letters grades are presented at Table 5.9. When each term on the right-hand side of Eq. 5.6 is substituted by a fuzzy set, the evaluation of the equation involves operations such as fuzzy-set addition, fuzzy-set multiplication, and fuzzy-set division. Definitions of these fuzzy operations, as one might expect, are different from their counterparts in conventional mathematics (Schmucker 1984). The detail of the calculations involved in developing the Fuzzy Number of Condition grade is presented in Chapter 6 “Case Study Implementation of Developed Models.

Table 5.9: Membership Functions of Fuzzy Grades of Condition Rating and Performance Measure Weights

Fuzzy Grade	Linguistic Condition Rating	Linguistic Weight of Measure	Membership Function			Performance Measure belonging to the Weight Grade (Water Mains)	Performance Measure belonging to the Weight Grade (Sewer Mains)	Performance Measure belonging to the Weight Grade (Roads)
A	No action required	Relatively Unimportant	f (y) =	5(y)	0 ≤ y ≤ 0.2	(S) - Pipe Sag	(SD) - Sag Depth	(PEC) - Pavement Edge Cracking
B	Repairs	Moderately Important	f (y) =	5 (y - 0.1)	0.1 ≤ y ≤ 0.3	(I) - Iron Concentration	(PI) - Pollution Incident	(TC) -Transverse Cracking
			f (y) =	5 (0.5 - y)	0.3 ≤ y ≤ 0.5			(RV) - Ravelling
								(CG) - Corrogation
C	Minor Rehabilitation	Important	f (y) =	5(y - 0.3)	0.3 ≤ y ≤ 0.5	(P) - Loss in Water Pressure at Peak	(IF) - Infilttration	(WP) - Water Ponding
			f (y) =	5 (0.7 - y)	0.5 ≤ y ≤ 0.7	(V) - Leakage Volume	(PJ) - Protuding Joint	(PM) - Pavement Marking
D	Major Rehabilitation	Very Important	f (y) =	5(y - 0.5)	0.5 ≤ y ≤ 0.7	(C) - Corrosion (R) - Roughness Coefficient (L) - Lead Concentration	(CMB) - Crack & Missing Bricks (RI) - Root Intrusion (DE) - Debris & Encrustation	(RT) - Rutting (LC) - Longitudinal Cracking
			f (y) =	5 (0.9 - y)	0.7 ≤ y ≤ 0.9			
E	Approaching to Failure	Extremely Important	f (y) =	5(y - 0.8)	0.8 ≤ y ≤ 1.0	(F) - Fracture /Crack Width (B) - Coliform Bacteria	(OJ) - Open Joint (EF) - Exfilteration	(AC) - Alligator Cracking (PD) - Pothole Density (SR) - Skid Resistance

5.3 Fuzzy Alpha Cut Theorem Based LoS-Condition Mapping Function

A fuzzy mapping function based on the algorithm proposed by Dong and Wong (1987) is used to map condition rating of water mains determined by the Fuzzy weighted average model to the desired level of service of the asset. The output calculated by this function is the condition of water main that corresponds to the performance based level of service established in Section 5.1. The case study corridor is used to illustrate the developed method, an overview of which is presented in Figure 5.3.

The process to develop this fuzzy mapping function involves the application of the fuzzy α-cut algorithm to the fuzzy number of the weighted sum condition rating. The weights of performance measures in case of condition rating are represented by fuzzy letter grades given at Table 5.9. This depends primarily on, how the concerned agency deals with a particular performance measure. It should be noted that the minimum and maximum values of the performance measures in cases of condition rating are the same as they were in the case of level of service but their ranges in each interval of condition rating is different. This is due to the expected difference in technical approach of municipal engineer while dealing with condition assessment as opposed to the community end user while using the service. To apply operations of fuzzy sets, the ά – cut algorithm developed by Dong and Wong (1987) was used. The main idea is to "defuzzify" each fuzzy set into a group of real intervals " ά " before entering into Eq.5.6, as shown in the Figure 5.3. Once this is accomplished, the conventional mathematics takes over, which results in non-fuzzy outputs at these intervals. The final fuzzy set is reconstructed from this group of non-fuzzy intervals.

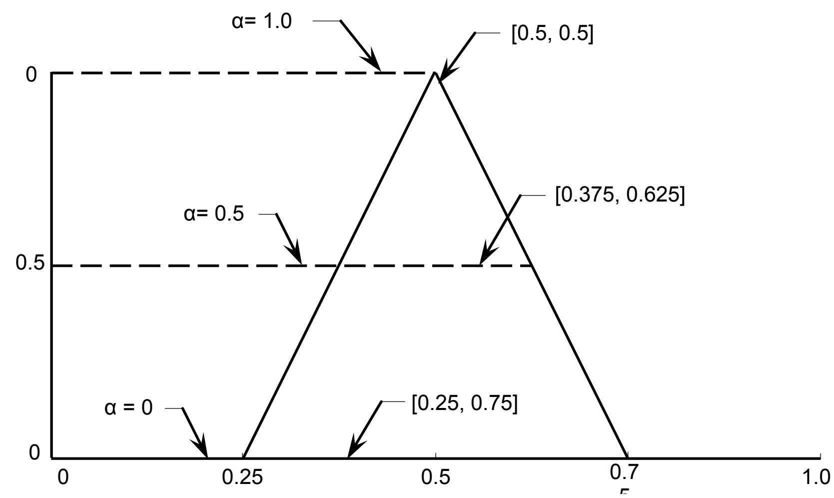


Figure 5.3: Fuzzy ά-cut Concept

The final quantitative mapping of the condition rating to level of service (service percentile) is achieved by converting the fuzzy set of condition rating into a crisp output. A Unified Water Main Distress Rating (UWMDR) is defined for this purpose as:

$$UWMDR = \frac{A_{left} - A_{right} + 1}{2} \quad \text{...Eq. (5.7)}$$

Where, A_{left} and A_{right} are respectively the areas enclosed to the left and right of the membership function that depicts the final fuzzy set. The defined UWMDR value ranges from 0.0 to 1.0, with 0.0 indicating perfect condition and 1.0 indicating the worst distress condition.

Numeric illustration of the concept is given in Chapter 6, by demonstrating the fuzzy computations of the existing situation at ά = 0 as defined in Eq. 5.6 and the calculation of UWMDR as defined in Eq.5.7

5.4 Identification of Municipal Corridor

As shown in Figure 5.4, the plan of a

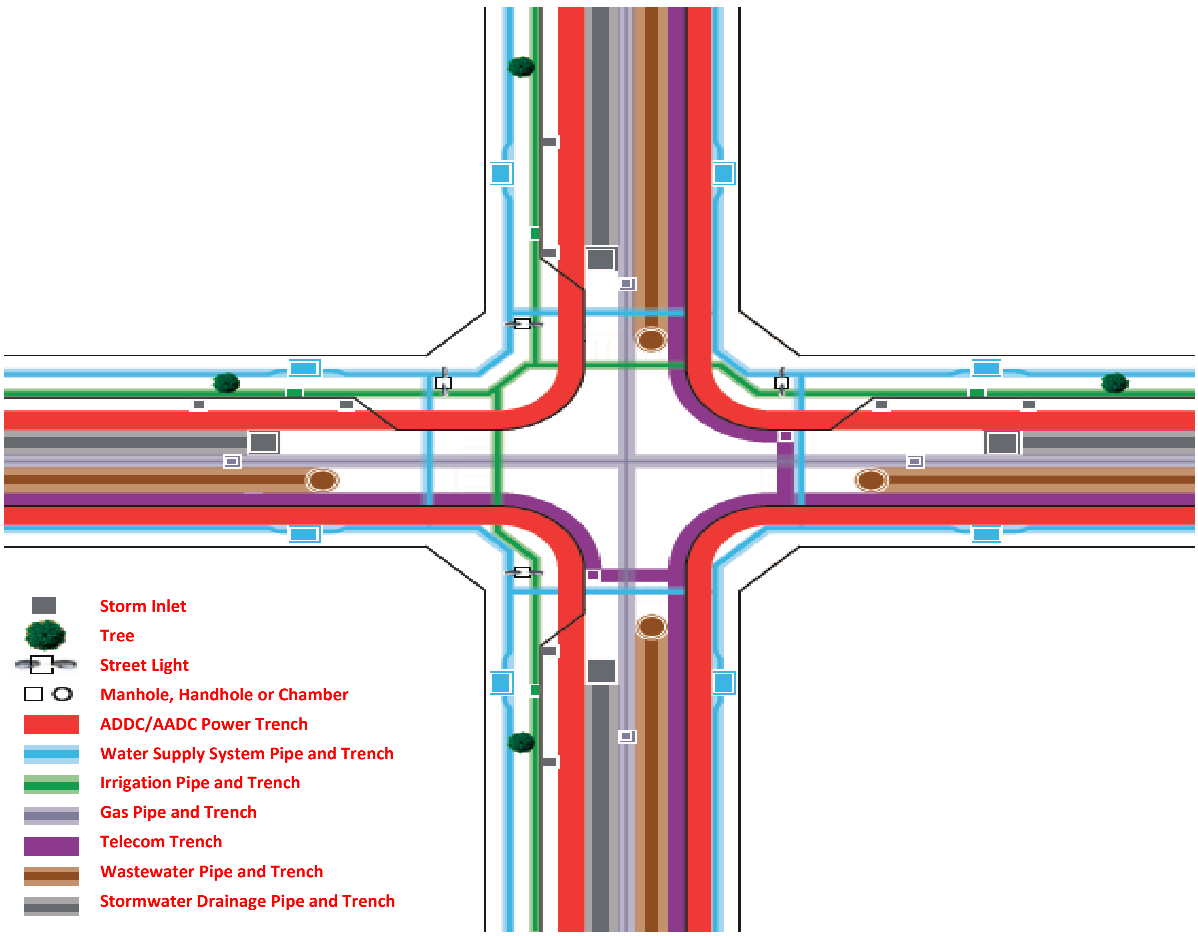


Figure 5.4: Typical Plan of Municipal Corridors indicating the asset segment mismatch problem (Abu Dhabi Urban Planning Council 2007)

typical municipal corridor the demarcation of corridors is not a simple exercise as stated earlier in Chapter 3.

Making use of the illustration shown in Figure 5.5, the generic rules used to establish the length of the corridor are:

IF $Y_{j1} > Y_{i1}$

AND $Y_{j2} > Y_{i2}$

THEN $CL_{12} = Y_{j2} - Y_{i1}$ ....Eq. (5.8)

OR IF $Y_{i1} > Y_{j1}$

AND $Y_{i2} > Y_{j2}$

THEN $CL_{12} = Y_{i2} - Y_{j1}$ ....Eq. (5.9)

OTHERWISE

$CL_{12} = \text{Max}(Li_{i2}, Lj_{12})$ ....Eq. (5.10)

where:

Water Main Segment = Asset 'i'

Water Main Assemblies (Joint/Valve) = A_i

Wastewater Main Segment = Asset 'j'

Waste Water Assemblies (Joint / Manhole) = A_j

Length of Corridor Segment 1 =CL_{12}

Overlap (Lag/Lead) between Asset Segments 'i' and 'j' = ΔCL_{12}

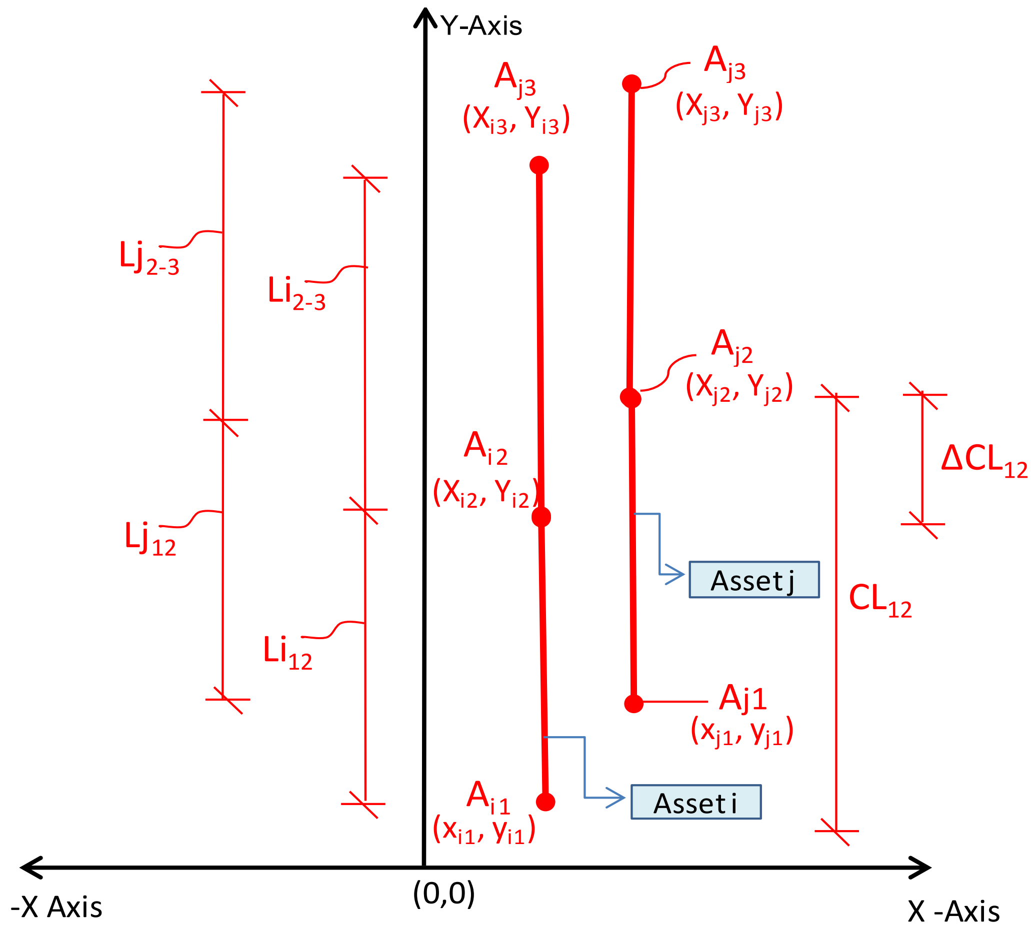


Figure 5.5: Layout Scenario for Two Spatially Co-existent Assets

Based on literature and practices referred to earlier the planning units for distance and time used in this research are:

Length Unit: Corridor Segment Length as per the above developed generic rules

Time Horizon: Pavement - 5 years, Water - 15 years, Wastewater - 15 years

The recommended frequency of assessment and implementation is yearly, however it shall be based on assets' conditions and agency preferences and available resources.

5.5 Weight Sum Model of Corridor Integrated Criticality

When there is increased frequency of complains by local residence on the performance of sub-networks, it implies that it has possibly reached to a critical state. Several quantitative and qualitative factors affect the criticality of a sub-network. The qualitative factors include the type of water network and the level of complaints by local residents, whereas the quantitative factors include the population density and tax base. The factors constituting the integrated corridor criticality are of different levels ranging from network, sub-network and corridor to asset level. Table 5.10 presents these six factors and their level in the hierarchy of the network structure and the notations used in the formulation of this weighted score model.

Table 5.10: Criticality Factors with their hierarchy and notations

Hierarchy in Network Structure	Criticality Factor	Notation on Model Formulation	
		Factor Weight	Factor Score
Network Level - W_N	Population Density	w(pd)	s(pd)
	Tax Base	w(tx)	s(tx)
Sub-network Level - W_{SN}	Level of Complaints	Pavement: wP(lc)	Pavement: sP(lc)
		Water: wW(lc)	Water: sW(lc)
		Wastewater: wS(lc)	Wastewater: sS(lc)
	Type of Sub-network	w(sn)	s(sn)
Corridor Level - W_{CL}	Spatial Co-Existence	w(co)	s(co)
Asset Level – W_{AL}	Asset Size.	wP(as)	sP(as)
		wW(as)	sW(as)
		wS(as)	sS(as)

A brief introduction of those factors which need some explanation is given below:

5.5.1 Qualitative factors

Level of complain by local residence - A significant number of complaints by local residences indicate that a sub-network has reached a critical state. Resident's complaints are divided into two types; either due to low quantity or due to low quality of water. A scale of 1 to 10 is considered suitable for this purpose. A score of 10 represents a high level of complaint and poor services related to the water distribution network whereas a score of 1 means the otherwise.

Type of the sub-network **-** The type of sub-network is important to measure the degree of criticality of a water main. A sub-network type can be classified as residential, commercial, industrial, or recreational. The type of network affects its criticality. It is a relative measure as its value depends upon its relative importance in the network. In addition, the criticality of the sub-network type varies from one city to another. Therefore, each city may have different scale to represent the importance of a sub-network. As an example, a parking sub-network can be given less importance than a hospital. A scale from 1 to 10 is considered suitable for this purpose.

5.5.2 Quantitative factors

Number of local residence - The population density of a sub-network proportionally affects the discharge of sub-network water. Sub-networks with a higher population density are considered more critical.

Tax return - The tax base of the sub-network is a key player in determining its criticality. A higher tax base though provides stronger financial capability but at the same time increases accountability and public expectation.

5.5.3 Developed Criticality Model

A qualitative scale presented at Figure 5.6 is designed to assign criticality score for each related factor. The higher the number is, the higher the degree of criticality.

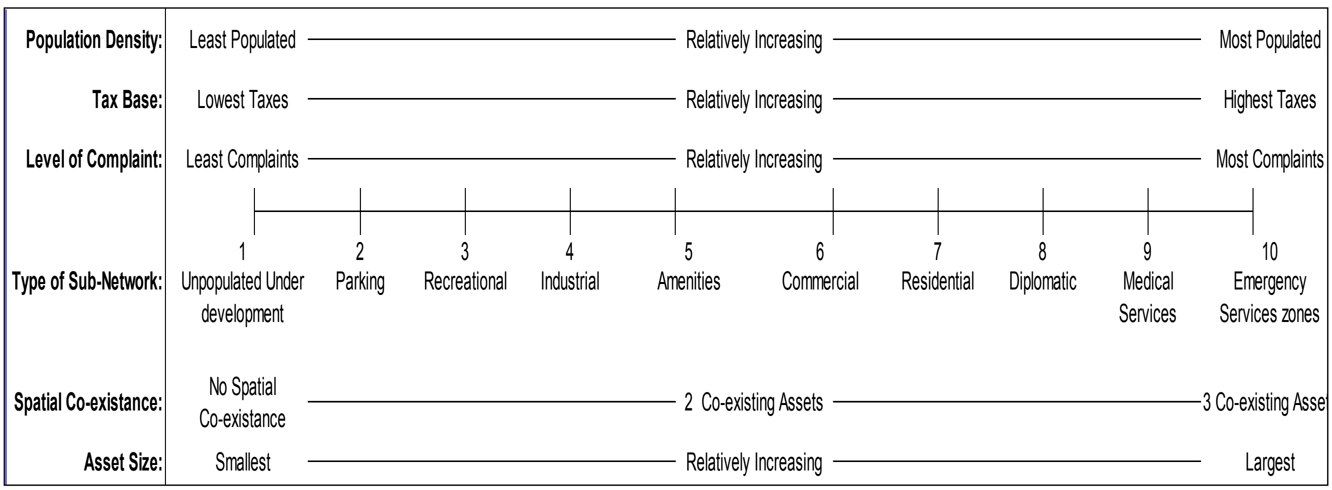


Figure 5.6: Criticality factors scale of score

The weights of all the factors used in the case study implementation are suggested by the municipal agency consultants referred earlier. Criticality of a sub-network is determined by the summation of the weighted scores of all factors. Based on the scale given at Figure 5.6 and the hierarchy given in Table 5.10, the weighted score model of corridor criticality takes the form of Eq. 5.11.

Corridor Criticality Score (CCS) = $\sum W_{NL}$ [w(pd)s(pd) + w(tx)s(tx)] + W_{SNL} [w(sn)s(sn) + w(lc){wP(lc)sP(lc) + wW(lc)sW(lc) + wS(lc)sS(lc)}] + W_{CL}[s(co)] +W_{AL}[wP(as)sP(as) +wW(as)sW(as) +wS(as)sS(as) …………………Eq. (5.11)

5.6 Artificial Neural Network Based Model of Corridor Prioritization

In order to achieve the objective of clustering the corridors under consideration into desired number of priority groups based on their integrated criticality scores and asset un-serviceability scores, un-supervised Artificial Neural Network model was considered. The integrated criticality scores is the output of the Corridor Criticality Model whereas asset un-serviceability scores are the compliment of the asset serviceability, calculated by Level of Service Model described in Section 3.4.3 and later in Section 5.1. The input factors used to train the model are presented in Table 5.11.

Table 5.11: Input Parameters for Corridor Integrated Prioritization ANN Model

SNo.	Corridor ID	Coordinate X	Coordinate Y	CCt	Water Asset		Wastewater Asset		Pavement	
					Wtw	LoUSw	Wtww	LoUSww	Wtp	LoUSp
	GIS identification number of corridors	Latitudes of the geographic coordinates	Longitudes of the geographic coordinates	Criticality score of the corridors	Relative weight of water assets in the corridors	Level of un-serviceability of water assets	Relative weight of wastewater assets in the corridors	Level of un-serviceability of wastewater assets	Relative weight of pavement assets in the corridors	Level of un-serviceability of pavement assets

Features of the model developed using Nueroshell 2 software are highlighted below in figures 5.7 and 5.71.

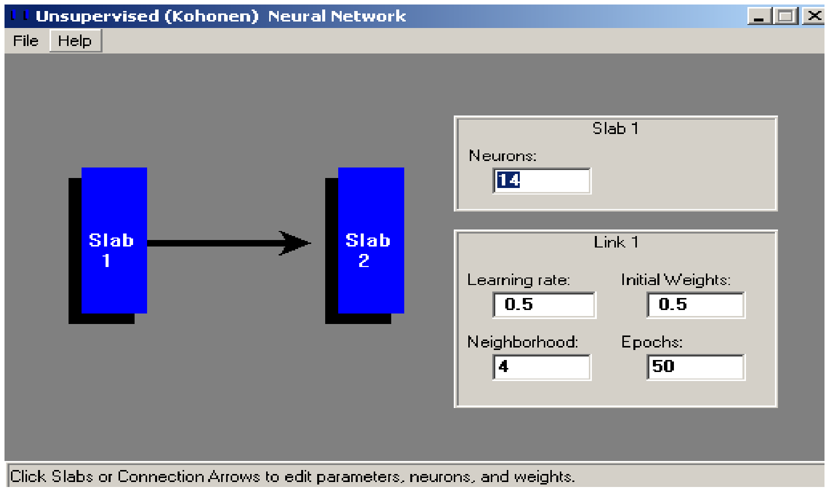


Figure 5.7: Architecture of Unsupervised (Kohonen) Neural Network- Slab 1

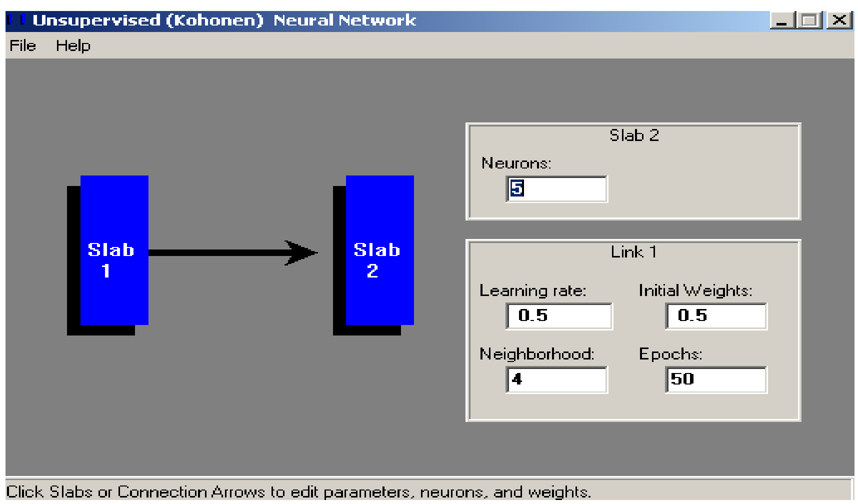


Figure 5.7.1 : Architecture of Unsupervised (Kohonen) Neural Network - Slab 2

Complete set of input data for the ANN corridor prioritization model is included in Appendix A1, and a sample of it is presented in Table 5.11.

Table 5.12: Part of the ANN Training Data

S.No.	Corridor ID	Coordinate X	Coordinate Y	Length (m) Lci	CCt	Water Asset Wtw	Water Asset LoUSw	Wastewater Asset Wtww	Wastewater Asset LoUSww	Pavement Wtp	Pavement LoUSp
	GIS identification number of corridors	Latitudes of the geographic coordinates	Longitudes of the geographic coordinates	Length of the Corridor ' *i* '	Criticality score of the corridors	Relative weight of water assets in the corridors	Level of un-serviceability of water assets	Relative weight of wastewater assets in the corridors	Level of un-serviceability of wastewater assets	Relative weight of pavement assets in the corridors	Level of un-serviceability of pavement assets
1	440201758M	681724	2745711	351	55.0	0.35	30.0	0.30	33.0	0.35	40.0
2	440202758M	681729	2745702	347	50.0	0.35	32.0	0.30	36.0	0.35	44.0
3	440203550M	682396	2744837	1425	60.0	0.35	31.0	0.30	36.5	0.35	46.0
4	440203550S			1140	65.0	0.35	30.0	0.30	36.0	0.35	46.0
5	440205758M	681251.98	2745356.31	816	50.0	0.35	33.0	0.30	38.5	0.35	48.0
6	440205759M	681307.46	2745203.49	740	60.0	0.35	34.0	0.30	40.0	0.35	50.0
7	440206759M	681520.26	2745284.79	373	55.0	0.35	32.0	0.30	33.5	0.35	39.0
8	440207759M	681204.13	2745133.8	245	55.0	0.35	35.0	0.30	32.5	0.35	34.0
9	440210758M	680327.87	2744897.41	714	55.0	0.35	29.0	0.30	36.0	0.35	47.0
10	440210759M	680355.91	2744761.69	735	60.0	0.35	40.0	0.30	39.5	0.35	43.0

5.7 Rehabilitation Techniques Feasibility Assessment

The selections of rehabilitation alternatives depend on the performance measures that collectively express and quantify the condition status of the asset. Following is the published literature based investigation of the performance measures of water mains, briefly describing their nature, and therefore an accordingly indication of their minimum and maximum desired range, distribution of values in the five condition ratings and the existing and desired values in the asset. This exercise is performed also for wastewater and pavement assets.

Crack / Fracture Width - This most important structural distress parameter is measured in millimeters. The acceptable limit differentiates between the structurally safe and unsafe state of the pipe segment. Categories within the safe limits further specify the segment's structural integrity. An analogy is drawn from a research on the crack development in water reactor pipes.

Performance Measure	Descriptio n	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
		A	B	C	D	E			
Fracture / Crack Depth (mm)	Grade	None	Negligible	Slight	Moderate	Extensive	Moderate	Moderate	None
	Acual Value	≤ 0.0	≤ 0.15	≤ 0.50	≤ 1.0	≤ 1.5	≤ 1.0	≤ 1.0	≤ 0.0
	Normalized Value	≤ 0.0	≤ 0.10	≤ 0.33	≤ 0.67	≤ 1.0	≤ 0.67	≤ 0.67	≤ 0.0
	Literature Reference	Slade and Gendron (2005)							

Pipe Sag – Belongs to the structural category; occurring generally due to deteriorated or faulty bedding conditions and (or) joint failure. Besides the above principle reasons, the magnitude depends upon segment diameter, the maximum acceptable limit of which is 10% of the inner diameter. In the illustrative example the acceptable sag values for a 12 inches diameter pipe are distributed in different condition ratings.

Performance Measure	Description	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
		A	B	C	D	E			
Sag (≤ 0.1 D mm) For 6" Ductile Pipe	Grade	Nil	Very Slight	Slight	Moderate	Extensive	Extensive	Slight	Slight
	Value	≤ 0.0	≤ 5	≤ 10	≤ 15	≤ 20	≤ 20	≤ 10	≤ 10
	Normalized Value	≤ 0.0	≤ 0.25	≤ 0.50	≤ 0.75	≤ 1.0	≤ 1.0	≤ 0.50	≤ 0.50
	Literature Reference	American Water Works Asociation (2004)							

Corrosion - Corrosion decreases the effective thickness of pipe therefore this distress of structural deterioration is gauged in terms of % reduction in pipe wall thickness. As identified in the report DNV 2010 a reduction of more than 60 % in pipe wall thickness makes the pipe structurally unsafe.

Performance Measure	Description	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
		A	B	C	D	E			
Corrosion (% Pipe Thickness Reduction)	Grade	Nil	Slight	Moderate	Extensive	Severe	Extensive	Extensive	Slight
	Value	≤ 0.0	≤ 10	≤ 35	≤ 60	≤ 85	≤ 60	≤ 60	≤ 10
	Normalized Value	≤ 0.0	≤ 0.10	≤ 0.40	≤ 0.70	≤ 1.0	≤ 0.70	≤ 0.70	≤ 0.10
	Literature Reference	DET NORSKE VERITAS (2010)							

Leakage Volume - This operation category distress measure does not only takes into account water loss, but also provides an indirect indication for structural condition. It is a rate depending on the time duration, length and the size (diameter) of the observed segment The unit is therefore litres /day/km/inch diameter.

Performance Measure	Description	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
		A	B	C	D	E			
Leakage Volume (Litres/Day/Km/in-dia)	Grade	Very Slight	Slight	Moderate	Extensive	Severe	Extensive	Extensive	Very Slight
	Value	≤ 10	≤ 50	≤ 75	≤ 150	≤ 250	≤ 150	≤ 150	≤ 10
	Normalized Value	≤ 0.35	≤ 0.50	≤ 0.70	≤ 0.85	≤ 1.0	≤ 0.85	≤ 0.85	≤ 0.35
	Literature Reference	Jones and Laven (2008)							

Roughness Coefficient (C-Factor) - This is another measure under the operations category and relates to the flow of water in a pipe and to the pressure drop caused by internal friction. It expresses the capability to provide flow for firefighting and addresses the fire safety concerns of the community Roughness co-efficient is a value, the greater the number the lower is the roughness and the better is the pipe's internal operational condition.

Performance Measure	Description	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
		A	B	C	D	E			
Roughness Coefficient (C-Factor) Range= (125 - 50)	Grade	Very High	High	Moderate	Low	Very Low	Low	Low	High
	Value	≥ 125	≥ 105	≥ 85	≥ 65	≥ 50	≥ 65	≥ 65	≥ 105
	Normalized Value *	≤ 0.0	≤ 0.25	≤ 0.55	≤ 0.80	≤ 1.0	≤ 0.80	≤ 0.80	≤ 0.25
	Literature Reference	Corr Tech Incorporated (2002)							

*-- A value of 1.0 is subtracted from the normalized value to change the order so that decrease in normalized value result in lower number of Condition Rating

Loss in Water Pressure - This operational measure directly concerns the community's comfort level. According to international standards (ICC 2012) most of the US and Canadian cities have adopted minimum and maximum pressure benchmarks equal to 20 psi (140 kPA) and 80 psi (550 kPA) for municipal drinking water supplies. An optimum household pressure of 60 psi is considered in this study. Acceptable loss in pressure at peak demand is distributed in the different condition ratings as given below.

Performance Measure	Description	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
		A	B	C	D	E			
Loss in Water Pressure (Psi) Household Supply Standard = 60 psi	Grade	Very Low	Low	Moderate	High	Very High	High	High	Low
	Value	≤ 10	≤ 15	≤ 20	≤ 25	≤ 30	≤ 25	≤ 25	≤ 15
	Normalized Value	≤ 0.0	≤ 0.25	≤ 0.50	≤ 0.75	≤ 1.0	≤ 0.75	≤ 0.75	≤ 0.25
	Literature Reference	ICC (2012)							

Water Quality Category - Lead, Iron and Total Coliform Bacteria Concentrations

Lead and Iron: Water quality concerns of the community are accounted in terms of concentration of the contaminants found in the distributed water, measured at the water main / segment level. Physical condition of the segment relevant to that particular distress is observed and if the segment is regarded as contributing to the overall network level contamination it is included in the rehabilitation plan. Three contaminants are suggested to be monitored including lead, iron and total coliform bacteria. For each contaminant the level of concentration raising health concerns is identified according to the internal health standards.

The range of concentration of lead and iron from negligible to maximum allowable is divided into the five levels of condition rating. A segment is considered to correspond to a certain contamination level (condition rating), if more than 10% of the samples tested at a certain time result positive for that level. Based on the international standards the maximum allowable concentration of lead and iron is 0.015 mg/l and 0.3 mg/l respectively.

Coliform Bacteria: It is the most important distress measure of water quality. The sources are the cross connection that do not follow recommended practices and/or of Wastewater / contaminate water into the main from fractures /misaligned joints during negative pressure conditions in the water main. As per US health standards, the unit of measurement of total coliform bacteria is the percentage positive monthly test samples.

Performance Measure	Description	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
		A	B	C	D	E			
Lead Concentration (Action Level at 10 % + ve Sample for 0.015 mg/l) Range= (0 - 100)	Grade	Very Low	Low	Moderate	High	Very High	Moderate	Moderate	Low
	Value	≤ 0.003	≤ 0.006	≤ 0.009	≤ 0.012	≤ 0.015	≤ 0.009	≤ 0.009	≤ 0.006
	Normalized Value	≤ 0.0	≤ 0.25	≤ 0.50	≤ 0.75	≤ 1.0	≤ 0.50	≤ 0.50	≤ 0.25
Iron Concentration (Action Level at 10 % + ve Sample for 0.3 mg/l) Range= (0 - 100)	Grade	Very Low	Low	Moderate	High	Very High	High	Very High	Low
	Value	≤ 0.1	≤ 0.15	≤ 0.20	≤ 0.25	≤ 0.3	≤ 0.25	≤ 0.3	≤ 0.15
	Normalized Value	≤ 0.0	≤ 0.25	≤ 0.50	≤ 0.75	≤ 1.0	≤ 0.75	≤ 1.0	≤ 0.25
Total Coliform Bacteria (% positive samples in a month)	Grade	None	Rare	Few	Occasional	Often	Rare	Few	None
	Value	0	≤ 1	≤ 2	≤ 4	≤ 5	≤ 1	≤ 2	0
	Normalized Value	≤ 0.0	≤ 0.20	≤ 0.40	≤ 0.80	≤ 1.0	≤ 0.20	≤ 0.40	≤ 0.0
	Literature Reference	EPA (2013)							

As seen above, a total of nine performance measures pertaining to water mains are investigated. On the other hand, a set of water main intervention alternatives, comprising seven structural, one semi structural and three non-structural operational rehabilitation techniques is identified. The entire analysis of the feasibility of rehabilitation techniques for water, wastewater and pavement, each consists of the following three parts:

<u>Techniques Applicability Matrices</u>: This is a one-time assessment for each asset type. Used rehabilitation techniques for the asset type are checked for their possibility to improve each performance measure of the asset. A check mark in the matrix implies that the particular technique is able to address that particular performance measure. Only those techniques are qualified to move to next stage that address all performance measures needing improvement.

<u>Techniques Capability Matrices:</u> This also is a one-time assessment for each asset type. Here a more detailed investigation is done about the capability of each technique that qualified in the applicability assessment above. For each performance measure, the worst condition that the technique can handle is determined. Similarly, the best state of

the performance measure that the technique can render after its application on the asset is also determined. Both states are expressed using the condition rating scale developed (Section 5.2).

Techniques Feasibility Matrices: This is the final stage in which the capability of each technique (worst and best condition) with respect to each performance measure is compared with the required condition improvement (existing and desired condition). A techniques is finally qualified to enter into the feasible solutions space for the developed optimization model only when it satisfy both the existing and desired condition requirements.

5.7.1 Techniques Applicability Matrix (Water Mains)

Table 5.13 is the matrix showing the applicability of each technique with respect to each performance measure. Out of the seven structural rehabilitation techniques, the four pipe replacement ones address all considered types of distress. The remaining three are structural liners which rectify all distress except pipe sag. The applicability score for structural rehabilitation category with 7x9 matrix size is 95%. Cured in Place Pipe (CIPP) which is the only semi structural rehabilitation considered, addresses only the corrosion, roughness coefficient, lead and iron concentration distresses and so have an applicability rate of 44%. The applicability of the three non-structural techniques is 26% which is much lower because each of these addresses some specific distresses only.

Table 5.13: Generic Form of Rehabilitation Techniques Applicability Matrix (Water Mains)

Rehabilitation Category	Rehabilitation Alternative	Fracture/ Crack Width (mm)	Sag (≤ 0.1 D mm) For 6" Ductile Pipe	Corrosion (% Pipe Thickness Reduction)	Leakage Volume (Gallons/ Day/Mile/ in-dia)	Roughness Coefficient (C-Factor) Range= (125 - 65)	Loss in Water Pressure (Psi) Household Supply Standard = 60 psi	Lead Concentration (Action Level at 10 % + ve Sample for 0.015 mg/l) Range= (0 - 100)	Iron Concentration (Action Level at 10 % + ve Sample for 0.3 mg/l) Range= (0 - 100)	Total Coliform Bacteria (% positive samples in a month)	$ /inch-Dia/Foot (As of Sept 2012)	Remaining Service Life (Yrs)
No Intervention	Do Nothing											
Structural	Open Cut Replacement (Concrete)	X	X	X	X	X	X	X	X	X	18	100
	Slip Lining	X		X	X	X	X	X	X	X	4 -6	40
	Closed Fit Site Folded Sliplining	X		X	X	X	X	X	X	X	4 - 6	50
	Cured in Place (CIPP) - Felt	X		X	X	X	X	X	X	X	6 - 14	60
	Pipe Bursting	X	X	X	X	X	X	X	X	X	7 - 9	90
	Horizontal Directional Drilling	X	X	X	X	X	X	X	X	X	10 -25	90
	Micro Tunneling	X	X	X	X	X	X	X	X	X	17 - 24	90
Semi-Structural	Cured in Place (CIPP) - Membrane			X		X		X	X		4 - 9	50
Non-Structural	Internal Joint Seals		X								(0.35 - 0.65)	25
	Spray Lining			X		X		X	X		9 - 15	75
	Spot Welding	X			X						0.25 -0.50	20

5.7.2 Techniques Capability Matrix (Water Mains)

The techniques capability matrix is presented at Table 5.14. A simple naming convention for labeling the techniques capability information is set here. While referring to Table 5.14, as per this convention, the improvement required either in the individual performance measure or in the overall condition of the asset can be represented by a label set, an example of which is (X31, X31'), where ' X31' refers to the initial condition grade corresponding to the 3rd technique and 1st performance measure. Similarly, ' X31' ' refers to the final condition grade corresponding to the same 3rd technique and 1st performance measure. Non-applicability of a technique for a certain measure is represented by (1 , 5) which is a label that logically cannot be selected in any case, thereby implies non-applicability. It should be noted that the last row in the matrix pertains to condition improvement requirement and includes existing and targeted condition of the asset for every performance measure.

Table 5.14: Generic Form of Techniques Capability Matrix

Rehabilitation Category	Rehabilitation Alternative	Performance Measure (PM_1)		Performance Measure (PMx)		Performance Measure (PMx)		Performance Measure (PMx)		Performance Measure (PMx)		Performance Measure (PMx)		Performance Measure (PMx)		Performance Measure (PMx)		Performance Measure (PMn)		$/inch-Dia/Foot (As of Sept 2012)	Remaining Service Life Yrs)
		(F)		(S)		(C)		(V)		(R)		(P)		(L)		(I)		(B)			
	Technique's Capability Assessment																				
No Intervention	Do Nothing	X01	X01'	X02	X02'	X03	X03'	X04	X04'	X05	X05'	X06	X06'	X07	X07'	X08	X08'	X09	X09'		
Structural	Rehabilitation Technique 1	X11	X11'	X12	X12'	X13	X13'	X14	X14'	X15	X15'	X16	X16'	X17	X17'	X18	X18'	X19	X19'	$	Yrs
	Rehabilitation Technique x	X21	X21'	X22	X22'	X23	X23'	X24	X24'	X25	X25'	X26	X26'	X27	X27'	X28	X28'	X29	X29'	$	Yrs
	Rehabilitation Technique x	X31	X31'	X32	X32'	X33	X33'	X34	X34'	X35	X35'	X36	X36'	X37	X37'	X38	X38'	X39	X39'	$	Yrs
Semi-Structural	Rehabilitation Technique x	X41	X41'	X42	X42'	X43	X43'	X44	X44'	X45	X45'	X46	X46'	X47	X47'	X48	X48'	X49	X49'	$	Yrs
Non-Structural	Rehabilitation Technique x	X51	X51'	X52	X52'	X53	X53'	X54	X54'	X55	X55'	X56	X56'	X57	X57'	X58	X58'	X59	X59'	$	Yrs
	Rehabilitation Technique x	X61	X61'	X62	X62'	X63	X63'	X64	X64'	X65	X65'	X66	X66'	X67	X67'	X68	X68'	X69	X69'	$	Yrs
	Rehabilitation Technique x	X71	X71'	X72	X72'	X73	X73'	X74	X74'	X75	X75'	X76	X76'	X77	X77'	X78	X78'	X79	X79'	$	Yrs
Maintenance	Rehabilitation Technique x	X81	X81'	X82	X82'	X83	X83'	X84	X84'	X85	X85'	X86	X86'	X87	X87'	X88	X88'	X89	X89'	$	Yrs
	Rehabilitation Technique n	X91	X91'	X92	X92'	X93	X93'	X94	X94'	X95	X95'	X96	X96'	X97	X97'	X98	X98'	X99	X99'	$	Yrs
Condition Improvement Requirement	Condition Improvement Requirement																				
		I1	I1'	I2	I2'	I3	I3'	I4	I4'	I5	I5'	I6	I6'	I7	I7'	I8	I8'	I9	I9'		

5.7.3 Techniques Feasibility Matrix (Water Mains)

To determine the suitability of rehabilitation techniques that fulfill the condition improvement requirement, the row of each technique in Table 5.14 is compared with the last row of that table that represents the asset requirement. Using a simple Excel Macro code, the feasibility of individual techniques are checked and thereby a list of the candidate techniques are identified for the selection of the best one according to the optimization criteria set by the agency / community. For a technique to be feasible the first numeral (the worst condition that the technique can address) of the candidate should be greater than the corresponding numeral (existing condition) of the asset. On the other hand, the second numeral of the candidate (post intervention condition of the asset) should be less than the corresponding numeral (targeted condition) of the asset. If the technique passes the test of both ends, it proves suitable for that particular measure. A technique is regarded as a feasible option for rehabilitation, only if it qualifies for all performance measures. The result is reflected by a ‘ Y ’ in the last ‘Feasibility’ column. If the technique does not qualify in any of the measures, it is disregarded as a feasible solution and is assigned ‘N’ as shown in Table 5.15.

Table 5.15: Generic Form of Rehabilitation Techniques Feasibility Matrix (Water Mains)

Rehabilitation Category	**Rehabilitation Techniques**	**Feasibility Assessment**																		**Applicability**
No Intervention	Do Nothing	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Structural	Rehabilitation Technique 1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Rehabilitation Technique x	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Rehabilitation Technique x	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Semi-Structural	Rehabilitation Technique x	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	Y	Y	N	N
Non-Structural	Rehabilitation Technique x	N	N	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	N	N	N	N
	Rehabilitation Technique x	Y	Y	Y	N	N	N	N	N	Y	N	Y	N	Y	N	Y	N	N	N	N
	Rehabilitation Technique x	N	N	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	N	N	N	N
Maintenance	Rehabilitation Technique x	Y	Y	Y	N	N	N	N	N	Y	N	Y	N	Y	N	Y	N	N	N	N
	Rehabilitation Technique n	N	N	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	N	N	N	N

5.8 Goal Programming Penalty Score Based Optimization Model for Rehabilitation Alternatives

Individually optimized solutions for water, wastewater and pavement assets are determined by a goal programming penalty score based formulation, customized according to the specific requirements of this study. As referred to in Section 3.5.2, the optimization criteria include asset condition improvement, unit cost of rehabilitation and post intervention remaining service life.

The nature of the optimization problem at hand requires that rehabilitation plans of different asset types are optimised individually. The three selected techniques, one for each asset, based on least penalty score, constitute the optimum work plan of the corridor. The detailed technical validity of the optimum solutions shall, however, be further investigated from execution point of view.

5.8.1 Optimization Model Formulation

Table 5.16: Goal Programming Optimization Model Formulation for Water Asset

Goal (Units)			Cost ($)/Lft	Condition	RSL
			75	0.19	15
Penalty Weights			Cost (Overrun)	Condition (Over/ Under Achieved)	RSL (x10 Yrs) (Under Achieved)
			4 (+)	20(+), 50 (-)	3 (-), 3(+)
Rehabilitation Technique		Cost ($ /in dia / Lft	Cost ($ / Lft) (18 in. Dia Pipe)	Post Intervention Condition Index	Remaining Service Life - RSL (Yrs)
Notation	WT	(CT)	(C'T)	(CIT)	(RSLT)
Do Noting	WT1	CT1	C'T1	CIT1	RSLT1
Water Main Rehabilitation Technique 2	WT2	CT2	C'T2	CIT2	RSLT2
Water Main Rehabilitation Technique 3	WT3	CT3	C'T3	CIT3	RSLT3
Water Main Rehabilitation Technique 4	WT4	CT4	C'T4	CIT4	RSLT4
Water Main Rehabilitation Technique 5	WT5	CT5	C'T5	CIT5	RSLT5
Water Main Rehabilitation Technique 6	WT6	CT6	C'T6	CIT6	RSLT6
Water Main Rehabilitation Technique 7	WT7	CT7	C'T7	CIT7	RSLT7
Water Main Rehabilitation Technique 8	WT8	CT8	C'T8	CIT8	RSLT8

The objective function of the developed optimization model for water asset is:

Minimize $Z = 4\,\Delta\$^{+} - 20\,\Delta C^{+} + 50\,\Delta C^{-} + 3\,\Delta RSL^{-} - 3\,\Delta RSL^{+}$ ……………..Eq. (5.12)

Goals: Water Techniques Selection

Goal 1: C'T = 75

Goal 2: CIT = 0.19

Goal 3: RSLT = 15

Table 5.17: Goal Programming Optimization Model Formulation for Wastewater Asset

<table>
<tr><th colspan="3" rowspan="2">Goal (Units)</th><th>Cost ($)/Lft</th><th>Condition</th><th>RSL</th></tr>
<tr><td>60</td><td>0.22</td><td>15</td></tr>
<tr><th colspan="3" rowspan="2">Penalty Weights</th><td>Cost (Overrun)</td><td>Condition (Over/ Under Achieved)</td><td>RSL (x10 Yrs) (Under Achieved)</td></tr>
<tr><td>4 (+), 4(-)</td><td>20(+), 50 (-)</td><td>3 (+), 2 (-)</td></tr>
<tr><th colspan="2">Rehabilitation Technique</th><td>Cost ($ /in dia / Lft</td><td>Cost ($ / Lft) (24 in. Dia Pipe)</td><td>Post Intervention Condition Index</td><td>Remaining Service Life - RSL (Yrs)</td></tr>
<tr><td>Notation</td><td>WWT</td><td>(CT)</td><td>(C'T)</td><td>(CIT)</td><td>(RSLT)</td></tr>
<tr><td>Do Noting</td><td>WWT1</td><td>CT1</td><td>C'T1</td><td>CIT1</td><td>RSLT1</td></tr>
<tr><td>Water Main Rehabilitation Technique 2</td><td>WWT2</td><td>CT2</td><td>C'T2</td><td>CIT2</td><td>RSLT2</td></tr>
<tr><td>Water Main Rehabilitation Technique 3</td><td>WWT3</td><td>CT3</td><td>C'T3</td><td>CIT3</td><td>RSLT3</td></tr>
<tr><td>Water Main Rehabilitation Technique 4</td><td>WWT4</td><td>CT4</td><td>C'T4</td><td>CIT4</td><td>RSLT4</td></tr>
<tr><td>Water Main Rehabilitation Technique 5</td><td>WWT5</td><td>CT5</td><td>C'T5</td><td>CIT5</td><td>RSLT5</td></tr>
<tr><td>Water Main Rehabilitation Technique 6</td><td>WWT6</td><td>CT6</td><td>C'T6</td><td>CIT6</td><td>RSLT6</td></tr>
<tr><td>Water Main Rehabilitation Technique 7</td><td>WWT7</td><td>CT7</td><td>C'T7</td><td>CIT7</td><td>RSLT7</td></tr>
<tr><td>Water Main Rehabilitation Technique 8</td><td>WWT8</td><td>CT8</td><td>C'T8</td><td>CIT8</td><td>RSLT8</td></tr>
</table>

Similarly, the objective function for wastewater asset rehabilitation is:

$$\text{Minimize } Z = 4\,\Delta\$^{+} + 4\,\Delta\$^{-} + 20\,\Delta C^{+} + 50\,\Delta C^{-} + 3\,\Delta RSL^{+} + 2\,\Delta RSL^{-} \quad \ldots\text{Eq. (5.13)}$$

Goals: Wastewater Techniques Selection

Goal 1: C'T = 60

Goal 2: CIT = 0.22

Goal 3: RSLT = 15

Table 5.18: Goal Programming Optimization Model Formulation for Pavement Asset

Goal (Units)			Cost ($)/Lft	Condition	RSL
			50	0.15	5
Penalty Weights			Cost (Overrun)	Condition (Over/ Under Achieved)	RSL (x10 Yrs) (Under Achieved)
			4 (+), 4(-)	20(+), 50 (-)	2 (+), 3 (-)
Rehabilitation Technique		Cost ($ /Lane ft)	Cost ($ / 2 Lane ft)	Post Intervention Condition Index	Remaining Service Life - RSL (Yrs)
Notation	PT	(CT)	(C'T)	(CIT)	(RSLT)
Do Noting	PT1	CT1	C'T1	CIT1	RSLT1
Water Main Rehabilitation Technique 2	PT2	CT2	C'T2	CIT2	RSLT2
Water Main Rehabilitation Technique 3	PT3	CT3	C'T3	CIT3	RSLT3
Water Main Rehabilitation Technique 4	PT4	CT4	C'T4	CIT4	RSLT4
Water Main Rehabilitation Technique 5	PT5	CT5	C'T5	CIT5	RSLT5
Water Main Rehabilitation Technique 6	PT6	CT6	C'T6	CIT6	RSLT6
Water Main Rehabilitation Technique 7	PT7	CT7	C'T7	CIT7	RSLT7
Water Main Rehabilitation Technique 8	PT8	CT8	C'T8	CIT8	RSLT8

And that for pavement asset is:

Minimize $Z = 4\,\Delta\$^{+} + 4\,\Delta\$^{-} + 20\,\Delta C^{+} + 50\,\Delta C^{-} + 2\,\Delta RSL^{-} + 3\,\Delta RSL^{-}$ …….Eq. (5.14)

Goals: Pavement Techniques Selection

Goal 1: C'T = 50

Goal 2: CIT = 0.15

Goal 3: RSLT = 5

Normalization of Penalty Points of the Goal Programing Models

The three optimization parameters have different units and so the numerical scale of their values vary widely. This can result in inaccurate or non-representative estimation of penalty points of corridors that can lead to non-optimum selections. This problem is solved by normalizing the penalty points of each of the optimization parameters for each asset class. For instance, in Chapter 6 it can be noted that for the water asset of ‘Corridor ‘i’ the cost of different feasible intervention alternatives are in a range of 5 to 21 ($/in dia. /Lft) whereas the remaining service life values range from 50 to 100 years. Data, including penalty points, are normalized on a scale of 0 to1, thereby giving uniform scale of comparison to the decision makers.

The output of the optimization process when summarized provides work plan of the corridor as presented in Table 5.19:

Table 5.19: Optimization Model Output (Corridors Work Plans)

Corridor ID (Prioritized Order)	**Optimum Rehabilitation Techniques**		
	Water Asset	**Wastewater Asset**	**Pavement Asset**
Corridor i	Water Asset Rehab. Tech i	Wastewater Asset Rehab. Tech i	Pavement Asset Rehab. Tech i
Corridor j	Water Asset Rehab. Tech j	Wastewater Asset Rehab. Tech j	Pavement Asset Rehab. Tech j
.	.	.	.
.	.	.	.
Corridor n	Water Asset Rehab. Tech n	Wastewater Asset Rehab. Tech n	Pavement Asset Rehab. Tech n

CHAPTER 6: IMPLEMENTATION OF DEVELOPED MODELS TO CASE STUDY

The data used in the case study is described in previous chapters. Reference is made here to Appendices C and D, Tables 4.4 to 4.11 as well as Tables 5.2 to 5.9, which contain Level of Service and Condition Rating data, and Tables 5.13, 5.14 and 5.15 which describe the generic structure of the matrices used for determining the applicability, capability and feasibility of the rehabilitation techniques.

In the tables referred to above, the response of the consultants is highlighted. Given the above, a relatively non-textual and direct approach is adopted to illustrate the implementation of the models. The approach includes indicating for water distribution mains only, all the models / rules, giving the mathematical formula, providing the tables generated in the analysis presented in a sequential order and finally showing the output of the model. However, analyses for wastewater and pavement assets are not repeated.

6.1 Performance Modeling & Quantification of Condition Improvement

The analyses under this section are as follows:

6.1.1 Scaling Asset Condition and Performance Measures

Tables 5.2, 5.3 and 5.4 respectively give the numerical and normalized values of the service thresholds, existing and desired targeted values of the water distribution mains, wastewater collection mains and pavement segments.

Here the analysis to calculate Level of service, condition rating and mapping of LoS to CR is performed. Since these analyses are generic therefore only those for water mains are presented here.

6.1.2 AHP Based Level of Service Quantification and Assessment

The formulation: Water Main Service Percentile = WMSP = $\sum_{i=1}^{n}\sum_{j=1}^{m}(SDWij)*(AEij)$

Reference Tables: 5.2 to 5.5

Table 6.1: Tabulation of AHP calculations and service percentile results for Water Main

No.	Factor	Consistency Index	Consistency Ratio	Main Factor Weight	Sub-Factor Weight	Sub-Factor Decomposed Weight	Attribute Effect Value		LoS Score	
							Existing	Target	Existing	Target
	Performance Indicator									
1.0	Structural			0.4622	-	-	-	-	-	-
2.0	Operational	0.0003	0.0004	0.3016	-	-	-	-	-	-
3.0	Water Quality			0.2361	-	-	-	-	-	-
	Structural Performance Measure									
1.1	Crack Width				0.1637	0.0757	43	100	3.25	7.57
1.2	Sag	0.0002	0.0003	0.4622	0.5391	0.2492	67	67	16.69	16.69
1.3	Corrosion				0.2971	0.1373	29	88	3.98	12.08
	Operational Performance Measure									
2.1	Leakage Volume				0.5376	0.1621	50	97	8.11	15.73
2.2	Roughness Coefficient	0.0006	0.001	0.3016	0.1638	0.0494	27	53	1.33	2.62
2.3	Loss in Water Pressure				0.2987	0.0901	100	60	9.01	5.41
	Water Quality Performance Measure									
3.1	Lead Concentration				0.329	0.0777	40	60	3.11	4.66
3.2	Iron Concentration	0.0005	0.0008	0.2361	0.529	0.1249	40	70	5.00	8.74
3.3	Coliform Bacteria				0.142	0.0335	60	100	2.01	3.35
								Service Percentile	52.49	76.85

Water Main Service Percentile (WMSP) presented by Equation 5.5, is calculated as follows:

- Multiply the “Sub-factor Decomposed Weight” column by the “Attribute Effect Value” column in Table 6.1, to obtain the Level of Service scores contributed by each performance measure towards the overall Service Percentile of the asset.
- Summation of the Level of Service scores made by all the performance measures is the Water Main Service Percentile (WMSP).

Using the developed WMSP model, the existing and targeted service percentiles of this illustrative example are calculated to be 52.49 and 76.85, respectively.

Table 6.2: Service Percentile Values of Water, Wastewater and Pavement Assets Using AHP Model of LoS

Service Percentiles	Existing	Targeted
Water Asset	0.5249	0.7685
Wastewater Asset	0.5130	0.7902
Pavement	0.5915	0.7568

6.1.3 Fuzzy weighted average Based Condition Rating and Mapping of LoS to CR

Model Formulation: $R = \Sigma (Ri \times Wi) / \Sigma Wi$

Reference: Tables 5.6 to 5.9

Brief illustration of the computational process that utilizes Equation 5.6, using ‘α’ cut theorem is described below. Only calculations at ά = 0 are presented. Calculations for other values of ‘ά’ were performed using the developed subroutine. Fuzzy grades and weights of distress measures for the existing and targeted scenarios are given in Table 6.3.

Table 6.3: Performance Measure Values, Weights & Fuzzy Sets for Existing & Target Condition of Water Mains

Performance Indicator	No.	Performance Measure		Existing Scenario			Targeted Scenario		
				Actual	Normalized	Fuzzy Grade	Actual	Normalized	Fuzzy Grade
Structural	1	Crack Width	Value	10	0.67	D	0	0	A
			Weight	-	-	E	-	-	E
	2	Sag	Value	10	0.5	C	10	0.5	C
			Weight	-	-	A	-	-	A
	3	Corrosion	Value	60	0.71	D	10	0.12	B
			Weight	-	-	D	-	-	D
Operational	4	Leakage Volume	Value	150	0.6	D	10	0.04	A
			Weight	-	-	C	-	-	C
	5	Roughness Coefficient	Value	65	0.48	D	105	0.16	B
			Weight	-	-	D	-	-	D
	6	Loss in Water Pressure	Value	25	0.83	D	15	0.5	B
			Weight	-	-	C	-	-	B
Water Quality	7	Lead Concentration	Value	0.0009	0.6	C	0.0006	0.4	B
			Weight	-	-	D	-	-	D
	8	Iron Concentration	Value	0.25	1	E	0.15	0.5	B
			Weight	-	-	B	-	-	B
	9	Coliform Bactria	Value	1	0.4	C	0	0	A
			Weight	-	-	E	-	-	E

The computational sub-routine for α – Cut theorem is described in the following step-by-step procedure:

1. Select a group of ά-values needed to de-fuzzify the fuzzy sets. In most cases, use of 11 values of ά from 0.0 to 1.0, with an increment of 0.1 is enough to de-fuzzify a fuzzy set. In this example for simplicity, only three values (0.0, 0.5, and 1.0) are used. For ά = 0.0, obtain the ά-cut interval values of each

input fuzzy set. According to the membership functions defined in Table 5.9 the following ά-cut intervals can be obtained for the existing condition of each of the inputs:

I_{R2}, I_{R7} and I_{R9} = Fuzzy Grade/Set "C" = (0.3, 0.7); I_{R1}, I_{R3}, I_{R4}, I_{R5} and I_{R6} = Fuzzy Grade/Set "D" = (0.5, 0.9); I_{R8} = Fuzzy Grade/Set "E" = (0.8, 1.0).

Similarly for weights:

I_{W2}, = Fuzzy Grade/Set "A" = (0.0,0.2); I_{W8} = Fuzzy Grade/Set "B" = (0.1, 0.5); I_{W4}, and I_{W6} = Fuzzy Grade/Set "C" = (0.3,0.7); I_{W3}, I_{W5} and I_{W7} = Fuzzy Grade/Set "D" = (0.5,0.9) and I_{W1} and I_{W9} = Fuzzy Grade/Set "E" = (0.8,1.0).

2. Calculate 'R' using Eq. 5.6, with ά -cut intervals (for ά = 0.0, 0.5 and 1.0). Multiplication and division operations on fuzzy intervals as required by the Eq.5.6 are performed as follows:

   Multiplication:

   $[a_1, a_3]\ (\bullet)\ [b_1, b_3] = [a_1 \bullet b_1 \wedge a_1 \bullet b_3 \wedge a_3 \bullet b_1 \wedge a_3 \bullet b_3,\ a_1 \bullet b_1 \vee a_1 \bullet b_3 \vee a_3 \bullet b_1 \vee a_3 \bullet b_3]$

   Division:

   $[a_1, a_3]\ (/)\ [b_1, b_3] = [a_1 / b_1 \wedge a_1 / b_3 \wedge a_3 / b_1 \wedge a_3 / b_3,\ a_1 / b_1 \vee a_1 / b_3 \vee a_3 / b_1 \vee a_3 / b_3]$

Based on the above formation, the following are the detailed calculations of the three ά -cut intervals values. The results are R (ά = 0) = (0.376, 0.753), R (ά = 0.5) = (0.46, 0.67) and R(ά =1.0) = (0.56, 0.56). The selected values of 'α' and the values of the distress measures calculated at these 'α' intervals, constitute the resulting fuzzy number of condition rating, as shown in Figure 6.1.

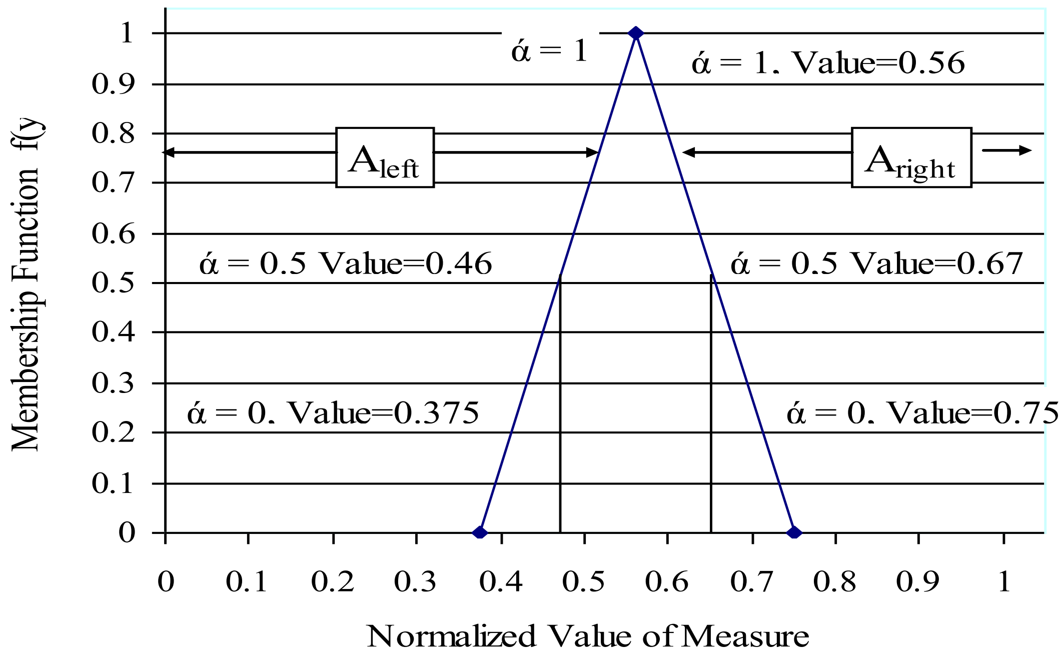


Figure 6.1: Calculation of Unified Water Main Distress Index

Based on the performance measure values assumed in this illustrative example, the Unified Water Main Distress Index (UWMDI) is calculated using Eq. 5.7.

$$\text{UWMDI} = \frac{A_{left} - A_{right} + 1}{2} \qquad \text{……………..……………………………Eq. (6.1)}$$

The UWMDI mapped to existing service percentile of 52.49 is calculated to be 0.4316. Similarly the Distress Index corresponding to the targeted service percentile of 76.85 is 0.2416. It should be noted that the smaller the performance measure values are , the greater the area ‘A_{right}’ in Figure 6.1, and the smaller the resulting ‘UWMDI’. Vice versa also holds true.

Using the same approach, the existing and targeted condition ratings of wastewater and pavement assets are calculated. The quantitative assessment of condition improvement needs can now be determined from the difference between the existing and targeted condition ratings as shown in Table 6.4 below.

Table 6.4: Condition Rating Values of Water, Wastewater and Pavement Assets

Asset Type	Existing	Targeted	Required Condition Improvement
Water Asset	0.4316	0.2416	0.19
Wastewater Asset	0.5460	0.3260	0.22
Pavement	0.4115	0.2615	0.15

6.2 Integrated Need-Based Corridor Prioritization

6.2.1 Weighted Sum Model of Corridor Integrated Criticality

Model Formulation: Corridor Criticality Score (CCS) = $\sum W_{NL}$ [w(pd)s(pd) + w(tx)s(tx)] + W_{SNL} [w(sn)s(sn) + w(lc){wP(lc)sP(lc) + wW(lc)sW(lc) + wS(lc)sS(lc)}] + W_{CL}[s(co)] +W_{AL}[wP(as)sP(as) +wW(as)sW(as) +wS(as)sS(as) ……………………………………………………………………………..Eq. (6.2)

References: Table 5.10, Figure: 5.6

As stated in Section 5.5.3, the weights and values of the parameters of the studied corridors are provided by the concerned municipal agency. Based on the above, the following template is prepared for the calculation of corridor criticality scores. As sample the value of the corridor under study is calculated and is found to be 62.2 percent.

Table 6.5: Corridor Criticality Data and Analysis

Asset Criticality Data and Analysis											
Level of Analysis	**Network Level Score (NLS)**		**Sub-Network Level Scores (SNLS)**				**Corridor Level Score (CLS)**	**Asset Level Score (ALS)**			**Corridor Integrated Criticality Score**
Level Weight	20%		30%				20%	30%			(Scale 1-10)
Criticality Parameter	**Population Density**	**Tax Base**	**Sub-Network Type (snt)**	**Level of Complaint (loc)**			**Asset Spatial Co-Existence (asce)**	**Pavement Asset Size**	**Water Asset Size**	**Sewer Asset Size**	
Parameter Weight	60%	40%	50%	50%			100%	35%	35%	30%	
Asset Type				35%	35%	30%					
Asset Type Weight	S(pd)	S(tx)	S(t)	S(Ploc)	S(Wloc)	S(Sloc)	S(ce)	S(Pas)	S(Was)	S(Sas)	
Corridor No.											
1											
2											
3											
.											
.											
i	5	10	7	9	3	5	7	5	6	4	6.22
.											
.											
.											
n-1											
n											

6.2.2 Artificial Neural Network Based Model of Corridor Prioritization

Reference Tables 5.10, 5.11and 5.12, Figures 5.7 and 5.71, Appendix E

The Unsupervised Kohonen Architecture Neural Network, trained using Neuroshell 2 software, clusters all the corridors into priority groups 1 to 5. Priority within the groups is governed by the geographic proximity determined by the sequence of the geographic coordinates. This inter group prioritization of corridors based on proximity is considered thoroughly rational as it suits the practical implementation of rehabilitation activities. The same order shall be respected while feeding the corridors to the optimization model to generate the work plans. Output of the ANN model is organized in Table 6.6 to provide the final integrated prioritization of corridors.

Table 6.6: Integrated Prioritization Ranking of Corridors

S.No	Corr. ID	Corr. Priority Group	S.No	Corr. ID	Corr. Priority Group	S.No	Corr. ID	Corr. Priority Group	S.No	Corr. ID	Corr. Priority Group	S.No	Corr. ID	Corr. Priority Group
1	440201758M	1	16	440203550M	2	27	440220759M	3	35	440205758M	4	59	441409550M	5
2	440202758M	1	17	440206759M	2	28	440705758M	3	36	440243758M	4	60	441410550M	5
3	440205759M	1	18	440211759M	2	29	440717758M	3	37	440245758M	4	61	441438550M	5
4	440207759M	1	19	440217758M	2	30	440721550M	3	38	440247758M	4	62	441712759M	5
5	440210758M	1	20	440225758M	2	31	441417550M	3	39	440247759M	4	63	441724758M	5
6	440210759M	1	21	440249758M	2	32	441421550M	3	40	440250759M	4	64	441726759M	5
7	440212550M	1	22	440701758M	2	33	441422550M	3	41	440301550M	4	65	441730759M	5
8	440213759M	1	23	440702758M	2	34	441426550M	3	42	440302550M	4			
9	440219550M	1	24	440708758M	2				43	440801550M	4			
10	440224758M	1	25	440709758M	2				44	440804550M	4			
11	440226758M	1	26	440715758M	2				45	440805550M	4			
12	440230758M	1							46	441406758M	4			
13	440232758M	1							47	441411550M	4			
14	440235758M	1							48	441413550M	4			
15	440237758M	1							49	441415550M	4			
									50	441423550M	4			
									51	441431550M	4			
									52	441433550M	4			
									53	441434550M	4			
									54	441435550M	4			
									55	441437550M	4			
									56	441713759M	4			
									57	441722758M	4			
									58	441723758M	4			

6.3 Rehabilitation Techniques Feasibility Assessment

Reference Tables 5.13, 5.14 and 5.15

6.3.1 Rehabilitation Techniques Feasibility Assessment – Water Mains

With reference to the approach described in Section 5.7, the Tables 6.7, 6.8 and 6.9 respectively present the Applicability, Capability and Feasibility of the water mains rehabilitation techniques in providing the condition improvement required in the water main of the case study corridor.

6.3.2 Rehabilitation Techniques Feasibility Assessment – Wastewater Mains

The Tables 6.10, 6.11 and 6.12 respectively present the Applicability, Capability and Feasibility of the wastewater mains rehabilitation techniques in providing the condition improvement required in the wastewater main of the case study corridor.

6.3.3 Rehabilitation Techniques Feasibility Assessment – Pavement Segment

The Tables 6.13, 6.14 and 6.15 respectively present the Applicability, Capability and Feasibility of the pavement rehabilitation techniques in providing the condition improvement required in the pavement segment of the case study corridor.

Table 6.7: Rehabilitation Techniques Applicability Matrix (Water Mains)

Rehabilitation Category	Rehabilitation Alternative	Fracture/ Crack Width (mm)	Sag (≤ 0.1 D mm) For 6" Ductile Pipe	Corrosion (% Pipe Thickness Reduction)	Leakage Volume (Gallons/ Day/Mile /in-dia)	Roughness Coefficient (C-Factor) Range= (125 - 65)	Loss in Water Pressure (Psi) Household Supply Standard = 60 psi	Lead Concentration (Action Level at 10 % + ve Sample for 0.015 mg/l) Range= (0 - 100)	Iron Concentration (Action Level at 10 % + ve Sample for 0.3 mg/l) Range= (0 - 100)	Total Coliform Bacteria (% positive samples in a month)	$ /inch-Dia/Foot (As of Sept 2012)	Remaining Service Life (Yrs)
No Intervention	Do Nothing											
Structural	Open Cut Replacement (Concrete)	X	X	X	X	X	X	X	X	X	18	100
	Slip Lining	X		X	X	X	X	X	X	X	4 -6	40
	Closed Fit Site Folded Sliplining	X		X	X	X	X	X	X	X	4 - 6	50
	Cured in Place (CIPP) - Felt	X		X	X	X	X	X	X	X	6 - 14	60
	Pipe Bursting	X	X	X	X	X	X	X	X	X	7 - 9	90
	Horizontal Directional Drilling	X	X	X	X	X	X	X	X	X	10 -25	90
	Micro Tunneling	X	X	X	X	X	X	X	X	X	17 - 24	90
Semi-Structural	Cured in Place (CIPP) - Membrane			X		X		X	X		4 - 9	50
Non-Structural	Internal Joint Seals		X								(0.35 - 0.65)	25
	Spray Lining			X		X		X	X		9 - 15	75
	Spot Welding	X			X						0.25 -0.50	20
Maintenance	Flushing										1.25-1.50	5
	Swabing										2.0-2.5	15

Table 6.8: Rehabilitation Techniques Capability Matrix (Water Mains)

Rehabilitation Category	Rehabilitation Alternative	Fracture / Crack Width (mm)		Sag (≤0.1 D mm) For 6" Ductile Pipe		Corrosion (% Pipe Thickness Reduction)		Leakage Volume (Gallons/Day/ Mile/in-dia)		Roughness Coefficient (C-Factor) Range=(125-65)		Loss in Water Pressure (Psi) Household Supply Standard = 60 psi		Lead concentration (Action Level at 10 % +ve Sample for 0.015 mg/l) Range= (0-100)		Iron Concentration (Action Level at 10 % +ve Sample for 0.3 mg/l) Range= (0-100)		Total Coliform Bacteria (% positive samples in a month)		$/ inch-Dia/Foot (As of Sept 2012)	Remaining Service Life (Yrs)
		(F)		(S)		(C)		(V)		(R)		(P)		(L)		(I)		(B)			
	Technique's Capability Assessment																				
No Intervention	Do Nothing	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	$	Yrs
Structural	Open Cut Replacement (Concrete)	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	$	Yrs
	Slip Lining	4	1	1	5	5	2	5	1	5	2	5	3	5	2	5	2	5	1	$	Yrs
	Closed Fit Site Folded Sliplining	4	1	1	5	5	2	5	1	5	1	5	2	5	2	5	2	5	1	$	Yrs
	Cured in Place (CIPP) – Felt	5	1	1	5	5	1	5	1	5	2	5	2	5	2	5	2	5	1	$	Yrs
	Pipe Bursting	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	$	Yrs
	Horizontal Directional Drilling	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	$	Yrs
	Micro Tunneling	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	$	Yrs
Semi-Structural	Cured in Place (CIPP) – Membrane	4	3	1	5	4	3	5	2	4	2	5	3	5	3	5	3	5	2	$	Yrs
Non-Structural	Internal Joint Seals	1	5	1	5	1	5	4	3	1	5	5	4	5	2	5	4	5	3	$	Yrs
	Spray Lining	4	3	1	5	4	2	4	2	4	2	5	3	5	4	5	2	5	3	$	Yrs
	Spot Welding	1	5	1	5	1	5	4	2	1	5	5	3	1	5	1	5	5	4	$	Yrs
Maintenance	Flushing	1	5	1	5	1	5	1	5	5	3	5	3	5	3	5	3	5	3	$	Yrs
	Swabbing	1	5	1	5	1	5	1	5	5	2	5	3	5	3	5	2	5	3	$	Yrs
Condition Improvement Requirement	**Condition Improvement Requirement**																				
	Existing – Target Condition	4	1	1	5	4	2	4	1	4	2	4	2	3	2	5	2	3	1		

Table 6.9: Rehabilitation Techniques Feasibility Matrix (Water Mains)

Techniques Feasibility Assessment										Applicability
Do Nothing	N	N	N	N	N	N	N	N	N	N
Open Cut Replacement (Concrete)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Slip Lining	Y	Y	Y	Y	Y	N	Y	Y	Y	N
Closed Fit Site Folded Sliplining	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Cured in Place (CIPP) - Felt	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Pipe Bursting	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Horizontal Directional Drilling	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Micro Tunneling	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Cured in Place (CIPP) - Membrane	N	Y	N	N	Y	N	N	N	N	N
Internal Joint Seals	N	Y	N	N	N	N	Y	N	N	N
Spray Lining	N	Y	Y	N	Y	N	N	Y	N	N
Spot Welding	N	Y	N	N	N	N	N	N	N	N
Flushing	N	Y	N	N	N	N	N	N	N	N
Swabing	N	Y	N	N	Y	N	N	Y	N	N

Table 6.10: Rehabilitation Techniques Applicability Matrix (Wastewater Mains)

Category	Rehabilitation Alternative	Cracks / Missing Bricks (No. per meter of pipe segment) (CMB)	Open Joints (No. per segment) (OJ)	Sag Depth (mm) (Per Segment) (SD)	Debris and Encrustation Debris and Encrustation (% Reduction in Diameter) (DE)	Root Intrusion (% Reduction in Diameter) (RI)	Protruding Joints (% Reduction in Diameter) (PJ)	Infiltration (Intensity Scale) (IF)	Exfiltration (Intensity Scale) (E)	No. of Pollution Incident (PI)	Cost ($ / Inch-Dia/Foot)	Remaining Service Life (Yrs)
	Do Nothing											
Structural	Open Cut Replacement	X	X	X	X	X	X	X	X	X	18	100
	Slip Lining	X	X		X	X	X	X	X	X	4-6	40
	Closed Fit Sliplining	X	X		X	X	X	X	X	X	4-6	50
	Cured in Place (CIPP) – Felt	X	X		X	X	X	X	X	X	6-14	60
	Pipe Bursting	X	X	X	X	X	X	X	X	X	7-9	90
	Horizontal Directional Drilling	X	X	X	X	X	X	X	X	X	10-25	90
	Micro Tunneling	X	X	X	X	X	X	X	X	X	17-24	90
Non- Structural	Chemical Grouting	X			X	X		X	X	X	1	20
	Internal Joint Seals		X					X	X		(0.35+ 0.65)	100
Operational	High Pressure Jetting				X	X		X	X	X	0.5	8

Table 6.11: Rehabilitation Techniques Capability Matrix (Wastewater Mains)

	Rehabilitation Alternative	Cracks / Missing Bricks (No. per meter of pipe segment)		Open Joints (No. per segment)		Sag Depth (mm) (Per Segment)		Debris and Encrustation Debris and Encrustation (% Reduction in Diameter)		Root Intrusion (% Reduction in Diameter)		Protruding Joints (% Reduction in Diameter)		Infiltration (Intensity Scale)		Exfiltration (Intensity Scale)		No. of Pollution Incident		Cost ($ / Inch-Dia/Foot)	Remaining Service Life (Yrs)
		(CMB)		(OJ)		(SD)		(DE)		(RI)		(PJ)		(IF)		(E)		(PI)			
Technique's Capability Assessment																					
	Do Nothing	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	0	100
Structural	Open Cut Replacement	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	11	100
	Slip Lining	5	2	5	2	1	5	5	1	5	1	5	2	5	2	5	2	5	2	4-6	40
	Closed Fit Sliplining	5	1	5	2	1	5	5	1	5	1	5	2	5	2	5	2	5	3	4-6	50
	Cured in Place (CIPP) – Felt	5	1	5	3	1	5	5	1	5	1	5	2	5	2	5	2	5	3	6-14	60
	Pipe Bursting	5	1	5	2	5	2	5	1	5	1	5	1	5	1	5	1	5	1	7-9	90
	Horizontal Directional Drilling	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	10-25	90
	Micro Tunneling	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	17-24	90
Non- Structural	Chemical Grouting	4	2	5	5	1	5	4	2	4	2	1	5	5	2	5	2	4	2	1	20
	Internal Joint Seals	1	5	5	1	1	5	1	5	1	5	1	5	4	3	4	3	1	3	(0.35-0.65)	100
Operational	High Pressure Jetting	1	5	1	5	1	5	5	2	5	2	1	5	1	5	1	5	4	3	0.5	75
Improvement Requirement Assessment																					
Existing – Target Condition		4	2	1	5	1	5	4	2	4	2	1	5	5	2	5	2	4	1		

Table 6.12: Rehabilitation Techniques Feasibility Matrix (Wastewater Mains)

Techniques Feasibility Assessment										Applicability
Do Nothing	N	Y	Y	N	N	Y	N	N	N	N
Open Cut Replacement	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Slip Lining	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Closed Fit Sliplining	Y	Y	Y	Y	Y	Y	Y	Y	N	N
Cured in Place (CIPP) - Felt	Y	Y	Y	Y	Y	Y	Y	Y	N	N
Pipe Bursting	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Horizontal Directional Drilling	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Micro Tunneling	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Chemical Grouting	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Internal Joint Seals	N	Y	Y	N	N	Y	N	N	N	N
High Pressure Jetting	N	Y	Y	Y	Y	Y	N	N	N	N

Table 6.13: Rehabilitation Techniques Applicability Matrix (Pavement Segment)

Type	Rehabilitation Technique	Ravelling	Longitudinal Cracking	Pavement Edge Cracking	Transverse Cracking	Alligator Cracking	Corrogation	Rutting	Pot Hole Density	Water Ponding	Pavement Marking Luminance	Sid Resistance	Cost/ Unit	RSL (Yrs)
	Do Noting													
Corrective Maintenance	Skin Paving and Routing Maintenance	x	x	x	x		x	x	x	x	x		1.86 $/SFT (2007)	4
	Fog Seal	x	x		x						x	x	0.15 $/SYD (2000)	1
	Micro surfacing	x	x	x	x		x	x	x	x	x	x	2.31 $/SYD (2007)	6
	Slurry Seal	x	x	x	x		x	x			x	x	1.05 $/SYD (2007)	5
	Patching with Slurry/Micro surfacing Material	x				x			x	x			0.85/SQY	2
Non-Structural Rehabilitation	Hot in Place Recycling	x	x	x	x		x	x	x	x	x	x	3.15 USD/SQM (1 in)	10
	Thin Overlay (Mill and Pave)	x	x	x	x		x	x	x	x	x	x	20 $/SYD (2007)	10
	Open Graded Surface (Friction Course)	x	x	x	x		x	x	x	x	x	x	3.25 $/SYD (2007)	10
Structural Rehabilitation	Cold in Place Recycling with HMA Overlay	x	x	x	x	x	x	x	x	x	x	x	4.5 USD/SQM (3 in) + 5.4 USD /SQM for Thin Overlays	7
	HMA Structural Overlay	x	x	x	x	x	x	x	x	x	x	x	35 $/SYD (2007)	15
	Reconstruction	x	x	x	x	x	x	x	x	x	x	x	90 $/SYD (2007)	25
	Pavement Marking										x		0.6 $/m	3

Table 6.14: Rehabilitation Techniques Capability Matrix (Pavement Segment)

Category	Rehabilitation Alternative	Ravelling		Longitudinal Center Line Cracking		Pavement Edge Cracking		Transverse Cracking		Alligator/ Block Cracking		Corrugation		Rutting		Pothole Density		Water Ponding		Pavement Marking		Skid Resistance		Cost ($ / Inch-Dia/Foot)	Remaining Service Life (Yrs)
		RV		LC		PEC		TC		AC		CG		RT		PD		WP		PM		SR			
Technique's Capability Assessment																									
	Do Nothing	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	0	1
Corrective Maintenance	Skin Paving and Routing Maintenance	3	2	3	2	1	2	3	2	1	5	3	2	3	2	2	1	3	2	5	1	1	5	20	4
	Fog Seal	4	3	3	2	1	5	3	2	1	5	1	5	1	5	1	5	1	5	5	1	4	2	0.18	1
	Micro surfacing	4	2	4	2	4	2	4	2	1	5	3	1	4	2	4	3	4	5	5	1	5	2	2.76	6
	Slurry Seal	4	1	3	2	3	2	3	2	1	5	3	2	3	2	1	5	1	5	5	1	5	2	1.25	5
	Patching with Slurry / Micro Surfacing Material	4	2	1	5	1	5	1	5	4	2	1	5	1	5	3	2	4	2	1	5	1	5	0.66	2
Non-Structural Rehabilitation	Hot Place Recycling	4	2	4	2	4	2	4	2	1	5	4	2	4	2	3	2	4	2	5	1	5	2	3.25	10
	Thin Overlay (Mill and Pave)	4	2	3	2	3	2	3	2	1	5	4	2	4	2	3	2	3	2	5	1	5	2	22	10
	Open Graded Surface (Friction Course)	4	2	4	3	4	3	4	2	1	5	3	2	3	2	3	2	4	2	5	1	5	1	3.88	10
Structural Rehabilitation	Cold in Place Recycling with HMA Overlay	5	1	4	1	4	1	4	1	4	2	5	1	47	1	4	2	4	1	5	1	5	1	10	7
	HMA Structural Overlay	5	1	5	1	5	1	5	1	5	2	5	1	5	1	4	1	5	1	5	1	5	1	42	15
	Reconstruction	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	5	1	108	25
	Pavement Marking	1	5	1	1	1	5	1	5	1	5	1	5	1	5	1	5	1	5	5	1	1	5	0.6	3
Improvement Requirement Assessment																									
Existing – Target Condition		5	1	4	1	1	5	4	1	1	5	4	2	4	2	1	5	1	5	4	2	5	2		

Table 6.15: Rehabilitation Techniques Feasibility Matrix (Pavement Segment)

Techniques Feasibility Assessment												**Applicability**
Do Noting	N	N	N	N	Y	N	N	Y	N	N	N	N
Skin Paving and Routing Maintenance	N	N	Y	N	Y	N	N	Y	Y	Y	N	N
Fog Seal	N	N	N	N	Y	N	N	Y	N	Y	N	N
Micro surfacing	N	N	Y	N	Y	N	Y	Y	Y	Y	Y	N
Slurry Seal	N	N	Y	N	Y	N	N	Y	N	Y	Y	N
Patching with Slurry/Micro surfacing Material	N	N	N	N	Y	N	N	Y	Y	N	N	N
Hot in Place Recycling	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y	N
Thin Overlay (Mill and Pave)	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y	N
Open Graded Surface (Friction Course)	N	N	N	N	Y	N	N	Y	Y	Y	Y	N
Cold in Place Recycling with HMA Overlay	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
HMA Structural Overlay	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Reconstruction	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Pavement Marking	N	N	N	N	Y	N	N	Y	N	Y	N	N

Results of the techniques feasibility assessment are summarized in Table 6.16. These results are fed to the optimization model to select the most optimum technique for each asset type. The final set of the optimum techniques of the three asset types constitute the corridor work plan.

Table 6.16: Summary of the results of the Techniques Feasibility Assessment

Asset Type	**Feasible Rehabilitation Technique for Corridor (*i*)**
Water Main	Open Cut Replacement (Concrete)
	Cured in Place (CIPP) – Felt
	Closed Fit Site Folded Slip lining
	Pipe Bursting
	Horizontal Directional Drilling
	Micro Tunneling
Wastewater Main	Open Cut Replacement
	Slip Lining
	Pipe Bursting
	Horizontal Directional Drilling
	Micro Tunneling
	Chemical Grouting
Pavement Segment	Cold in Place Recycling with HMA Overlay
	HMA Structural Overlay
	Reconstruction

6.4 Selection of the Optimum Solution – Corridor Work Plan

Reference: Table 5.16. 5.17, 5.18 and 5.19

Reference Eq. Nos. 5.12, 5.13 and 5.14

In order to run the optimization formulation for any of the three asset types, the following are needed:

1) Targeted values of the optimization parameters set by the community:

   Cost ($) / Unit

   Post Intervention Condition of Asset

   Post Intervention Remaining Service Life (RSL)

2) Values of above optimization parameters in case of each rehabilitation technique:

   Cost ($)/Unit – Obtained from Manufacturers / Service Providers

   Post Intervention Condition – By Condition Rating Analysis using the developed Fuzzy CR Model, as demonstrated in Tables 6.17, 6.18 and 6.19 for Water, Wastewater and Pavements assets, respectively.

   Remaining Service Life (RSL) – Obtained from Manufacturers/ Service Providers

3) Penalty Scores per unit violation of the above targets set by the community

The post intervention condition grade of the asset is determined for each technique and the difference between this value and the targeted condition is the basis of the penalty score calculation while optimizing.

Table 6.17: Post Intervention Condition Grades of Water Main with respect to each Rehabilitation Technique

Technique	Fuzzy Intervals			Post Intervention Condition Index	Asset Targeted Condition	Improvement Differential
	α = 0	α = 0.5	α = 1.0			
Do Nothing	(0.8 - 1.0)	(0.85 - 0.95)	(0.9 - 0.9)	0.90	0.19	-0.71
Open Cut Replacement (Concrete)	(0.0 - 0.2)	(0.05 - 0.15)	(0.1 - 0.1)	0.10	0.19	0.09
Slip Lining	(0.0 - 0.4)	(0.1 - 0.3)	(0.2 - 0.2)	0.20	0.19	-0.01
Closed Fit Site Folded Sliplining	(0.0 - 0.3)	(0.075 - 0.225)	(0.15 - 0.15)	0.15	0.19	0.04
Cured in Place (CIPP) - Felt	(0.0 - 0.3)	(0.075 - 0.225)	(0.15 - 0.15)	0.15	0.19	0.04
Pipe Bursting	(0.0 - 0.2)	(0.05 - 0.15)	(0.1 - 0.1)	0.10	0.19	0.09
Horizontal Directional Drilling	(0.0 - 0.2)	(0.05 - 0.15)	(0.1 - 0.1)	0.10	0.19	0.09
Micro Tunneling	(0.0 - 0.2)	(0.05 - 0.15)	(0.1 - 0.1)	0.10	0.19	0.09
Cured in Place (CIPP) - Membrane	(0.0 - 0.44)	(0.11 - 0.33)	(0.22 - 0.22)	0.22	0.19	-0.03
Internal Joint Seals	(0.24 - 1.0)	(0.43 - 0.81)	(0.61 - 0.61)	0.62	0.19	-0.43
Spray Lining	(0.16 - 0.60)	(0.27 - 0.49)	(0.38 - 0.38)	0.37	0.19	-0.18
Spot Welding	(0.46 - 0.89)	(0.59- 0.78)	(0.71- 0.71)	0.70	0.19	-0.51
Flushing	(0.42 - 0.80)	(0.53 - 0.70)	(0.60- 0.60)	0.60	0.19	-0.41
Swabing	(0.41 - 0.79)	(0.52 - 0.69)	(0.59- 0.59)	0.52	0.19	-0.33

Table 6.18: Post Intervention Condition Grades of Wastewater Main with respect to each Rehabilitation Technique

Technique	Fuzzy Intervals			Post Intervention Condition Index	Asset Targeted Condition	Improvement Differential
	α = 0	α = 0.5	α = 1.0			
Do Nothing	(0.8 - 1.0)	(0.85 - 0.95)	(0.9 - 0.9)	0.90	0.22	-0.68
Open Cut Replacement	(0.0 - 0.2)	(0.05 - 0.15)	(0.1 - 0.1)	0.10	0.22	0.12
Slip Lining	(0.25 - 0.45)	(0.30 - 0.40)	(0.35 - 0.35)	0.35	0.22	-0.13
Closed Fit Sliplining	(0.2 - 0.6)	(0.30 - 0.50)	(0.4 - 0.4)	0.40	0.22	-0.18
Cured in Place (CIPP) - Felt	(0.2 - 0.62)	(0.31 - 0.52)	(0.41 - 0.41)	0.41	0.22	-0.19
Pipe Bursting	(0.0 - 0.24)	(0.06 - 0.18)	(0.12 - 0.12)	0.12	0.22	0.10
Horizontal Directional Drilling	(0.0 - 0.2)	(0.05 - 0.15)	(0.1 - 0.1)	0.10	0.22	0.12
Micro Tunneling	(0.0 - 0.2)	(0.05 - 0.15)	(0.1 - 0.1)	0.10	0.22	0.12
Chemical Grouting	(0.34 - 0.70)	(0.43 - 0.61)	(0.52 - 0.52)	0.48	0.22	-0.26
Internal Joint Seals	(0.34 - 0.70)	(0.43 - 0.61)	(0.52 - 0.52)	0.48	0.22	0.22
High Pressure Jetting	(0.56 - 0.86)	(0.64 - 0.79)	(0.71 - 0.71)	0.71	0.22	-0.49

Table 6.19: Post Intervention Condition Grades of Pavement Segment with respect to each Rehabilitation Technique

Technique	Fuzzy Intervals			Post Intervention Condition Index	Asset Targeted Condition	Improvement Differential
	α = 0	α = 0.5	α = 1.0			
Do Noting	(0.8 - 1.0)	(0.85 - 0.95)	(0.9 - 0.9)	0.90	0.15	-0.68
Skin Paving and Routing Maintenance	(0.16 - 0.60)	(0.27 - 0.49)	(0.38 - 0.38)	0.38	0.15	-0.16
Fog Seal	(0.42 - 0.80)	(0.53 - 0.70)	(0.60 - 0.60)	0.60	0.15	-0.38
Microsurfacing	(0.17 - 0.47)	(0.25 - 0.40)	(0.32 - 0.32)	0.32	0.15	-0.10
Slurry Seal	(0.36 - 0.56)	(0.41 - 0.51)	(0.46 - 0.46)	0.46	0.15	-0.24
Pathcing with Slurry /Micro surfacing Material	(0.42 - 0.80)	(0.53 - 0.70)	(0.60- 0.60)	0.60	0.15	-0.38
Hot in Place Recycling	(0.2 - 0.4)	(0.25 - 0.35)	(0.3 - 0.3)	0.30	0.15	-0.08
Thin Overlay (Mill and Pave)	(0.2 - 0.4)	(0.25 - 0.35)	(0.3 - 0.3)	0.30	0.15	-0.08
Open Graded Surface (Friction Course)	(0.17 - 0.47)	(0.25 - 0.40)	(0.32 - 0.32)	0.32	0.15	-0.10
Cold in Place Recycling with HMA Overlay	(0.0 - 0.26)	(0.06 - 0.20)	(0.13 - 0.13)	0.13	0.15	0.09
HMA Structural Overlay	(0.0 - 0.22)	(0.05 - 0.17)	(0.11 - 0.11)	0.11	0.15	0.11
Reconstruction	(0.0 - 0.2)	(0.05 - 0.15)	(0.1 - 0.1)	0.10	0.15	0.12
Pavement Marking	(0.68 - 0.98)	(0.75 - 0.90)	(0.83 - 0.83)	0.83	0.15	-0.61

The next step in the optimization analysis is to run the actual optimization formulation. Tables No's 6.20, 6.21 and 6.22, show the penalty scores assessment of all the feasible rehabilitation techniques of water, wastewater and pavement asset the structure of the optimization tables is self-explanatory. However, it shall be noted that since the three optimization parameters have different units and so the numerical scale of their values vary widely. This has resulted in a non-representative estimation of penalty points of the corridor that can lead to non-optimum selection. This problem is solved by normalizing the penalty points of each of the optimization parameters for each asset class on a scale of 0 to 1, thereby giving uniform scale of comparison to the decision makers. The Tables No's 6.23, 6.24 and 6.25 are respectively the final normalized penalty score tables for water, wastewater and pavement asset also showing the final suitability rank of the feasible techniques of each asset type.

Table 6.20: Penalty Score Assessment of Water Asset Rehabilitation Techniques for the Selection of Optimum One

Budget / Target	**Cost ($)/Lft**	**Condition**	**RSL**			**Penalty Points**	**Cost (x 100 $)**	**Condition (Over Achieved)**	**Condition (Under Achieved)**	**RSL (x10 Yrs) (Under Achieved)**	**RSL Over Achieved (3)**
	75	0.19	15					4	(20)	50	(3)
Rehabilitation Technique	Cost ($ /in dia / Lft	Cost ($ / Lft) (18 in. Dia Pipe)	Deviation from Target Cost	Penalty Points	Post Intervention Condition Index	Deviation from Target Condition	Penalty Points	Remaining Service Life -RSL (Yrs)	Deviation from Target RSL (Yrs)	Penalty Points	Total Penalty Points
Open Cut Replacement (Concrete)	18.00	324.00	249.00	9.96	0.10	-0.09	-1.80	100	85	-25.5	-17.34
Closed Fit Site Folded Sliplining	5.00	90.00	15.00	0.60	0.15	-0.04	-0.83	50	35	-10.5	-10.73
Cured in Place (CIPP) - Felt	10.00	180.00	105.00	4.20	0.15	-0.04	-0.83	60	45	-13.5	-10.13
Pipe Bursting	8.00	144.00	69.00	2.76	0.10	-0.09	-1.80	90	75	-22.5	-21.54
Horizontal Directional Drilling	18.00	324.00	249.00	9.96	0.10	-0.09	-1.80	90	75	-22.5	-14.34
Micro Tunneling	21.00	378.00	303.00	12.12	0.10	-0.09	-1.80	90	75	-22.5	-12.18

Table 6.21: Penalty Score Assessment of Wastewater Asset Rehabilitation Techniques for the Selection of Optimum One

Budget / Target	**Cost ($)/Lft**	**Condition**	**RSL**		**Penalty Points**	**Cost (x 100 $) (Overrun)**	**Cost (x 100 $) (Saving)**	**Condition (Over Achieved)**	**Condition (Under Achieved)**	**RSL (x10 Yrs) (Over Achieved)**	**RSL (x10 Yrs) (Under Achieved)**
	60	0.22	15			4	4	20	50	3	2
Rehabilitation Technique	Cost ($ /in dia / Lft	Cost ($ / Lft) (24 in. Dia Pipe)	Deviation from Target Cost	Penalty Points	Post Intervention Condition Index	Deviation from Target Condition	Penalty Points	Remaining Service Life -RSL (Yrs)	Deviation from Target RSL (Yrs)	Penalty Points	Total Penalty Points
Open Cut Replacement	18.00	432.00	372.00	14.88	0.10	-0.12	2.40	100	85	25.50	42.78
Slip Lining	5.00	120.00	60.00	2.40	0.20	-0.02	0.45	40	25	7.50	10.35
Pipe Bursting	8.00	192.00	132.00	5.28	0.10	-0.12	2.40	90	75	22.50	30.18
Horizontal Directional Drilling	17.00	408.00	348.00	13.92	0.10	-0.12	2.40	90	75	22.50	38.82
Micro Tunneling	21.00	504.00	444.00	17.76	0.10	-0.12	2.40	90	75	22.50	42.66
Chemical Grouting	1.00	24.00	-36.00	-0.04	0.22	0.00	0.02	50	35	10.50	10.48

Table 6.22: Penalty Score Assessment of Pavement Asset Rehabilitation Techniques for the Selection of Optimum One

Budget / Target		**Cost $/Lft**	**Condition**	**RSL**	**Penalty Points**	**Cost (x 100 $) (Overrun)**	**Cost (x 100 $) (Saving)**	**Condition (Over Achieved)**	**Condition (Under Achieved)**	**RSL (x10 Yrs) (Over Achieved)**	**RSL (x10 Yrs) (Under Achieved)**
		50	0.15	5		4	4	20	50	2	3
Rehabilitation Technique	Cost ($ /Lane Lft	Cost ($ / Lft) 2 Lane Pavement	Deviation from Target Cost	Penalty Points	Post Intervention Condition Index	Deviation from Target Condition	Penalty Points	Remaining Service Life - RSL (Yrs)	Deviation from Target RSL (Yrs)	Penalty Points	Total Penalty Points
Cold in Place Recycling with HMA Overlay	10.00	20.00	-30.00	-1.20	0.13	-0.02	0.40	7	2	0.40	-0.40
HMA Structural Overlay	42.00	84.00	34.00	1.36	0.11	-0.04	0.80	15	10	2.00	4.16
Reconstruction	108.00	216.00	166.00	6.64	0.10	-0.05	1.00	25	20	4.00	11.64

Table 6.23: Normalized Penalty Score of Water Asset Rehabilitation Techniques Identifying the Optimum One

Rehabilitation Technique	Cost Penalty Points	Cost Penalty Points (Normalized)	Condition Penalty Points	Condition Penalty Points (Normalized)	RSL Penalty Points	RSL Penalty Points (Normalized)	Total of Normalized Penalty Points (Normalized)	Normalized Penalty Score	Feasibility Ranking
Open Cut Replacement (Concrete)	9.96	0.81	0.05	0.00	-25.50	0.00	0.81	0.25	2
Closed Fit Site Folded Sliplining	0.60	0.00	0.10	1.00	-10.50	1.00	2.00	0.93	5
Cured in Place (CIPP) - Felt	4.20	0.31	0.10	1.00	-13.50	0.80	2.11	1.00	6
Pipe Bursting	2.76	0.19	0.05	0.00	-22.50	0.20	0.39	0.00	1
Horizontal Directional Drilling	9.96	0.81	0.05	0.00	-22.50	0.20	1.01	0.36	3
Micro Tunneling	12.12	1.00	0.05	0.00	-22.50	0.20	1.20	0.47	4

Table 6.24: Normalized Penalty Score of Wastewater Asset Rehabilitation Techniques Identifying the Optimum One

Rehabilitation Technique	Cost Penalty Points	Cost Penalty Points (Normalized)	Condition Penalty Points	Condition Penalty Points (Normalized)	RSL Penalty Points	RSL Penalty Points (Normalized)	Total of Normalized Penalty Points (Normalized)	Normalized Penalty Score	Feasibility Ranking
Open Cut Replacement	14.88	0.84	2.40	1.00	25.5	1.00	2.84	1.00	6
Slip Lining	2.40	0.14	0.45	0.18	7.5	0.00	0.32	0.06	2
Pipe Bursting	5.28	0.30	2.40	1.00	22.5	0.83	2.13	0.74	3
Horizontal Directional Drilling	13.92	0.78	2.40	1.00	22.5	0.83	2.62	0.92	4
Micro Tunneling	17.76	1.00	2.40	1.00	22.5	0.83	2.83	1.00	5
Chemical Grouting	-0.04	0.00	0.02	0.00	10.5	0.17	0.17	0.00	1

Table 6.25: Normalized Penalty Score of Pavement Asset Rehabilitation Techniques Identifying the Optimum One

Rehabilitation Technique	Cost Penalty Points	Cost Penalty Points (Normalized)	Condition Penalty Points	Condition Penalty Points (Normalized)	RSL Penalty Points	RSL Penalty Points (Normalized)	Total of Normalized Penalty Points (Normalized)	Normalized Penalty Score	Feasibility Ranking
Cold in Place Recycling with HMA Overlay	-1.20	0.00	0.40	0.00	0.4	0.00	0.00	0.00	1
HMA Structural Overlay	1.36	0.33	0.80	0.67	2	0.44	1.44	0.48	2
Reconstruction	6.64	1.00	1.00	1.00	4	1.00	3.00	1.00	3

Given the existing conditions of the assets and the preferences and needs of the community, the framework suggests the following interventions:

Water Main - Pipe bursting

Wastewater Main – Chemical Grouting

Pavement – Cold in place Recycling with HMA

The system is comprehensive and flexible. It takes into account changes in all variables and can modify the results accordingly. A sensitivity analysis of the results of the framework due to changes in optimization criteria values is presented in the following section.

6.5 Sensitivity Analysis of Framework Results

It was important to investigate the sensitivity of framework results with respect to changes in the selection/optimization criteria. It also confirmed the flexibility and proper working of the framework. Three analyses, one each to investigate the variability of results for water, wastewater and pavement asset with respect to cost, condition improvement requirement and remaining service life are done and the results are presented in Tables 6.26, 6.27 and 6.28. It shall be noted that when an optimization criteria such as cost is varied the other two criteria of condition improvement and remaining service life are kept constant.

Table 6.26: Sensitivity of Water Asset Optimum Technique Selection

Cost ($) / Lft	Optimum Technique
10	Closed Fit Site Folded Sliplining
20	Closed Fit Site Folded Sliplining
75	Pipe Bursting
100	Pipe Bursting
Condition Improvement	
0.1	Pipe Bursting
0.15	Pipe Bursting
0.25	Cured in Place (CIPP) - Felt
0.5	Closed Fit Site Folded Sliplining
Remaining Service Life	
5	Cured in Place (CIPP) - Felt
10	Cured in Place (CIPP) - Felt
15	Pipe Bursting
50	Open Cut
90	Open Cut
100	Open Cut

Table 6.27: Sensitivity of Wastewater Asset Optimum Technique Selection

Cost ($) / Lft	Optimum Technique
10	Chemical Grouting
20	Chemical Grouting
40	Chemical Grouting
75	Chemical Grouting
Condition Improvement	
0.1	Pipe Bursting
0.15	Pipe Bursting
0.22	Chemical Grouting
0.5	Chemical Grouting
Remaining Service Life	
10	Slip Lining
15	Chemical Grouting
25	Chemical Grouting
40	Chemical Grouting
50	Pipe Bursting
90	Pipe Bursting
100	Open Cut Replacement

Table 6.28: Sensitivity of Pavement Asset Optimum Technique Selection

Cost $/Lft	Optimum Technique
10	Cold in Place Recycling with HMA Overlay
50	Cold in Place Recycling with HMA Overlay
75	Cold in Place Recycling with HMA Overlay
125	HMA Structural Overlay
Condition Improvement	
0.1	HMA Structural Overlay
0.15	Cold in Place Recycling with HMA Overlay
0.25	Cold in Place Recycling with HMA Overlay
Remaining Service Life (Yrs)	
1	Cold in Place Recycling with HMA Overlay
5	Cold in Place Recycling with HMA Overlay
7	Cold in Place Recycling with HMA Overlay
15	HMA Structural Overlay
25	Reconstruction

A brief analysis of the sensitivity results is given below:

Water Assets

At lower cost situations, Closed Fit Site Folded Slip lining is the solution. However, at moderate and comfortable budget situations, Pipe Bursting is recommended. At higher performance requirements Pipe Bursting is the solution, however as the condition improvement requirement decreases, the solution moves to Cured in Place (CIPP) Felt and ends at Closed Fit Site Folded Slip lining. At low remaining service life requirement, Cured in Place (CIPP) Felt is proposed by the system which changes to Pipe Bursting for moderate RSL and finally to Open Cut at higher RSLs.

Wastewater Assets

Chemical Grouting is the solution at all variations in the cost. This is because the RSL of grouting is quite good and much more that the required so it does not allow others to win. At higher performance requirements Pipe Bursting is the solution, however as the condition improvement requirement decreases, the solution shifts to Chemical Grouting. At low remaining service life requirement, Slip lining is proposed by the system. After a little increase Chemical Grouting is the solution which stays until moderate requirements. For moderate RSLs the solution changes to Pipe Bursting and finally to Open Cut at higher RSLs

Pavement Assets

Cold in Place Recycling with HMA Overlay is the solution at all variations in the cost except for the highest cost level where it is replaced by HMA Structural Overlay. At higher performance requirements, HMA Structural Overlay is the solution, however, as the condition improvement requirement decreases, the solution shifts to Cold in Place Recycling with HMA Overlay. At low remaining service life requirement, Cold in Place Recycling with HMA Overlay is proposed by the system which stays until moderate requirements. For moderate RSLs the solution changes to HMA Overlay and finally to Open Cut at higher RSLs

Chapter 7: Summary and Conclusion

7.1 Summary and Conclusion

It was found that in the United States, Canada and Australia, municipalities are facing increasing challenges due to aging and deterioration of infrastructure assets, inadequate renewal budgets, climbing renewal deficits, increasing demand levels, and new requirements to comply with stricter environmental and accounting regulations. The increasing complexity and sophistication of infrastructure management processes have resulted in creating diverse areas of knowledge, expertise, and responsibilities within and across municipal departments of water, wastewater and roads. Altogether, these challenges have placed significant pressures on municipalities to improve effectiveness in managing their infrastructure by adopting more efficient, sustainable, and proactive asset management strategies.

On the other hand, it is also a well-established fact that there is no such thing as unlimited natural resources. There is need to rehabilitate the aging infrastructure together with a consensus and concern for preservation of the resources and environment. Sustainable asset management requires creation of new technologies such as green design/technology, but also can employ established approaches such as optimization, specifically life-cycle cost optimization. Besides, interdisciplinary thinking and collaboration of disciplines is also expected to solve complex problems, open new frontiers, and lead to true innovations.

Review of literature and current industry practices revealed that in order to be sustainable, efforts to renew and rehabilitate ageing infrastructure should now focus on prolonging the functional life of municipal assets and their components by providing technically optimum and cost effective solutions that meet community expectations. To have such sustainable solutions, decisions should be done keeping in view the integrated need. Also interventions shall be done in a coordinated manner so as to cause on one hand, the least amount of disruption to community and environment and on the other hand to satisfy agency objectives of providing required level of service at least cost. Caring about the initial impact by doing integrated and co-ordinated interventions, help in having optimised solutions that lead towards sustainable municipal asset management. Presently, asset management systems typically support the management of one specific class of municipal assets (e.g. roads, water or wastewater) with little or no consideration to their inter-dependencies. Most of the existing systems operate on one utility at a time and deals with the analysis and decision making processes of that particular utility only. Alternatively stated, they perform process or vertical integration only. Due to the absence of interdisciplinary integration i.e. horizontal integration of asset management classes there are significant inefficiencies in asset planning and maintenance coordination. There was need to develop rehabilitation methodologies that are capable to simultaneously deal with all the essential asset management activities of all the concerned asset classes.

In the above context a community driven level of service based methodology is developed for integrated management of municipal infrastructure. This system integrates technical and financial plans of the municipality, in accordance with the best practices of municipal asset management. The concept of right of way, termed here as municipal corridor, is augmented and implemented for the purpose of determining integrated priority ranking of corridor and their repair/rehabilitation alternatives. This is also stated as municipal corridor rehabilitation. For non-corridor or non-integrated assets, corridor ranking shall not apply. Instead, criticality and priority may be determined on asset level. Performance measures for road, water and wastewater networks are identified and a generic methodology to quantify and measure level of service is developed. This level of service is then mapped to asset condition to quantify the improvement in asset condition required to meet the level of service, set according to community expectations. In order to select the best alternative for the corridor, potential intervention alternatives for each corridor of the network under consideration are analysed by an optimization model with respect to cost and gain in service life. Output of the proposed system is the repair/rehabilitation plan of the corridor which yields the most suitable rehabilitation strategy for road, water distribution and wastewater collection segments of the corridor, according to the pre-set selection criteria. Specifically, the developed methodology comprised of the following three phases:

- Phase I: Asset Performance Modeling Framework
- Phase II: System Integration and Corridor Prioritization Framework

- Phase III: Work Plan Optimization Framework

Summary of the various processes constituting the above three phases are as under:

Performance indicators and measures for the three asset types were identified and their thresholds and desired values were suggested. Their ranges of values were also divided in five levels of service (community perspective). This exercise was repeated for condition rating (agency perspective) also. Subsequently, the community expectation was quantitatively expressed in terms of performance measures based on level of service.

A customised asset condition rating protocol was developed. Thereafter, the desired asset level of service was mapped to the required asset condition. Integrated corridor criticality analysis was conducted as a subroutine for corridor prioritization. Neural network oriented prioritization of corridors based on the integrated parameters of un-serviceability and criticality of water, wastewater and roads assets of the corridor was established.

A simple but elaborate system of expressing the existing and targeted condition of the asset was designed, taking into consideration each distress measure of the asset. Rehabilitation techniques for road, water and wastewater mains were thoroughly investigated, firstly in general about their applicability to a certain condition level, then in particular about their capability to address each of the distress measures. Technique Applicability and subsequently a Technique Capability Matrix were developed for the three asset types. This created the asset rehabilitation feasible solutions space. Parametric estimation of costs of different levels of intervention / rehabilitation for water, wastewater and road assets were worked out separately.

A penalty score based optimization formulation derived on the concept of Discrete Goal Programming, tests the solution space to individually identify the best possible solution for all asset types of the corridor under consideration. Finally, the results of the optimization model are tabulated as the corridor work plan which provides the cost of selected rehabilitation techniques, the post intervention condition & post intervention remaining service lives of water, wastewater and road assets in the corridor. Sensitivity analysis of framework results is also performed for each asset type to check the variability of results with respect to changes in the optimization criteria and to confirm the flexibility and proper working of the system.

If results generated by the system do not meet network level requirements, a three-step process can be followed. Initially, the goals and penalty values of the Goal Programming Optimization Model may be revised. In the second round the planning assumptions and performance thresholds that were set during models development may be reviewed. If the results still do not suit the requirements then changing the performance measures may also be considered.

The end-user of this system is the middle order municipal management that includes municipal engineers and asset managers. These professionals will be able to make such decisions which will be implemented at the operational level but will collectively contribute to meet the broad-based strategic targets of sustainable asset management.

The conclusions of the research are summarised as follows:

- In order to enhance the benefits of the level of service concept and asset condition ratings for operational purposes, the two measurements shall not be dealt in isolation to one another; rather these two should be linked together. Mapping level of service to condition rating determines optimum quantity of improvement required in asset condition to meet level of service targets.
- To achieve the above only such parameters related to the physical distress of assets should be selected which can measure the loss in functionality also. This allows the use of the same set of parameters, to develop both, the level of service as well as the condition rating.
- Determining the length of the corridor for intervention purposes is challenging. Therefore a reference length can be considered but the exact length will vary in each case, depending on the assets layout with respect to each other on the site.
- Criticality of a corridor depends not only upon the corridor and asset attributes but also upon the characteristics of the network and sub-network to which it belongs. This is essential, especially when the criticality score is intended to be used for establishing a prioritization ranking of corridors in a municipal jurisdiction.
- Corridors could be segregated into priority groups. However, a further prioritization leading to an efficient work program from an operational point

of view could be achieved according to the geographic proximity, in term of geographic coordinates.

- The expression and measurement of level of services in discrete levels leads to considerable approximation. Percentage score based on accumulated contribution of individual parameters is more representative of the actual and desired situations and therefore reduces subjectivity in evaluation.
- Selection of rehabilitation techniques based on discrete levels of condition rating is liable to provide non-optimum solutions. The selection while considering the asset condition and technique capability with respect to every distress measure provides a set of feasible alternatives that when assessed under the given optimization criteria can lead to an optimum solution.
- The final selection among the feasible alternatives that are ranked under the optimization criteria shall be governed by the site accessibility and job execution constraints.
- Sensitivity analysis reveals that since the solution is dependent on several variables, any generalization of choices under a particular set of requirement criteria cannot be made. Each corridor shall be assessed individually.

7.2 Research Contributions

- A completely generic framework is developed, each model of which can be set according to user preferences and needs.

- This research provides a structured methodology to manage the three utility networks at a time while meeting public expectations at the least possible cost.
- This framework provides a structured method of decision making that performs horizontal and vertical integration. Horizontally, it links the three asset classes (water, wastewater and pavement) and vertically it integrates processes (condition assessment, technique selection and optimization), thereby leading to well-coordinated assessment and decisions.
- This research provides a method to quantify and express expected levels of service of municipal assets.
- The subjectivity in transforming asset inspection observations into condition rating is minimized by the development of a fuzzy logic based condition assessment protocol. Further, a method to determine the capability of an asset to provide the intended service is developed by expressing asset condition as a function of performance measures.
- Capability to determine the optimum quantity of condition improvement, needed to meet community expectation is developed, by designing a fuzzy logic based LoS-CR mapping function between level of service and asset condition.
- The concept of municipal corridor is enhanced and implemented to perform corridor integrated management as follows:

- Corridor criticality is determined based on an integrated assessment of the three asset types while taking into account factors pertaining from network level to individual asset level.
- Subsequent to this, an integrated prioritization ranking of corridors is established.

- Unlike most of the DSS that determine rehabilitation alternatives based on overall condition grade, this research introduces the concept of "Technique Capability" which identifies the potential of each technique to address each of the distress measures. This ensures providing the technically most effective solutions.
- Agencies technical and financial plans are integrated as per recommendations of InfraGuide best practices. This is achieved by the development of corridor work plans that are optimized with respect to multiple objectives of cost, condition / level of service and gain in asset service life.

7.3 Potential Future Development

- Keeping in view, the nature of the domain and the developed methodology, its implementation could be more efficiently done in any Geographic Information System (GIS). If the inputs and output of the framework models are linked with any GIS, it can form a comprehensive tool for municipal asset management. The geographic and asset attribute data storage, handling and presentation capabilities of GIS can be used. Besides, results can be graphically presented and scenarios can be generated that can make decision making much easier.

- More investigation and development is needed in the area of deciding whether a corridor shall be managed with or without integrated approach. Further development can be done on the initial framework of time and space concurrence of intervention, as described in section 3.4.1. Also more robust rules for deciding upon the length of a corridor considered for integrated intervention shall be created. Those should not only be based on road length or intersection but should also take into account the layout of the buried utilities.
- Regular asset inspections are still not an established practice in several municipalities. An alternative to coping up with the situation would be to have deterioration curves as a function of individual performance measures that can give a forecasted value of the measure, in the absence of inspection. The benefit of these functions would be the ability to forecast the root cause of the failure, in addition to the time of failure.
- The scope of estimating condition improvement requirements should be expanded to take into account the accessories of the buried utilities, such as valves and fittings.

- The approach adopted in this research is to continue considering corridors according to their priority ranking to rehabilitate each to the desired level of service and to stop once the annual budget / funds are exhausted. Another approach that shall be further investigated is to determine and provide maximum level of service that can be attained within a given budget.

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APPENDICES

Appendix A: Case Study Attempting Integrated Management (Halifax Regional Municipality)

National Guide to Sustainable Municipal Infrastructure (InfraGuide)

InfraGuide®

Case Study

DECISION MAKING AND INVESTMENT PLANNING/POTABLE WATER BEST PRACTICE

HALIFAX SAVES TIME, MONEY, AND DISRUPTIONS BY COORDINATING CAPITAL WORKS

The program has resulted in a noticeable improvement in the partners' image in the community.

SUMMARY

When Jamie Hannam of the Halifax Regional Water Commission (HRWC) walked into David Hubley's office at the Halifax Regional Municipality (HRM) with InfraGuide's best practice guide *Coordinating Infrastructure Works*[1] in hand, he had a clear mission: minimize the disruption to the public caused by capital works projects. David readily agreed.

Together Jamie and David developed a strategy to achieve that mission guided by the best practice recommendations. They established a committee to improve the level of coordination between all parties involved in water, sewer, storm water and road-works and agreed on a standardized approach to prioritizing projects. The committee's goal was to make sure the best overall results were delivered to citizens across the municipality.

Results have been positive. A greater number of capital projects are being delivered based on the coordination program. The impact of this coordination has been to increase the number of joint projects, reduce the number of road cuts and customer complaints, and increase productivity for all the partners. Importantly, the program has resulted in a noticeable improvement in the partners' image in the community.

The impact of this coordination has been to increase the number of joint projects, reduce the number of road cuts and customer complaints, and increase productivity for all the partners.

1. InfraGuide best practice publication DMIP 5: *Coordinating Infrastructure Works*, Ottawa, Ontario, 2004.

HALIFAX REGIONAL MUNICIPALITY · Halifax Regional Water Commission "Striving for World Class" · NRC·CNRC · FCM Federation of Canadian Municipalities / Fédération canadienne des municipalités · Canada

Appendix B: Case Study Attempting Integrated Management

National Guide to Sustainable Municipal Infrastructure (InfraGuide)

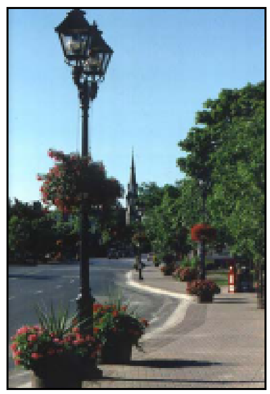
RICHMOND HILL'S STORMWATER MANAGEMENT PROGRAM DELIVERS SUSTAINABLE STORMWATER MANAGEMENT

MISSION STATEMENT

"Richmond Hill: a safe, clean town committed to managing growth, which provides a welcoming, diverse and environmentally sustainable community that enhances residents' quality of life."

SUMMARY

John Nemeth, manager of water resources in Richmond Hill, realized in 2001 the town needed to take a more strategic approach to stormwater management when the municipality faced the daunting task of assuming over eighty constructed stormwater management facilities from the development community over the next three to five years. He and his team had to accept those facilities in such a way that the potential liability to the town was minimized, financial responsibilities were shared fairly among partners, assets were designed well enough to stand the test of time, and facilities performed to meet all regulatory standards. In addition, they had to make sure everyone on the water resources team had the skills and knowledge to efficiently and effectively operate and maintain the facilities after they assumed responsibility for their operation.



Richmond Hill's Stormwater Management Program encapsulates best-practices-based stormwater monitoring and testing procedures, a prioritized capital investment program, a description of the staff and equipment necessary to ensure sustainable storm water management, operations and maintenance procedures and a skills development program for all staff. The program was built based on the frameworks and technical guidance provided in InfraGuide's best practices publications: *Stormwater Management Planning*[1], *Developing Levels of Service*[2], *Defining Municipal Infrastructure Needs*[3], *Source and On-Site Controls for Municipal Drainage Systems*[4], *and Conveyance and End-of-Pipe Measures for Stormwater Control*[5].

1. InfraGuide best practice on Storm and Wastewater (SWW) #11: *Stormwater Management Planning*, 2005. Ottawa, Ontario.
2. InfraGuide best practice on Decision Making and Investment Planning (DMIP) #3: *Developing Levels of Service*, 2003. Ottawa, Ontario.
2. InfraGuide best practice on Storm and Wastewater (SWW) #3: *Source and On-Site Controls for Municipal Drainage Systems*, 2003. Ottawa, Ontario.
3. InfraGuide best practice on Storm and Wastewater (SWW) #13: *Conveyance and End-of-Pipe Measures for Stormwater Control*, 2005. Ottawa, Ontario.

Town of Richmond Hill

NRC·CNRC FCM Canada

Appendix C: Communication with the Municipal Agency Consultant for Case Study Data Collection and Verification of Results

From: Mostafa Abdelaziz Abdelwahab M. Amer
Sent: Monday, October 14, 2013 15:04:00
To: Zafar Khan **[mailto:zafarkhan66@hotmail.com]**

Subject: RE: Feedback on Proposed Solution

Mr. Khan,

As requested by you, we referred to our asset inventory and found that in 2011, we treated only the pavement segment and applied the same Cold In Place Recycling treatment, whereas for storm water segment, we had some spot repairs only.

As far as your suggested solution is concerned, we consider it quite feasible from the point of view of asset performance and asset life. This can also compete on the cost side as in our case, there are indications that infiltration and ex-filtration have occurred on the segment so now there is need of inspection and possible intervention.

Regards,

Mostafa Abdul Aziz
Zuhair Fayez Partnership, KSA
Asset Management Specialist
Riyadh East West Corridor Project
Phone : +96.611-4521720

From: Zafar Khan [mailto:zafarkhan66@hotrnail.com]
Sent: Thursday, October 3, 2013 10:53 PM

To: Mostafa Abdelaziz Abdelwahab M. Amer
Subject: Feedback on Proposed Solution

Mr. Mostafa,

With reference to the previous communication below, this is to gladly inform you that while utilising the information and data received from your esteemed office, I have performed the various analyses of my methodology on the Corridor ID No: 440249758M and the final results are as under:

Water Asset:
Existing Service Percentile:
52.49
Existing Condition Rating:
0.5624
Targeted Service Percentile:
76.85
Targeted Condition Rating:
0.1900

Optimum Rehabilitation Alternative:
Pipe Bursting

Wastewater Asset:
Existing Service Percentile:
63.60
Existing Condition Rating:
0.4855

Targeted Service Percentile:
75.20
Targeted Condition Rating:
0.2200

Rehabilitation Alternative:
Chemical Grouting

Pavement Asset:
Existing Service Percentile:
59.15
Existing Condition Rating:
0. 5014

Targeted Service Percentile:
79.84
Targeted Condition Rating:
0.2200

Optimum Rehabilitation Alternative:
Cold In place Recycling with HMA Overlay

As was discussed with you during the data collection phase, please assess the proposed solution for the above referred corridor and give your opinion on its suitability with respect to the criteria of fulfilling the functional requirement, cost and asset life. Your opinion would be of extreme practical value and would be useful for me to fine tune the developed models.

Thanking you in anticipation.

Best regards,
Zafar Khan
Office: (02) 2873014
Mobile: 05097973619

Attachments: Criticality Data - ZFP Re-l.xlm (94 KB); Optimization Data-**ZFP** R~l.xlsx (35 KB)
From: Mostafa Abdelaziz Abdelwahab M. Amer
Sent: Tuesday, September 10, 2013 15:04:00
To: Zafar Khan [mailto:zafarkhan66@hotmail.com]
Subject: RE: Data for Research - Feedback on Asset Criticality and Selection of Alternatives

Engr. Zafar Khan,

We attach our response on the estimated values of criticality parameter for segment ID No: 440249758M. Our opinion on the optimization criteria is provided in the second file.

We hope this will be helpful.

Mostafa Abdul Aziz
Asset Management Specialist
Zuhair Fayez Partnership, KSA
Riyadh East West Corridor Project
Phone : +96611-4521720

Attachments: Criticality Data - ZFP Re-l.xlm (90 KB); Optimization Data-ZFP R~l.xlsx (31 KB)

From: Zafar Khan **[maiito:zafarkhan66@hotmaiI.com]**
Sent: Wednesday, August 28, 2013 7:31 PM
To: Mostafa Abdelaziz Abdelwahab M. Amer

Subject: Data for Research - Feedback on Asset Criticality and Selection of Alternatives

Dear Mr. AbdulAziz,

Hope you are doing well. Mr. Saleh Faraj advised me to communicate with you in connection with some asset management data.

Before I proceed I wish to thank you and your team for sparing time and doing effort in providing data and feed back in relation to my first request.

Right now, I wanted to request for some feedback / data about asset criticality and optimization criteria for selecting rehabilitation techniques. From the GIS data on corridors that you provided to me, I have selected as case study for the implementation of my models the corridor ID No: 440249758M, the starting geographic coordinators of which are E680844.52 and N274138.35.
In the first file titled "Criticality Data" while referring to the suggested generic scale of criticality score, please estimate the values of the criticality parameters for the assets of the selected corridor referred above. In the second file titled "Optimization Data" your suggestions for the optimization criteria for selecting the optimum technique of rehabilitation are requested. The optimization file may need some clarification, so I will give you a call at the time of your convenience.

As my research will greatly benefit from your input, I would really appreciate receiving the same. I can be reached anytime on the following numbers:

Office: (02) 2873014
Mobile: 05097973619

Best regards.
Zafar Khan

Attachments: Level of Service Tables.xlsx (409 KB) ; Condition Rating Tables -~1.xlxs (422 KB)
From: sfaraj@zfp.com
To: zafarkhan66@hotmail.com
Subject: RE: Data for Research Purpose (Ref: Dr. Adham Salamah)
Date: Thursday, 8 Aug 2013 14:00:29 +0000

Dear Mr. Khan,

Please find attached the two files that you forwarded to me. My team for the Riyadh Municipality East -West Corridor Project has provided maximum possible feedback. They agree with the possibility of using the parameters you have proposed. The distribution of values in different grades is reasonable and they have not changed anything in this regard.

You will find the proposed threshold values in the attached files. Finally, in connection with the existing and proposed values of the assets you requested, note that almost all the values for pavement segment were available in our database for year 2011 (last inspection), though the unit of measurements are different in our surveys but here those are converted to yours. However, in case of both water and wastewater segments there are two parameters that we do not observe and so the asset manager has given an estimated value of the same, keeping in view the overall condition grade of the assets.

For the other set of information you referred in your mail, I suggest you can directly contact the Project Manger. Mr. Mosatafa AbdulAziz. You can get his contact information from my office.

Wish you good luck.

Saleh Faraj, PhD. PMP,
Director Asset Management Division
Zuhair Fayez Partnership, KSA
Phone: +96626129540
Fax:+966-2-6129955

Attachments: Level of Service Tables.xlsx (401 KB) ; Condition Rating Tables -~1.xlxs (408 KB)
From: Zafar Khan [mailto:zafarkhan66@hotmail.corn]
Sent: Monday, July 29, 2013 8.34 AM
To: Saleh Abdullah Faraj
Subject: Data for Research Purpose (Ref: Dr. Adham Salamah)

Dear Engr. Abu Abdullah,

I thank you for accepting my request to give your professional opinion on certain parts of my research and to share some data on water, wastewater and pavement assets.
I will describe the entire feedback that I need from you esteemed institution in two emails. This first one is about the performance measures of levels of service and condition rating, the distribution of their values in different grades, their thresholds and lastly the existing and targeted values of these measures for the assets of any one segment. The second email will pertain to asset criticality and segment(corridor) prioritization.

I would appreciate, if I could be provided with the geographic coordinates information of a set of interconnected segments / corridors, of any part of the network. For collecting feedback as indicated above, I am attaching two Excel files titled "Level of Service Tables" and "Condition Rating Tables", each containing three tables, one each of water, wastewater and pavement. Please arrange the review of the files to:

1. Give opinion about the suitability of suggested performance measures in measuring and quantifying level of service and condition rating

2. Give opinion on the suggested distribution of these values into five different grades of service and condition.
3. To suggest the threshold values of these measures
4. To provide actual /estimated existing values and suggested targeted values for the set of assets of any one segments (corridor).

I will really appreciate your personal and your team's cooperation in this regard. It will greatly facilitate me in completing my research. I will be in touch with Mr. Mostafa AbdulAziz, your Project Manager for Riyadh Municipality East West Corridor Project.

Besides this email address, I can be reached anytime at the following numbers:
Landline: (02) 2873014
Mobile: 05097973619

Best regards
Zafar Khan

Appendix D: Snap Shot of Corridor Identification and Other Attributes Data Obtained from the Asset Management Consultant of Municipality of Riyadh, Saudi Arabia

SECTION_NO	DISTRICT NO	DISTRICT NAME	STREET NO	STREET NAME	FROM STREET NO	FROM STREET NAME	TO STREET NO	TO STREET NAME	STREET WIDTH	SECTION LENGTH	SECTION WIDTH	SECTION AREA	LOCATION TYPE	TRAFFIC EASTING	TRAFFIC NORTHING	CONDITION STATUS	UPDATE DATE	SURVEY DRAWING	MAINT TYPE	GEOMETRY sk
440201758M	4402	اليرموك	758	أبو جعفر المنصور	616	شارع رقم 616	615	طريق النجاح	40	351	14.6	5124.6	سكنية	681724	2745711	وسط	14-Apr-10		FULL	1bM]WuG
440202758M	4402	اليرموك	758	أبو جعفر المنصور	615	طريق النجاح	616	شارع رقم 616	46	347	16.4	5691	لايوجد	681729	2745702	مقبول	14-Apr-10		FULL	1bM]WuG
440203550M	4402	اليرموك	550	الإمام عبدالله بن سعود بن عبدالعزيز	616	شارع رقم 616	B26	البحر العربي	80	1425	10.868	15486.9	تجارية	682396	2744837	جيد	14-Apr-10		FULL	1bM]Wuf
440203550S	4402	اليرموك	550	الإمام عبدالله بن سعود بن عبدالعزيز	B26	البحر العربي	616	شارع رقم 616	80	1140	9.973	11369.22	تجارية			جيد			FULL	1bM]Wuf
440205758M	4402	اليرموك	758	أبو جعفر المنصور	B26	البحر العربي	615	طريق النجاح	40	816	15.74	12846	سكنية	681251.98	2745356.31	مقبول	14-Apr-10		FULL	1bM]WuF
440205759M	4402	اليرموك	759	محمد علي جناح	615	طريق النجاح	B26	البحر العربي	40	740	14.69	10873	ترفيهية	681307.46	2745203.49	مقبول	14-Apr-10	\\EISPC200\Survey\Drawing\440205759M.dwg	FULL	1bM]WuF
440206759M	4402	اليرموك	759	محمد علي جناح	477	الهفوف	615	طريق النجاح	40	373	14.95	5576.4	سكنية	681520.26	2745284.79	وسط	14-Apr-10		FULL	1bM]WuF
440207759M	4402	اليرموك	759	محمد علي جناح	B26	البحر العربي	477	الهفوف	40	245	14.85	3638.3	سكنية	681204.13	2745133.8	وسط	14-Apr-10		FULL	1bM]WuF
440210758M	4402	اليرموك	758	أبو جعفر المنصور	987	الصحابة	647	أبو الفتوح الخباز	40	714	14.2	10138.8	سكنية	680327.87	2744897.41	وسط	14-Apr-10		FULL	1bM]Ws
440210759M	4402	اليرموك	759	محمد علي جناح	647	أبو الفتوح الخباز	987	الصحابة	40	735	14.4	10584	سكنية	680355.91	2744761.69	وسط	14-Apr-10		FULL	1bM]Ws
440211759M	4402	اليرموك	759	محمد علي جناح	650	الميسمية	774	بحر العرب	40	513	16.9	8669.7	سكنية	680896.72	2744993.86	وسط	14-Apr-10		FULL	1bM]Ws
440212550M	4402	اليرموك	550	الإمام عبدالله بن سعود بن عبدالعزيز	B26	البحر العربي	987	الصحابة	80	985	11.048	10882.28	تجارية	680477	2743890	جيد	14-Apr-10		FULL	1bM]Ws
440212550S	4402	اليرموك	550	الإمام عبدالله بن سعود بن عبدالعزيز	B26	البحر العربي	987	الصحابة	80	855	10.05	8592.75	تجارية			جيد			FULL	1bM]Ws
440213759M	4402	اليرموك	759	محمد علي جناح	987	الصحابة	650	الميسمية	40	321	11.5	3692	سكنية	680363.97	2744738	مقبول	14-Apr-10	\\EISPC200\Survey\Drawing\440213759M.dwg	FULL	1bM]WUu
440217758M	4402	اليرموك	758	أبو جعفر المنصور	B71	راجية	987	الصحابة	36	615	10.36	6371	سكنية	679676.88	2744601.03	جيد	14-Apr-10		FULL	1bM]WUs
440217759M	4402	اليرموك	759	محمد علي جناح	987	الصحابة	B71	راجية									14-Apr-10		FULL	1bM]WUs
440218759M	4402	اليرموك	759	محمد علي جناح	667	المروج	987	الصحابة									14-Apr-10		FULL	1bM]WUs
440219550M	4402	اليرموك	550	الإمام عبدالله بن سعود بن عبدالعزيز	987	الصحابة	755	طريق الشيخ حسن بن حسين بن علي	80	1860	11.048	20549.28	تجارية	680019	2743701	جيد	14-Apr-10		FULL	1bM]WUp
440219550S	4402	اليرموك	550	الإمام عبدالله بن سعود بن عبدالعزيز	987	الصحابة	755	طريق الشيخ حسن بن حسين بن علي	80	978	14.951	14622.078	سكنية			جيد			FULL	1bM]WUp
440220759M	4402	اليرموك	759	محمد علي جناح	256	الخندق	667	المروج	40	525	16.95	8898.7	سكنية	679073	2744229	وسط	14-Apr-10		FULL	1bM]WUU
440223759M	4402	اليرموك	759	محمد علي جناح	755	طريق الشيخ حسن بن حسين بن علي	256	الخندق									14-Apr-10		FULL	1bM]WUp
440224758M	4402	اليرموك	758	أبو جعفر المنصور	755	طريق الشيخ حسن بن حسين بن علي	256	الخندق	40	733	14.2	10408.6	سكنية	678350.67	2743988.73	جيد	14-Apr-10		FULL	1bM]WUp
440224759M	4402	اليرموك	759	محمد علي جناح	256	الخندق	755	طريق الشيخ حسن بن حسين بن علي									14-Apr-10		FULL	1bM]WUp
440225758M	4402	اليرموك	758	أبو جعفر المنصور	442	كوالالمبور	987	الصحابة	40	366	14.3	5233.8	سكنية	680310.87	2744916.28	وسط	14-Apr-10		FULL	1bM]WUu
440226758M	4402	اليرموك	758	أبو جعفر المنصور	647	أبو الفتوح الخباز	442	كوالالمبور	30	231	14.3	3303.3	سكنية	680537.87	2745024.31	وسط	14-Apr-10		FULL	1bM]Ws
440230758M	4402	اليرموك	758	أبو جعفر المنصور	987	الصحابة	887	سومطرة	40	371	14.6	5416.6	سكنية	679666.35	2744616.9	وسط	14-Apr-10		FULL	1bM]WUs
440232758M	4402	اليرموك	758	أبو جعفر المنصور	887	سومطرة	B71	راجية	40	236	14.6	3445.6	سكنية	679297.5	2744447.63	وسط	14-Apr-10		FULL	1bM]WUU
440235758M	4402	اليرموك	758	أبو جعفر المنصور	B71	راجية	B75	بغداد	40	513	14.8	7592.4	سكنية	679070.71	2744344.71	وسط	14-Apr-10		FULL	1bM]WUp
440237758M	4402	اليرموك	758	أبو جعفر المنصور	B75	بغداد	755	طريق الشيخ حسن بن حسين بن علي	40	323	14.4	4651.2	سكنية	678339.59	2744009	وسط	14-Apr-10		FULL	1bM]WUW
440243758M	4402	اليرموك	758	أبو جعفر المنصور	615	طريق النجاح	B96	الباقرة	40	338	13.4	4529.2	سكنية	681371.92	2745434.28	وسط	14-Apr-10		FULL	1bM]WuF
440245758M	4402	اليرموك	758	أبو جعفر المنصور	B96	الباقرة	647	أبو الفتوح الخباز	40	498	14	6972	سكنية	681244.63	2745372.25	وسط	14-Apr-10		FULL	1bM]WuF
440247758M	4402	اليرموك	758	أبو جعفر المنصور	256	الخندق	B71	راجية	40	51	14.5	739.5	سكنية	679078.33	2744327.92	وسط	14-Apr-10		FULL	1bM]WUUn
440247759M	4402	اليرموك	759	محمد علي جناح	B71	راجية	256	الخندق	40	100	15.25	1525	سكنية	679086	2744251	وسط	14-Apr-10		FULL	1bM]WUUN
440249758M	4402	اليرموك	758	أبو جعفر المنصور	647	أبو الفتوح الخباز	B26	البحر العربي	40	105	14.4	1512	سكنية	680844.52	2745138.35	جيد	14-Apr-10		FULL	1bM]WuH-
440250759M	4402	اليرموك	759	محمد علي جناح	B26	البحر العربي	647	أبو الفتوح الخباز	40	106	14.6	1548	سكنية	680886.06	2745018.45	جيد	14-Apr-10		FULL	1bM]WuH-
440301550M	4403	إشبيلية	550	الإمام عبدالله بن سعود بن عبدالعزيز	755	طريق الشيخ حسن بن حسين بن علي	987	الصحابة	80	1860	11.176	20787.36	سكنية	678640	2743012		14-Apr-10		FULL	1bM]WUp
440301550S	4403	إشبيلية	550	الإمام عبدالله بن سعود بن عبدالعزيز	755	طريق الشيخ حسن بن حسين بن علي	987	الصحابة	80	1643	10.139	16658.377	سكنية						FULL	1bM]WUp
440302550M	4403	إشبيلية	550	الإمام عبدالله بن سعود بن عبدالعزيز	987	الصحابة	774	بحر العرب	80	985	11.422	11250.67	تجارية	680480	2743900		14-Apr-10		FULL	1bM]Ws
440302550S	4403	إشبيلية	550	الإمام عبدالله بن سعود بن عبدالعزيز	987	الصحابة	774	بحر العرب	80	985	10.027	9876.595	تجارية						FULL	1bM]Ws
440312550M	4403	إشبيلية	550	الإمام عبدالله بن سعود بن عبدالعزيز	774	بحر العرب	616	شارع رقم 616	80	1420	10.98	15591.6							FULL	1bM]Wuf
440312550S	4403	إشبيلية	550	الإمام عبدالله بن سعود بن عبدالعزيز	774	بحر العرب	616	شارع رقم 616	80	1264	9.985	12621.04	لايوجد						FULL	1bM]Wuf
440701758M	4407	غرناطة	758	أبو جعفر المنصور	A68	عثمان بن سليمان	768	بعلبك	40	482	15.97	7697.5	سكنية	677265.68	2743507.89	وسط	14-Apr-10		FULL	1bM]WUv
440702758M	4407	غرناطة	758	أبو جعفر المنصور	770	النبهانية	755	طريق الشيخ حسن بن حسين بن علي	40	713	15.58	11108.5	سكنية	677458.88	2743577.77	وسط	14-Apr-10		FULL	1bM]WUV
440702759M	4407	غرناطة	759	محمد علي جناح	755	طريق الشيخ حسن بن حسين بن علي	770	النبهانية									14-Apr-10		FULL	1bM]WUV
440705758M	4407	غرناطة	758	أبو جعفر المنصور	768	بعلبك	765	ابن خزيمة الأنصاري	40	238	16.71	3976	سكنية	676973.03	2743371.06	وسط	14-Apr-10		FULL	1bM]WUvF

SECTION_NO	DISTRICT NO	DISTRICT NAME	STREET NO	STREET NAME	FROM STREET NO	FROM STREET NAME	TO STREET NO	TO STREET NAME	STREET WIDTH	SECTION LENGTH	SECTION WIDTH	SECTION AREA	LOCATION TYPE	TRAFFIC EASTING	TRAFFIC NORTHING	CONDITION STATUS	UPDATE DATE	SURVEY DRAWING	MAINT TYPE	GEOMETRY sk
440708758M	4407	غرناطة	758	أبو جعفر المنصور	765	ابن خزيمة الأنصاري	522	خالد بن الوليد	40	387	17.76	6872	سكنية	676595.67	2743193.56	مقبول	14-Apr-10		FULL	1bM]WUOp
440709758M	4407	غرناطة	758	أبو جعفر المنصور	522	خالد بن الوليد	768	بعلبك	40	689	15.55	10713.9	سكنية	676604.24	2743179.09	وسط	14-Apr-10		FULL	1bM]WU
440709759M	4407	غرناطة	759	محمد علي جناح	768	بعلبك	522	خالد بن الوليد									14-Apr-10		FULL	1bM]WU
440715758M	4407	غرناطة	758	أبو جعفر المنصور	768	بعلبك	770	النبهانية	40	81	16.4	1328.4	سكنية	677272.66	2743490.34	وسط	14-Apr-10		FULL	1bM]WUvI
440715759M	4407	غرناطة	759	محمد علي جناح	770	النبهانية	768	بعلبك									14-Apr-10		FULL	1bM]WUv
440717758M	4407	غرناطة	758	أبو جعفر المنصور	755	طريق الشيخ حسن بن حسين بن علي	A68	عثمان بن سليمان	40	320	16.4	5248	سكنية	677986.28	2743843.19	وسط	14-Apr-10		FULL	1bM]WUV
440720759M	4407	غرناطة	759	محمد علي جناح	770	النبهانية	755	طريق الشيخ حسن بن حسين بن علي									14-Apr-10		FULL	1bM]WUV
440721550M	4407	غرناطة	550	الإمام عبدالله بن سعود بن عبدالعزيز	755	طريق الشيخ حسن بن حسين بن علي	522	خالد بن الوليد	80	1840	11.07	20368.8	تجارية	678513	2742975	جيد	14-Apr-10		FULL	1bM]WUV
440721550S	4407	غرناطة	550	الإمام عبدالله بن سعود بن عبدالعزيز	755	طريق الشيخ حسن بن حسين بن علي	522	خالد بن الوليد	80	1558	9.58	14925.64	تجارية			جيد			FULL	1bM]WUV
440732759M	4407	غرناطة	759	محمد علي جناح	522	خالد بن الوليد	770	النبهانية									14-Apr-10		FULL	1bM]WU
440801550M	4408	الحمراء	550	الإمام عبدالله بن سعود بن عبدالعزيز	522	خالد بن الوليد	969	البحار	80	1836	11.178	20522.808	تجارية	673397	2723789		14-Apr-10		FULL	1bM]WUw
440801550S	4408	الحمراء	550	الإمام عبدالله بن سعود بن عبدالعزيز	522	خالد بن الوليد	755	طريق الشيخ حسن بن حسين بن علي	80	1505	10.538	15859.69	تجارية						FULL	1bM]WUV
440804550M	4408	الحمراء	550	الإمام عبدالله بن سعود بن عبدالعزيز	969	البحار	965	الحيا	55	587	10.2	5987.4	خدمية	677669	2742550	ضعيف	14-Apr-10		FULL	1bM]WUV
440805550M	4408	الحمراء	550	الإمام عبدالله بن سعود بن عبدالعزيز	965	الحيا	755	طريق الشيخ حسن بن حسين بن علي	55	194	10	1940	خدمية	678327	2742861	ضعيف	14-Apr-10		FULL	1bM]WUX>
441401758M	4414	القادسية	758	أبو جعفر المنصور	699	الكواكب	756	الشيخ جابر الأحمد الصباح	40	41	16.6	680.6	لايوجد			وسط	14-Apr-10		FULL	1bM]WuG>
441402550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	B80	الكواكب	657	ابن عساكر									14-Apr-10		FULL	1bM]Wuj
441402758M	4414	القادسية	758	أبو جعفر المنصور	756	الشيخ جابر الأحمد الصباح	699	الكواكب	40	25	16.56	414	سكنية			مقبول	14-Apr-10		FULL	1bM]WuGC
441403758M	4414	القادسية	758	أبو جعفر المنصور	I82	وادي الشاطئ	699	الكواكب	40	213	16.6	3535.8	سكنية			وسط	14-Apr-10		FULL	1bM]Wuf
441406758M	4414	القادسية	758	أبو جعفر المنصور	699	الكواكب	I82	وادي الشاطئ									14-Apr-10		FULL	1bM]Wuf
441409550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	I86	وادي الحياة	J40	جبل الظنة									14-Apr-10		FULL	1bM]Wuc
441410550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	C98	طريق الجنادرية	I86	وادي الحياة									14-Apr-10		FULL	1bM]Wu>
441411550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	756	الشيخ جابر الأحمد الصباح	B80	الكواكب									14-Apr-10		FULL	1bM]Wuj
441413550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	B80	الكواكب	I88	وادي زمزم									14-Apr-10		FULL	1bM]WuI
441415550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	I88	وادي زمزم	I90	وادي حلي									14-Apr-10		FULL	1bM]WuJ
441417550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	I90	وادي حلي	C88	السلطان قابوس بن سعيد									14-Apr-10		FULL	1bM]Wu
441421550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	C88	السلطان قابوس بن سعيد	I86	وادي الحياة									14-Apr-10		FULL	1bM]Wua
441422550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	I86	وادي الحياة	C98	طريق الجنادرية									14-Apr-10		FULL	1bM]Wu>
441423550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	I77	وادي الساحل	J03	شارع رقم J03									14-Apr-10		FULL	1bM]WuJf
441426550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	J30	وادي بيحان	B80	الكواكب									14-Apr-10		FULL	1bM]WuI
441431550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	J40	جبل الظنة	J41	جبل الصفورية									14-Apr-10		FULL	1bM]Wucf
441433550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	J41	جبل الصفورية	J38	وادي جيزان									14-Apr-10		FULL	1bM]Wuby5
441434550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	J38	وادي جيزان	C88	السلطان قابوس بن سعيد									14-Apr-10		FULL	1bM]Wubx
441435550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	C88	السلطان قابوس بن سعيد	J36	جبل الرحا									14-Apr-10		FULL	1bM]Wu
441437550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	J36	جبل الرحا	J35	جبل الذبياني									14-Apr-10		FULL	1bM]WuQ;
441438550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	J35	جبل الذبياني	E45	وادي الرمة									14-Apr-10		FULL	1bM]WuQ?-
441439550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	E45	وادي الرمة	J34	وادى وج									14-Apr-10		FULL	1bM]WuQ-
441440550M	4414	القادسية	550	الإمام عبدالله بن سعود بن عبدالعزيز	J34	وادى وج	I77	وادي الساحل									14-Apr-10		FULL	1bM]WuJ
441712758M	4417	الشهداء	758	أبو جعفر المنصور	769	الدوحة	B15	عبدالرحمن بن عزاز									14-Apr-10		FULL	1bM]WUo
441712759M	4417	الشهداء	759	محمد علي جناح	B15	عبدالرحمن بن عزاز	769	الدوحة	40	113	12.9	1457.7	سكنية	675558.93	2742508.24	وسط	14-Apr-10		FULL	1bM]WUo
441713759M	4417	الشهداء	759	محمد علي جناح	C16	الشملول	522	خالد بن الوليد	40	330	16	5280	سكنية	676215.78	2742811.94	ضعيف	14-Apr-10		FULL	1bM]WUP-
441714759M	4417	الشهداء	759	محمد علي جناح	K08	العلمين	769	الدوحة	40	267	14.28	3812	سكنية			وسط	14-Apr-10		FULL	1bM]WUof
441722758M	4417	الشهداء	758	أبو جعفر المنصور	B15	عبدالرحمن بن عزاز	ERR	طريق الدائري الشرقي	40	879	13.7	12042.3	سكنية	675862	2742927	وسط	14-Apr-10		FULL	1bM]WUf
441723758M	4417	الشهداء	758	أبو جعفر المنصور	522	خالد بن الوليد	B18	وادي اللجام	40	351	15.16	5321.1	سكنية	682245	2744499	وسط	14-Apr-10		FULL	1bM]WUN
441724758M	4417	الشهداء	758	أبو جعفر المنصور	B18	وادي اللجام	B15	عبدالرحمن بن عزاز	40	225	13.8	3105	سكنية	675862	2742927	وسط	14-Apr-10		FULL	1bM]WUo>
441726759M	4417	الشهداء	759	محمد علي جناح	769	الدوحة	C16	الشملول	40	520	19.6	10192	سكنية	675562.56	2742498.23	وسط	14-Apr-10		FULL	1bM]WUN
441730758M	4417	الشهداء	758	أبو جعفر المنصور	B15	عبدالرحمن بن عزاز	522	خالد بن الوليد					سكنية				14-Apr-10		FULL	1bM]WUN
441730759M	4417	الشهداء	759	محمد علي جناح	522	خالد بن الوليد	B15	عبدالرحمن بن عزاز	40	740	13.2	9768	سكنية	676210.08	2742820.74	وسط	14-Apr-10		FULL	1bM]WUN
441731758M	4417	الشهداء	758	أبو جعفر المنصور	ERR	طريق الدائري الشرقي	K08	العلمين	30	293	12.2	3574.6	سكنية			وسط	14-Apr-10		FULL	1bM]WUMp
441734758M	4417	الشهداء	758	أبو جعفر المنصور	K08	العلمين	769	الدوحة	40	245	13.3	3258.5	سكنية			وسط	14-Apr-10		FULL	1bM]WUo
441734759M	4417	الشهداء	759	محمد علي جناح	769	الدوحة	K08	العلمين	40	267	14	3738	سكنية			وسط	14-Apr-10		FULL	1bM]WUof

Appendix-E: Outputs of ANN Based Corridor Prioritization Model

S.No	Corr. ID	Network(1)	Network(2)	Network(3)	Network(4)	Network(5)	Corr. Priority Group
1	440201758M	1	0	0	0	0	1
2	440202758M	1	0	0	0	0	1
3	440203550M	0	1	0	0	0	2
4	440205758M	0	0	0	1	0	4
5	440205759M	1	0	0	0	0	1
6	440206759M	0	1	0	0	0	2
7	440207759M	1	0	0	0	0	1
8	440210758M	1	0	0	0	0	1
9	440210759M	1	0	0	0	0	1
10	440211759M	0	1	0	0	0	2
11	440212550M	1	0	0	0	0	1
12	440213759M	1	0	0	0	0	1
13	440217758M	0	1	0	0	0	2
14	440219550M	1	0	0	0	0	1
15	440220759M	0	0	1	0	0	3
16	440224758M	1	0	0	0	0	1
17	440225758M	0	1	0	0	0	2
18	440226758M	1	0	0	0	0	1
19	440230758M	1	0	0	0	0	1
20	440232758M	1	0	0	0	0	1
21	440235758M	1	0	0	0	0	1
22	440237758M	1	0	0	0	0	1
23	440243758M	0	0	0	1	0	4
24	440245758M	0	0	0	1	0	4
25	440247758M	0	0	0	1	0	4
26	440247759M	0	0	0	1	0	4
27	440249758M	0	1	0	0	0	2
28	440250759M	0	0	0	1	0	4
29	440301550M	0	0	0	1	0	4
30	440302550M	0	0	0	1	0	4

S.No	Corr. ID	Network(1)	Network(2)	Network(3)	Network(4)	Network(5)	Corr. Priority Group
1	440702758M	0	1	0	0	0	2
2	440705758M	0	0	1	0	0	3
3	440708758M	0	1	0	0	0	2
4	440709758M	0	1	0	0	0	2
5	440715758M	0	1	0	0	0	2
6	440717758M	0	0	1	0	0	3
7	440721550M	0	0	1	0	0	3
8	440801550M	0	0	0	1	0	4
9	440804550M	0	0	0	1	0	4
10	440805550M	0	0	0	1	0	4
11	441406758M	0	0	0	1	0	4
12	441409550M	0	0	0	0	1	5
13	441410550M	0	0	0	0	1	5
14	441411550M	0	0	0	1	0	4
15	441413550M	0	0	0	1	0	4
16	441415550M	0	0	0	1	0	4
17	441417550M	0	0	1	0	0	3
18	441421550M	0	0	1	0	0	3
19	441422550M	0	0	1	0	0	3
20	441423550M	0	0	0	1	0	4
21	441426550M	0	0	1	0	0	3
22	441431550M	0	0	0	1	0	4
23	441433550M	0	0	0	1	0	4
24	441434550M	0	0	0	1	0	4
25	441435550M	0	0	0	1	0	4
26	441437550M	0	0	0	1	0	4
27	441438550M	0	0	0	0	1	5
28	441712759M	0	0	0	0	1	5
29	441713759M	0	0	0	1	0	4
30	441722758M	0	0	0	1	0	4
31	441723758M	0	0	0	1	0	4
32	441724758M	0	0	0	0	1	5
33	441726759M	0	0	0	0	1	5
34	441730759M	0	0	0	0	1	5