A Value-based Approach For Municipal Asset Management

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ABSTRACT

Title: A Value-based Approach for Municipal Asset Management

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Asset management serves to schedule interventions to maximize the condition of municipal assets. However, municipalities face the daunting task of dealing with a wide variety of assets (civil infrastructure, facilities, buildings, vehicles, machinery and equipment) with a limited budget. There is a lack of an approach to optimize the scheduling of interventions across all types of municipal assets. There is also a disconnection between the effectiveness of the budget and its ability to upkeep the value of the assets as demanded by accounting and financial regulations. Previous attempts to handle multiple assets face problems in budget balancing given the dissimilar units of measurement of condition indicator for each asset type. This research proposes a value-based approach supported by deterioration and depreciation curves. Treatments are used to sustain or increase the value of all assets. A case study of the municipality of Kindersley is presented to showcases how the value-based approach is more financially-sustainable, yet cost-effective. The approach is flexible enough to accommodate all types of municipal assets, however for limitations of data the case study considers: street names, signs, hydrants, lighting, sidewalks, roads, sanitary pipes and water mains. An Excel platform with a special Add-in is used to host the database and performance curves and to define the optimization problem. An external solver is used to find the optimal solution. Results demonstrate a more stable long term progression for the value-based approach as compared to the condition-based. Meanwhile budget remain at very similar levels.

KEY WORDS

Municipal; Asset Management Systems; Optimization; Decision Making; Condition-based approach; Value-based approach

DEDICATION

To

My family for their support

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Standards Test Method
AMS	Asset Management System
BMS	Bridge Management System
CGI	Consultants to Government and Industries
CIRC	Canada Infrastructure Report Card
CP	Compromise Programming
ELECTRE	ELimination Et Choix Traduisant la REalite
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
GASB	Governmental Accounting Standards Board
ICAO	International Civil Aviation Organization
IRI	International Roughness Index
LOS	Level-Of-Service
LCCA	Life-Cycle Cost Analysis
M&R	Maintenance and Rehabilitation
MUTCD	Manual on Uniform Traffic Control Devices
MCDM	Multi-Criteria Decision Making
NAMS	National Asset Management Steering
NCHRP	National Cooperative Highway Research Program
O&M	Operation and Maintenance
PCI	Pavement Condition Index
RSIG	Retro-reflective Sheeting Identification Guide
SMS	Safety Management System
SOC	Social Overhead Capital
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

PROMETHEE	The Preference Ranking Organisation METhod for Enrichment Evaluations
TPM	Transition Probability Matrix
TAM	Transportation Asset Management
TEA	Treatment and Effectiveness Assessment
ULI	Urban Land Institute
VIKOR	VIse Kriterijumska Optimizacija Kompromisno Resenje
VIR	Visual Inspection Rating
MCO	Multi-Criteria Organization
WMS	Water Management System
WPM	Weighted Product Model
WSM	Weighted Sum Model

Chapter 1 Introduction

1.1 Background

For decades, most municipalities focused on a wide range of new constructions and developments in order to establish a social overhead capital (SOC). Necessity of maintenance and rehabilitation of assets has emerged as a serious social problem due to the rapid decay of assets condition and the imminent risk of failure or collapse. However, many municipalities are still having difficulty solving these problems for various reasons such as insufficient funding or lack of an appropriate approach. The contemporary reality is one of extensive networks of infrastructure, and large numbers of machinery, equipment, vehicles and facilities that support municipal operations. In consideration of this trend, new construction of roads and infrastructure has declined, while maintenance continues to grow up.

Municipalities face the daunting task of dealing with a wide variety of assets (roads, vehicles, pipes, buildings, parks, airports, fire equipment and so on) with a restricted budget, which is required to be economically distributed across all the assets within their jurisdiction. Present asset management practices optimize scheduling of interventions to maximize condition of multiple assets and sustain them at good levels of service across time. Currently, all such decision on budget allocation use a condition-based model. This research proposes value-decay curves which are calibrated from depreciation or deterioration curves, and treatment effectiveness that is matched to increase the value of all assets.

1.2 Problem Statement

Currently, most municipalities own a variety of civil infrastructure assets. In order to manage them efficiently, they are operated and maintained to deliver important services and ensure a standard of living within their communities that supports economic prosperity, well-being and safety. In general, municipality assets include buildings, water treatment facilities, wastewater systems, water distribution networks, roads, sidewalks or paths, bridges, landfills, culverts, equipment, streetlights, etc.

For the sake of successful and efficient management, there is a requirement to allocate a wide range of treatments (crack-sealing, micro-surfacing, overlay, packing, (spot) painting, water proofing, retrofitting and/or replacement) to existing asset. But that implies complex decision making process that often utilize different assets indicators with dissimilar units of measurement. There is a lack of an approach to optimize multiple assets; including machinery, vehicles, buildings, civil infrastructure and equipment own by the municipality. Hence, there is a need to count with an approach to combine various municipal assets within an optimization framework to support successfully decision making.

1.3 Research Objective

1.3.1 Overall Goal

The overall goal of this research is to propose a value-based approach that supports the allocation of interventions to achieve increasing value of municipal assets while holding them at good levels of condition.

1.3.2 Research Tasks

Two tasks were identified to address the main goal of this research:

Task 1

This task sets up a benchmark case study: a condition-based optimization approach for the same level of budget and inventory of assets used in task 2.

Task 2

The main purpose of this task is to test the suitability of alternate approach to multiple-assets optimization, which considers current and expected value of all assets within all analysis periods and uses their lifespans and value progression instead of condition indicators.

1.4 Scope and Limitations

This research demonstrates its proposed methods through a case study which limits its reach to those assets available. The first limitation comes from the database which was provided by the municipality of Kindersley, Saskatchewan, Canada and consisted of spatial records of civil infrastructure data with the location of all assets on a shape file. Vehicles and machinery were not available. The second limitation is that the condition assessment is only based on visual inspection ratio (VIR), generally a task performed manually by engineers in the municipality. The case study considered street names, signs, hydrants, lighting, sidewalks, roads, storm pipes, sanitary pipes and water mains. Finally, the solver program was limited to annual optimizations runs connected together to obtain a multi-period solution.

1.5 Organization of the Thesis

This research is composed of five chapters as follows. Chapter 1 identifies the problem and explains the objectives of the research and the scope of the thesis. Chapter 2 contains the literature review, including a historical timeline for asset management systems, decision support systems, conditions assessment, deterioration models and the need for a value-based approach that provides the justification for this research.

Chapter 3 contains the methodology, including condition-based and value-based approaches. It also provides details for the database used in the case study.

Chapter 4 presents the case study which was prepared in the format of a journal paper to be submitted for publication to a journal. Finally, chapter 5 provides the conclusions, lessons learnt and recommendations for future research.

Chapter 2 Literature Review

2.1 Introduction

This chapter serves two purposes: Firstly, it provides the reader with background on municipal infrastructure management and secondly, it justifies the need for a better approach for the management of municipal assets, including non-traditional assets such as vehicles, machinery, equipment and buildings or facilities.

The chapter is divided in six major parts;

1) Section 2.1.1 gives a general background for asset management systems (AMS)
2) Section 2.1.2 explains how AMS have been extended to non-traditional assets
3) Section 2.2.1 provides historical timeline about asset management systems.
4) Section 2.2.2 explains condition assessment and deterioration modeling on municipal infrastructure management.
5) Section 2.2.3 describes some decision support systems for multi assets decision making using deterministic and stochastic optimum methods.
6) Section 2.2.4 supplies gaps on the literature in the field of asset management system and justifies the need for a value-based approach to support decision-making.

2.1.1 The Need for Asset Management Systems

Approximately 24 percent of the main roads in the United States are in faulty to disagreeable condition and 25.4 percent of bridges are assessed as poor and insufficient (ULI 2008). The management of infrastructure assets can aid to address such issues, however, it is a complex and daunting task, especially for municipalities and agencies (NAMS 2006). Nevertheless, municipalities should supply lasting networks of infrastructures with appropriate levels of services to the users (NAMS 2006). Many governments have begun to explore solutions to schedule replacement of their aging infrastructure (Sægrov, 2006; Selvakumar and Tafuri, 2012; Vanier, 2001). In accordance with Cardoso *et al.* (2012), strategic infrastructure management depends on essential information about the predicted condition of assets as time passed. Faghih-Imani *et al* (2012) enunciated that municipalities rely on diverse assets in order to appropriately assist travel and living-style; government tasks and commerce, transportation system, energy provision system, water and disposal systems, fitness and educational systems. But while having the most merit and going down the expenditures, it is mightily important to retain infrastructure assets in suitable condition to assist economic and social development. The failure in one element can bring to collapse both in special system and in other networks.

In 1996, the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) showcased the concept of asset management on the United States through a series of workshops (TAM 2002). Asset management planning is an important method for municipalities to supply sustainable level of services, manage risks and meet responsibilities. It supplies a systematic way to prioritize and deliver on municipal service demands, in a financial and proactive manner (Union of Nova Scotia Municipalities). Park and Kim (2013) described that asset management system is an organized tool that optimizes the operating, maintaining, preservation and implementation of physical assets from their service life expectancy at the lowest cost. Infrastructure asset management started experimentally with the road test experiment of the 1950's by the American Association of State Highway Officials (AASHO) which characterized the correlation between pavement life and traffic loads (FHWA, 2011).

Tactical planning was primarily suggested by Infra-guide (2003) after acknowledging the requirement to prepare coordinated interventions of municipal infrastructure. Faghih-Imani (2013) suggested the need to re-optimize the results from the long-term strategic optimization to obtain coordinated programs of works as suggested previously by Amador and Magnusson (2011) and by Islam and Moselhi (2012). The outcome of tactical analysis is used by engineers in municipalities to create operational plans with tenders that group interventions together.

2.1.2 Non-traditional assets

From a historical point of view, pavement management systems are the precursor of all other asset management systems. Management systems for other various assets had arrived recently. In 2001 AASHTO published specifications for sign structural supports, namely Standard Specifications for Structural Supports (2001), and guidelines on roadside structures (Roadside Design Guide 2002). Those guidelines introduced scope and details for common decisions models for signs, the applicable criteria, test processes, and associated documents, explaining various features such as different grades and colors for sign sheeting (NCHRP 371). Safety Management System (SMS) is an overall management system designed to operate safety elements in the workspace. It contains policy, goals, plans, progress, organization, responsibilities and other essential measures. The SMS is used in industry areas that manage outstanding safety risks, aviation and others. In 2001, Transport Canada's Rail Safety Directorate incorporated SMS into the rail industry and also the International Civil Aviation Organization (ICAO) published a Safety Management Manual (ICAO, 2006). SMS is the official, top-down, organization-wide method to manage safety risk and ensuring the effectiveness of safety risk controls. It contains systematic progress, practices, and regulations for the management of safety risk [Federal Aviation Administration (FAA)] and also introduces evolutionary steps in system safety and safety management. SMS is a structured progress that obligates organizations to manage safety with the same condition of priority that other main sectors are managed. This applies to not only internal (FAA) but also external aviation industry organizations (Chen *et al*. 2012).

Lighting improves remarkably visibility and contributes to safety. According to the NCHRP 371, road lighting has the highest benefit–cost ratio of all safety implementations, other countries have shown a deduction of approximately 25% in night crashes or accidents after road lighting was installed (Hasson and Lutkevich 2002). Lighting can also play a role not only in helping to reduce crime but also in adding beauty and influencing the nighttime visual character of an historic district or urban area (NCHRP 371).

Traffic signals control flows from intersecting streams of cars, trucks, pedestrians, cyclists, and other road users by allocation the right-of-way to individual flows in turn. In 2003, the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) found standards and warrants for signal installation and operation, as well as general guidance on responsibility for maintenance. (NCHRP 371).

At the final step of any pavement project, it is required to paint markings in order to separate lanes and that provide information and warnings to road users. Pavement markings include lane striping, raised lane markers, and painted symbols and messages on the road surface. In 2003, MUTCD created U.S. policies and standards for pavement markings in Part 3 of the NCHRP 371. Pavement markings are used, in conjunction with safety assets such as warning signs and signals, where particular attention is needed of motorists; at main crosswalks; when advance warning is required approaching intersections or junctions, rail crossings, distributions in fast level, needed stops, and so on; and for informative policy in school zones, in areas with old persons and handicapped populations; and for turning their actions in intersections of multilane roads (NCHRP 371).

Sidewalks or footways are paths along the side of a road and play an important role in transportation, as they provide a safe area for people in order to walk along that is divided from the motorized traffic. They assist road safety by minimizing interaction between motorized traffic flow and pedestrians. AASHTO established guidelines for pedestrian facilities in 2004 (NCHRP 371).

2.2 Municipal Asset Management System

2.2.1 Historical Timeline

There are several records of attempts trying to identify an optimal decision making since the 1960s. Roy and Sussman, in 1966, proposed a new technique called *ELimination Et Choix Traduisant la REalite* (ELECTRE) for multi-criteria decision making of bridges. In the subsequent year (1967), Fishburn proposed the use of a Weighted Sum Model (WSM) in order to determine an appropriate solution for asset management in the domain of dams (Kabir *et al.* 2014).

Pavement asset management was initially developed in the 1970's as a method to enable a comprehensive allocation of pavement-related works such as construction, maintenance, rehabilitation, inspection and assessment of pavement conditions (Rehan *et al.* 1994). Geiger (2005) explained that during the 1970s a design tool to forecast pavement performance over time was produced. During that time most pavements were attended on a worst-first approach. In New Zealand the Local Government Act imposed the need to develop an annual schedule by each assembly in 1974. It had to contain performance inspections, economic systems and regulations related to yearly objectives on a balanced budget (Howard,

R. J., 2001).

In the 1980s, the World Bank issued the Highway Design Manual System (HDMS) which included fundamentals of road management related to the decision making progress (Finn, 1998) with the aim of the optimum choice of interventions from a long term perspective. Despite the development of science, there were a wide range of fatal collapses of bridges; various bridges collapsed such as: Severn railway bridge (England, 1960), Heron road bridge (Ottawa, 1966), Silver bridge (United States, 1967), Tasman bridge (Australia, 1975), and so on. No systematic maintenance programs were yet in place for monitoring the condition of bridge networks and treatment to prevent those failures. The intention of bridge management systems (BMS) was to rehabilitate bridges before deterioration reached a critical condition. Since the 1980s, interest in the improvement of BMS has risen at both the state and the national levels. In 1985, the national cooperative highway research program (NCHRP) launched a program with the goal of developing a model for an effective BMS. Krugler *et al.* (2006) addressed the development of asset management systems that included bridge management system in a combined solution which eventually grew up asset management systems. BMS is a means for managing structures, throughout making design, execution, operation and maintenance of the bridges and helps agencies in order to meet their purposes; structure inventories and survey databases, organization for maintenance, treatment interventions in a systematic method, optimizing the distribution of economic materials, and increasing the safety of bridge users (Elbehairy, 2007).

Pipe culverts and box culverts facilitate drainage under and around roads, highways, streets, and sidewalks, providing sustainability to the road structure and protection flooding of surrounding areas. Most culverts are gradually being used for animal passages under road embankments. According to the NCHRP 371, in 1987, national standards and guidelines were published by the FHWA and AASHTO with sections referring to box culvert design (Highway Drainage Guidelines) and culvert inspection.

Malm *et al.* (2012) proposed to introduce asset management systems for clean-water pipes in Gothenburg, Sweden, accordingly this required data spanning for over 100 years to develop deterioration models. Meanwhile, one of the Multi-Criteria Decision Makings, Analytical Hierarchy Process (AHP) was used by Saaty in 1980. In the very next year, Hwang and Yoon (1981) applied a new approach called *Technique Order of Preference by Similarity to Ideal Solution* (TOPSIS). In 1982, a software called Compromise Programming (CP) was used by Zeleny. Brans and Vincke to produce the known solution *Preference Ranking Organization METhod for Enrichment Evaluations* (PROMETHEE).

With the arrival of the 1990s, the Accounting Standard 27 in 1993 (Howard, R. J., 2001) brought rapid awareness of the role of municipal asset management system as they serve to prevent the negative effects of deteriorated municipal road infrastructures as they were essential to support a productive and competitive economy. In the meantime, Opricovic worked take advantage of *VIse Kriterijumska Optimizacija Kompromisno Resenje* (VIKOR) in the domain of transit in 1998.

In the early 2000s, Stalebrink and Gifford (2002) asset management systems became extensively used all around the world with the introduction of the International Manual of Asset Management (NAMS 2006).

In the late 2000s, (Louis and Magpili) explained asset management system (AMS) using Capacity-Based Approach and (Xu *et al.*) also descripted AMS by utilizing the Risk-Return Trade-Off. In addition, (Bernhardt *et al*. 2008) studied Agent-Based Modeling as a paradigm in order to develop asset optimization. Moreover, in 2009, (Corotis) suggested the need to use a life-cycle cost approach for the management of Civil Infrastructure Systems and Stewart (2009) joined Life-Safety Risks and Optimization, their analysis applied to various assets for commercial buildings in the US.

In 2010, Elhakeem *et al.* introduced building asset management system; which is a comprehensive framework with a unique formulation. Building Management System uses a microprocessor system, installed to monitor and manage all structures technical systems and services; air conditioning, ventilation, lighting and hydraulics, etc. Building Management System is now based on open communications protocols and access from anywhere in around the world. Bus Rapid Transit System is utilized by (Caicedo *et al*. 2010) to show a reliability cost-based optimization model.

In 2011, Dynamic Programming Models were taken by Mafakheri in the field of bridges management to optimize (inspection, maintenance and rehabilitation) groups of structures. In 2013, Peng *et al.* analyzed infrastructure management system using a Time-Dependent Analysis based on an investigations of carbonation-induced deterioration in three typical Chinese cities under a changing weather.

In 2014, Zayed *et al.* explained Infrastructure Performance Rating Models in order to manage wastewater treatment plants and Sigtryggsdóttir *et al*. (2016) suggested the use of a Geo-Hazard Monitoring system for safety management. In 2016, Kobayashi *et al*. introduced Big Data-Based Deterioration Prediction Models to figure out the optimal solution to the maintenance problem. Figure 2.1 summarizes the historical time line of advancement in civil infrastructure management systems.

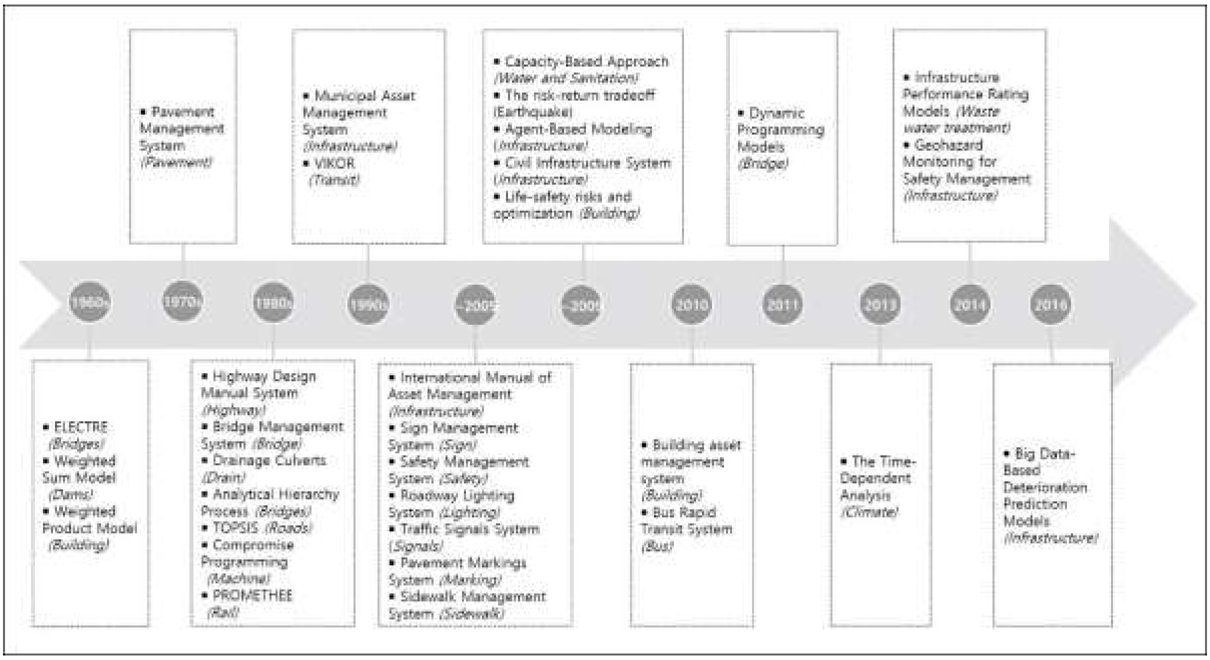


Figure 2-1 Evolution of Asset Management System (Approaches)

2.2.2 Condition Assessment and Deterioration modeling

The condition of a given road section can expressed by a pavement condition index (PCI), which is a standard for the pavements condition (ASTM 2007). Pavement condition inspections supply, in terms of pavement management system, an indication of its physical condition and consist on the rating of the quality of a given element. Data collection methods include: manual (human investigation) and automated (ground penetrating radars, acoustic sensors, etc.). Their use is extensively selected in accordance with municipality's priorities, applicable resources and geographic constraints. Ozden *et al.* (2016) highlighted that condition ratings are needed for managing the maintenance and repair tasks. Fwa *et al.* (2012) divided a bridge into three individual elements: deck, superstructure, and substructure. They suggested to evaluate each bridge component state in terms of up to five discrete "condition states" ranging from 1 to 5, where 1 and 5 are the best and the worst condition states, respectively. Wellalage *et al.* (2015) explained that bridge investigation data comprise condition ratings of main elements such as superstructure, deck, substructure, etc., or sub main elements.

There are a wide range of deterioration models. They can be grouped in two types: deterministic and stochastic or probabilistic models. Deterministic models describe that the output of the model is fully determined by the parameter values (formula) and the initial conditions (Amador and Mrawira 2009), while stochastic models possess some inherent randomness. Deterministic modeling are usually used in instances where the relationships between components are certain. Garza et al (2011) provide a good example for the calculation of pavement deterioration rates deterministically from historical data. Edirisinghe *et al.* (2012) established a reliability based methodology for deterioration of community facilities.

According to the research written by Wellalage in 2015, establishing Optimal Deterioration Models is definitely mandatory to accomplish an expansive Bridge Management System (BMS). The principal work is to inspect Transition Probability Matrixes (TPMs) in State Based Markov Deterioration (SBMD) modeling.

2.2.3 Decision Support Systems

Friesz and Fernandez (1979) established one of the first Maintenance and Rehabilitation (M&R) optimization models for transportation infrastructure, at the time, the main concern was to identify the best allocation of resources and of interventions in the long term. Other researchers have continued pursuing such strategic analysis often using Dynamic Linear Programming (Kuhn and Madanat 2005, Arif and Bayraktar 2012). Garza et al. (2011) and Gao *et al.* (2012) developed and implemented Network-Level Optimization models for pavement's M&R. A Zero/One Knapsack Model was proposed by Edirisinghe *et al.* (2012) for project selection of railway bridge elements. Gay et al. (2012) developed a resilience assessment methodology for water distribution systems using a Stochastic Simulation

Approach (El-Abbasy et al. 2016). Faghih-Imani et al. (2012) reviewed various historical models such as PONTIS which can be used for bridge management system and PAVER, HDM4, HERS-ST for road management system.

Another group of researchers have concentrated their attention in shorter term issues. Li *et al.* (2011) showed a New Grouping Model useful for coordination of pipeline and road programs. Faghih-Imani *et al*, (2012) showed a similar analysis for roads and bridges. Molinos-Senante *et al.* (2011) described a Theoretical Methodology to evaluate internal and external economic influences the economic possibility assessments of their water-reuse projects should quantitatively appraise economic, environmental and resource availability.

One of the main concerns of the literature is to identify the best multi-criteria decision support system capable of handling several assets at a time. Many researchers have studied this issue and recommended various methods to figure out the best appropriate answer for the distribution of budget-expenditures across competing alternatives (NCHRP 2005). Among them we can distinguish prescriptive and descriptive methods. Ashok A. Divekar et al. (2012) explained that prescriptive decision makers are concerned with prescribing ways for making optimal decisions, meanwhile descriptive decision makers are interested in the bounded way in which the decisions are practically made. This issue has been investigated through traditional (Linear Programming, Goal Programming and Weighted Objective, Non-Linear Programming, Integer Programming, Dynamic Programming, Multi Objective Programming) and other alternative models (heuristic methods). Gühnemann et al. (2012), incorporated Cost-Benefit Analysis results into a multi-criteria analysis framework.

Kabir *et al.* (2014) did a comprehensive literature review of Multi-Criteria Decision-Making (MCDM) for asset management with 300 published papers between 1980 and 2012: they found MCDM approaches were used on several applications which shared some common mathematical factors such as the Weighted Sum Model (WSM), Weighted Product Model, Compromise Programming (CP), Analytical Hierarchy Process (AHP), ELECTRE, TOPSIS, PROMETHEE and VIKOR.

According to the Kabir *et al.* (2014) the WSM (Fishburn 1967) is the most commonly used approach in the literature. It determines the appropriate substitute as the one which coincides to the ‘best’ value (maximum for all benefit-type standard and minimum for cost-type standard) of the weighted total. There are major differences of WPM (Bridgeman 1922), in comparison with WSM; the weighted parameters are multiplied instead of summed. Each substitute is compared with the others by multiplying a number of ratios, one for each standard. In addition, CP (Zeleny 1982) is affiliated to a class of multi-criteria analytical tools which is called 'distance-based' tools. Distance-based techniques are designed to confirm non-dominated settlements that are nearest to an ideal solution by some distance gauge. AHP (Saaty 1980) is based on gaining of preferences or weights of importance to the standard and substitutes. In this manner, standard and substitutes can be formed in a hierarchical way. The original ELECTRE method (Benayoun *et al.* 1966) is normally named as 'ELECTRE I', because some different versions of the ELECTRE tool were consequently given: ELECTRE II (Roy & Bertier 1971), ELECTRE III (Roy, 1978), ELECTRE IV (Hugonnard & Roy, 1982), ELECTRE IS (Roy & Skalka, 1984), ELECTRE and ELECTRE TRI (Yu, 1992). ELECTRE III is the most famous and most used tools of them. All the versions of ELECTRE are based on the same essential concepts while are operationally more or less different. ELECTRE is based on the definition of outranking relations between substitutes, taken two at one time.

(Hwang *et al.* 1981) advanced technique for order of preference by similarity to ideal solution (TOPSIS): value-based compensatory tool in conception and application. TOPSIS tool tries to select substitutes that simultaneously have the nearest distance from the positive ideal settlement and the farthest distance from the negative-ideal solution. The positive one maximizes the benefit standard and minimizes the cost standard. Moreover, Brans (1982) firstly advanced the preference ranking organization method for enrichment evaluations (PROMETHEE) and additional extended by Brans and Vincke (1985). PROMETHEE is an outranking tool for a limited set of substitute actions to be ranked and selected among conflicting standard; it is applicable even when simple and efficient information is needed. The VIKOR [the Serbian name is '*Vlse Kriterijumska Optimizacija Kompromisno Resenje*' which means Multi-Criteria Optimization (MCO) and compromise solution] (Opricovic 1998), is developed to figure out MCDM problems with contradictory and non-commensurable standard: it provide maximum group utility of majority and minimum individual regret of opponent.

Table 2-1 and 2-2 update those presented by Kabir *et al.* (2014) to 2016. Such tables provide a good example of how common the before mentioned multi-criteria decision making approaches are. This research, however, proposes an alternate method, called value-based optimization approach which is presented in the following chapter.

In recent years non-traditional assets have started to arrive into the decision support systems. Frackelton *et al.* (2013) collected data for more than 40 sidewalk sections across the city of Atlanta and deployed the Quality Assessment Inspection in order gather feedback from more than 100 national transportation specialists and shareholders on sidewalk quality expert ratings.

New methods to handle multi-criteria decisions have also been recently proposed: Zhou *et al.* (2014) proposed a decision support model that included two-phase optimizations for bridges. On top of that, the Markowitz Mean-Variance Model was utilized to formulate the lower bound risk of project merits for an allowed budget level. Yepes *et al.* (2016) pictured an optimization method based on a hybrid Greedy Randomized Adaptive Search Procedure (GRASP) considering Threshold Accepting (TA) with relaxed limitations.

Table 2-1 Distribution of MCDM papers by methods and applications [Adapted from: Kabir *et al.* (2014)]

Application area	WSM	AHP	ELECTRE	PROMETHEE	CP	TOPSIS	VIKOR	Combined Methods	Total
Water resources system	5	6	5	10	10	2	4	36	78
Water and waste water main	2	15	8	7	4	1	1	15	53
Transportation	2	30	5	1	0	4	0	14	56
Bridges	0	8	0	0	0	0	0	51	59
Buildings	1	5	2	1	1	6	3	16	35
Underground Infrastructure	1	4	1	2	1	0	0	3	12
Others	1	6	0	0	0	5	0	9	21
Total	**12**	**74**	**21**	**21**	**16**	**18**	**8**	**144**	**314**

Table 2-2 Distribution of MCDM papers by methods between 1960 and 2016 [Adapted from: Kabir *et al.* (2014)]

Years	WSM	AHP	ELECTRE	PROMETHEE	CP	TOPSIS	VIKOR	Combined Methods
1960-1979	1	0	1	0	0	0	0	0
1980-1982	0	1	0	0	1	1	0	1
1983-1985	0	0	0	1	0	0	0	1
1986-1988	0	1	0	1	0	0	0	1
1989-1991	0	3	0	0	1	0	0	4
1992-1994	0	3	0	0	1	0	0	6
1995-1997	1	2	4	4	1	0	0	8
1998-2000	0	4	2	1	0	0	1	12
2001-2003	3	9	1	2	2	2	1	5
2004-2006	1	11	3	4	4	2	0	34
2007-2009	3	16	2	3	3	3	4	31
2010-2016	3	24	8	5	3	10	2	41
Total	**12**	**74**	**21**	**21**	**16**	**18**	**8**	**144**
Percentage	**3.8**	**23.6**	**6.7**	**6.7**	**5.1**	**5.7**	**2.5**	**45.9**

In terms of the use of the value or the cost of an asset as part of the decision support system, various have proposed the use of life cycle analysis, for instance Marzouka *et al.* (2012) are a good example. They studied the life cycle M&R based on minimum cost: they proposed the advancement and use of LCCA for public tasks investments as this can contribute to the objectives of decreased building, management and maintenance costs. The fundamental formula for life-cycle M&R cost is represented in Equation (1). As seen this formula neglects the value of the assets and their progression through time, it rather concentrates the attention into the expenditure in maintenance.

$$C\text{pv} = \sum_{i=1}^{N} \frac{Cti}{(1 + idis)ti} \qquad 1)$$

Where:

C_{PV}: present value of the cumulative (life cycle) cost due to all maintenance interventions;

N: number of maintenance interventions;

C*ti*: cost of maintenance interventions applied at time ti and

idis: discount rate.

Table 2-3 provides a summary of the advances on decision support systems from the perspective of the type of assets covered, it differs from that presented in Table 2-1 and 2-2 because such tables concentrate on existing methods and how often they are used. Instead, Table 2-3 covers the type of prediction associated to the objective and the type of decision making system for academic non-commercial solutions.

Table 2-3 Decision-Makings Table

Decision-Making	**Type of Assets**	**Prediction Types (Objectives)**	**References**	**Year**
Dynamic Maintenance Optimization Model	Roads	Condition	Friesz and Fernandez	1979
PAVER	Roads	Condition, Cost	AASHTO	1993
HERS-ST	Roads	Condition, Cost	FHWA(2002)	1999
PONTIS programming	Bridge	Condition, Cost	Lake N and Seskis J	2008
HDM-4	Roads	Condition, Cost	AASHTO	2010
Maintenance Grouping optimization (MGO) model	Roads and Water Systems	Condition	Li *et al.*	2011
Theoretical Methodology	Water Systems	Economy, Environment and Demands	Molinos-Senante *et al.*	2011
Bridge Management System	Bridge (Deck, Superstructure, Substructure)	Condition	FHWA(1985), Fwa et al.(2012)	2012
Cost-Benefit Analysis	Roads	Condition (initial ranking)	Gühnemann *et al*.	2012
Network-level Optimization Model	Pavement	Treatment (M&R)	Garza *et al*. (2011) and Gao	2012

Decision-Making	**Type of Assets**	**Prediction Types (Objectives)**	**References**	**Year**
			et al. (2012)	
Zero-one knapsack model	Bridge	Condition and Deterioration	Edirisinghe *et al.*	2012
Life Cycle M&R Module	Building	Cost and Condition	Marzouka *et al.*	2012
Dynamic Linear Programming	Roads and Bridge	Condition	Arif and Bayraktar	2012
Weighted Product Model (WPM)	Water Systems	Cost	Bridgman(1922), Kabir et al.(2013)	2013
Quality Assessment Tool	Sidewalk	Quality	Frackelton *et al.*	2013
Markowitz Mean-Variance model	Bridge	Cost and Condition	Zhou *et al.*	2014
Greedy Randomized Adaptive Search Procedure (GRASP)	Infrastructure	Cost	Yepes *et al.*	2016
Integrated performance assessment model	Water Systems	Condition, Cost	El-Abbasya *et al.*	2016

2.2.4 The need for a value-based approach

Asset Management System supports the mission of the municipal agencies to meet their requirements of delivering customer-oriented service within an aging infrastructure and ever more constrained resources. One of the key tasks in the asset management process is an improved and optimized coordination of all influencing engineering parameters together with the asset value to the expectations and requirements of the public (Deix *et al.* 2012). Asset management has evolved over the past decades, assets systems were increasingly added as well as objectives. Today the frontier in asset management pushes towards having resilient systems to natural hazards, integrated infrastructure analysis that account for cross interactions, policy oriented systems that can support government's decisions and infrastructure that supports sustainability goals.

Municipalities have an increasing focus on ensuring effective operation and optimal investment in their civil infrastructure assets. However, few municipalities have a management system in place that ensures factual decision-making and stringent implementation. Most municipalities are realizing that an asset management process is required to address the rising costs for, and competing priorities associated with, infrastructure aging and the need for better services (National Guide to Sustainable Municipal Infrastructure 2004). Effective asset management planning enables a decision making process that balance engineering and economic approaches to deliver a better value for money. As many organizations develop an understanding of the physical condition of their assets, it is inevitably required to reflect and transform this condition with the service that the asset provides. This will lead to asset management processes that focus on managing services and how investment decisions may be used to best support the delivery of these services (CIRC 2014).

Most of municipal agencies deal with different assets such as pavements, bridges, street light, signs, building, rails, vehicles and equipment to perform their asset management planning. In fact, all these assets use different criteria's in determining an optimal long term planning. In addition to that, previous attempts to handle multiple assets face problems in budget balancing given the dissimilar units of measurement of condition for each network. Many agencies are focused on managing a single asset type and very few are making cross-asset analysis. However, the main challenge facing the industry today is how to distribute available limited budget among different asset types to achieve the best overall asset value performance (Laumet and Bruun 2016).

Based on ISO 55000 - International Standard for Asset Management encourages organizations to foster a consistent understanding and approach to asset management so as to ensure an optimal service deliverables. This raises a need for cross asset optimization with a key question of how to achieve a better value for money, especially in this era where the infrastructure gap keeps increasing with shrinkage of budget. It is clear that, the asset value may be different for different organizations and it may vary as the assets age, but by using a value-based approach the investment can be optimized and well managed over time.

However, it is not common for the asset management practitioners to integrate asset value and engineering deterioration of the asset as part of the optimization and benefit parameters. Most agencies often consider asset value as a parameter to calculate and seek funds for their maintenance and operation budget. It is therefore necessary to consider asset values together with or as a supplement to the normally applied asset management optimization parameters, in order to realize the full economic benefits of different funding scenarios.

In other words, it is important for the agencies consider financial performance and engineering deterioration criteria's for their asset management planning. This paper considers the use of value decay curves which is calibrated from assets deterioration curves, and treatment effectiveness to improve the financial performance and the level of service of the assets with an ultimate goal of ensuring maximum returns of an investment.

A comprehensive asset optimization requires continuous improvement in the effectiveness of the overall asset management by providing more holistic adjustments across different asset types (CGI 2015). Due to the facts that, often assets are different, the need to analyze assets based on its adjustable value is paramount. Combination of asset cost and its engineering deterioration model can scientifically support decision making processes to better justify the allocation of limited resources (budget) across the organization. The core basis of adopting a value-based optimization model is to shift the focus of the asset itself and onto the value that the asset provides to the organization. The goals of reducing costs and risk, and increasing performance, are neither mutually exclusive nor interdependent, but they are interrelated.

Obviously, business as usual is not an option in today's economy with increasing pressure on the budget while aging infrastructure gap widening. Any assets planning decision which is not well optimized with its associate asset value performance, its potential impacts of those decisions remain unknown and indefensible. The value-based optimization is centered on a balanced routing model in order to frame decision-making of the organization. Furthermore, the value-based model provides the foundation for an efficient and structured approach to ensure that all parameters of asset management information's are part of the process and those resources are used prudently. This paper will demonstrate how asset values are part of the optimization algorithms process.

It is true that, infrastructure assets require ongoing investment to sustain it. In other words, infrastructure assets have monetary value (financial) and it does deteriorate over its useful life (engineering). Integrating asset value in asset management is essential as it offers the most optimized, cost-effective ways while maintaining or enhancing the value of those assets (Alyami and Tighe 2016). The value-based optimization approach will help the organization to make informed, proactive infrastructure and budget decisions based on their priorities and needs. The menace in decision-making will be lower as the decision maker will be scientifically informed of the probability of making the right decision at the right time. In addition, there will be a better understanding of the relationship between the budget, asset condition deterioration and service levels.

Generally, the value-based optimization focuses on identifying what is important and adds value to the organization considering its strategic objectives. This is backed up by the recent initiation requirements by the government and public sector in Canada to apply cost based accounting systems in the public sector (GASB 1999).

Availability of a proper tool in decision-making and investment planning best practices can transform complex and technical information into non-technical principles and guidelines for decision making, and facilitate the realization of high level service with minimum budget over the life cycle of the assets (National Guide to Sustainable Municipal Infrastructure 2004). The integration between engineering condition and financial performance of an asset provides a systematic approach to prioritize and maintain an asset level of service, in an economical and proactive manner. In summary, it is a significant to demonstrate a proper management of infrastructure assets and effective utilization of tax payer’s money. The value-based optimization takes place over the entire lifecycle of the assets, and value is optimized through the coherent management of costs, risks and performance.

By shifting from an engineering-driven asset management model to the one driven by both engineering and value asset management, an organization will expand the benefits of asset management beyond the physical to encompass all its business objectives such as higher performance, minimum cost, less risk and more customer focus (Sidney 2014).

Chapter 3 Methodology

This chapter presents the methodology used to obtain optimal decision plans for all assets of a municipal. The chapter is divided in three parts: one dedicated to explain the traditional condition-based approach, another-one for the value-based approach and a third one to explain the data to be used on the case study presented in chapter 4 (given that such chapter is a self-contained journal manuscript and hence the space limitations impede us from having such contents there).

The condition-based approach provides the reader with a mathematical characterization of the decision support tools in order to find out an appropriate solution to the optimization problem.

The value-based optimization approach, concentrates on explaining the development of value curves from the depreciation or the deterioration of the various assets considered and divided for simplicity into: vehicles and machinery, civil infrastructures, and buildings.

3.1 Condition-based Optimization Approach

3.1.1 Mathematical Formulation

Watanatada *et al*. (1987), Li *et al.* (1998) and Vitale *et al.* (1996) are among the first to proposed a mathematical formulation for optimizing decisions in a network of spatially allocated infrastructures. This classical optimization try to minimize budget while subject to the achievement of acceptable levels of condition constraints.

Linear programming has several characteristics; feature, time, space and objective. As many researchers mention, linear programming formulates very similar to network flow and uses binary across links between zero and one. Additionally, to acknowledge multiple decision paths, this has the calculating ability of not only across time but across assets; this also figures out to find only single objective such as condition of assets, required budgets, level of service of infrastructure, etc.

Binary linear programming is widely accepted to solve civil infrastructure optimization problems. A decision variable takes a value of one when an action j is taken on asset $i, in\ year\ t$ otherwise its value is 0 (zero). This is applicable to multiple types of infrastructure, in which case $X_{t,i}$ (a binary decision variable) is used to determine which segment of each asset (street name, hydrant, lighting, sidewalk, road, sanitary, storm and water main) (i) will be treated on an given period (t) with an intervention (j).

A transfer function (equation 2) follows up the level of service of individual segments across time upgrading their value in accordance with their Improvement (I) or Deterioration (D). $Q_{t,i}$ indicates the condition of the asset; this condition is described by a Visual Inspection Rating (VIR) that ranges between zero and ten and associated the International Roughness Index (IRI) as roads; deterioration prediction as street name and hydrants; Retro-reflective Sheeting Identification Guide (RSIG) for lighting and sign; and pipe condition index (PCI) through initial defect, collapse and overflow, that is to say structural and Operation and Maintenance (O&M) in the domain of storm, sanitary and water main. A pipe condition index (PCI) was improved in terms of pipe age, and it ranges between zero and one hundred for pipes with age from 170 year or 200 year to zero years (accordingly). The values of VIR, PCI, and RSIG were updated on an annual basis rely on whether an improvement ($I_{t,i}$) was applied or otherwise the asset deteriorated ($D_{t,i}$).

The optimal decision analysis has the purpose to maximize the aggregated network level of service (equation 3) subject to a given budget (B_t) per planning period (equation 4).

$$Q_{t,i} = (1 - X_{t,i})(Q_{t-1,i} \pm D_{t,i}) + X_{t,i}(Q_{t-1,i} \pm I_{t,i}) \quad (2)$$

$$\text{MAX} \quad Z = \sum_{i=1}^{N} Q_{t,i} L_i \quad (3)$$

$$\text{Subject to:} \quad \sum_{i=1}^{N} \sum_{j=1}^{J} C_{t,i,j} X_{t,i,j} L_i \le B_t \quad (4)$$

$$Q_L \le Q_{i,t} \le Q_U \quad (5)$$

$$x_{t,i,j} \in [0 \text{ or } 1], \text{ binary decision variable for asset } i \quad (6)$$

Where:

$X_{t,i} = \{0, 1\}$: 1 if treatment (*j*) is applied on asset (*i*) on time (*t*), zero otherwise

$Q_{t,i}$ = Condition of asset (*i*) on time (*t*)

$I_{t,i}$ = Improvement of asset (*i*) condition on time (*t*)

$L_{t,i}$ = Length (size) of the asset (segment) (*i*)

$C_{t,i}$ = Monetary Cost for asset (*i*) on time (*t*) per unit length (size)

Q_U, Q_L= Upper and lower bound for level of service indicator

B_t= Planning budget on time (*t*)

A similar approach can be used to calculate the amount of budget to maintain or achieve a no deterioration level of service, as shown on equations (7) and (8).

$$\text{MINIMIZE: } Z= \sum_{t=1}^{T}\sum_{i=1}^{N} C_{t,i}X_{t,i}L_i \qquad (7)$$

$$\text{Subject to}: \sum_{i=1}^{N}\sum_{t=1}^{T} L_i Q_{i,t} \geq \sum_{i=1}^{N}\sum_{t=1}^{T} L_i Q_{i,t-1} \qquad (8)$$

3.2 Value-based Optimization Approach

In order to compare and identify the value and depreciation condition through the value-based optimum approach, it is strongly required to inspect different asset types as follows; vehicle and machinery; civil infrastructures such as street name, hydrants, lighting and pipes, and so forth; buildings including structures and dwelling spaces.

3.2.1 Vehicles and machinery

There are several common ways to calculate depreciation such as straight line, double declining balance and sum of the year's digits. The methods selected rely on the asset to be depreciated and how the asset is used in the business. It should be aware that the purpose of depreciation is to precisely reflect an asset's decline in value over time. As a result, the depreciation tool selected should be the one that most accurately reflects this reduction in value.

One common method for calculating depreciation is called straight-line tool. This method produces a static depreciation value for each year and is appropriate for assets that depreciate at a constant rate. Calculating depreciation using the straight-line method utilizes an asset's original cost, and requires estimation of its salvage value and years of useful life. The formula for straight-line depreciation is:

$$\text{Annual Depreciation} = \frac{\text{Original Cost} - \text{Salvage Value}}{\text{Years of Useful Life}} \tag{9}$$

To illustrate, assume a vehicle has a purchase price of CAD 100,000, an economic life of 10 years, and a salvage value (10%) of CAD 10,000. In this example, the annual depreciation for this asset is as follows (Table 3.1):

Table 3-1 Depreciation Value of Assets each methods

Year	Straight Line	Double Declining Balance	Sum of the year
1	100,000	100,000	100,000
2	90,000	80,000	83,636
3	80,000	64,000	68,909
4	70,000	51,200	55,818
5	60,000	40,960	44,364
6	50,000	32,768	34,545
7	40,000	26,214	26,364
8	30,000	20,972	19,818
9	20,000	16,777	14,909
10	10,000	13,422	11,636

The second of methods is "Double Declining Balance" which includes an "accelerator," so the asset depreciates more in the beginning of its useful life. This depreciation method is used with vehicles. For example, we know that a new car depreciates more than an older one.

Depreciation expense in the 1^{st} *year of asset lifespan = original purchase price × 2 × straight-line depreciation rate (if we reflect the first method's rate: 10%)*

The proper salvage value of this sample vehicle which reflects depreciation data is CAD 80,000. Through the same process, we can identify that remaining value of asset on second year is CAD 64,000 as can be seen from the (Table 3.1).

The last one is “Sum of the Years' Digits”. In this method, the number of years in the useful life are summed. For example, if an asset had a useful life of 10 years, the digits would be added: 10 + 9 + 8 + 7 + 6 + 5 + 4 + 3 + 2 + 1 = 55. Then annual depreciation would be determined as follows:

Year 1 = 10/55 = 18.2 % times the cost (or cost less salvage)

- Year 2 = 9/55 = 16.4 %
- Year 3 = 8/55 = 14.5 %

……

- Year 10 = 1/55 = 1.8 %

As can be seen from (Figure 3.1), the result of analysis of depreciation value illustrate different types and characters of its own; straight line pictures theoretical features, while double declining balance and sum of the year describe significantly flexible features.

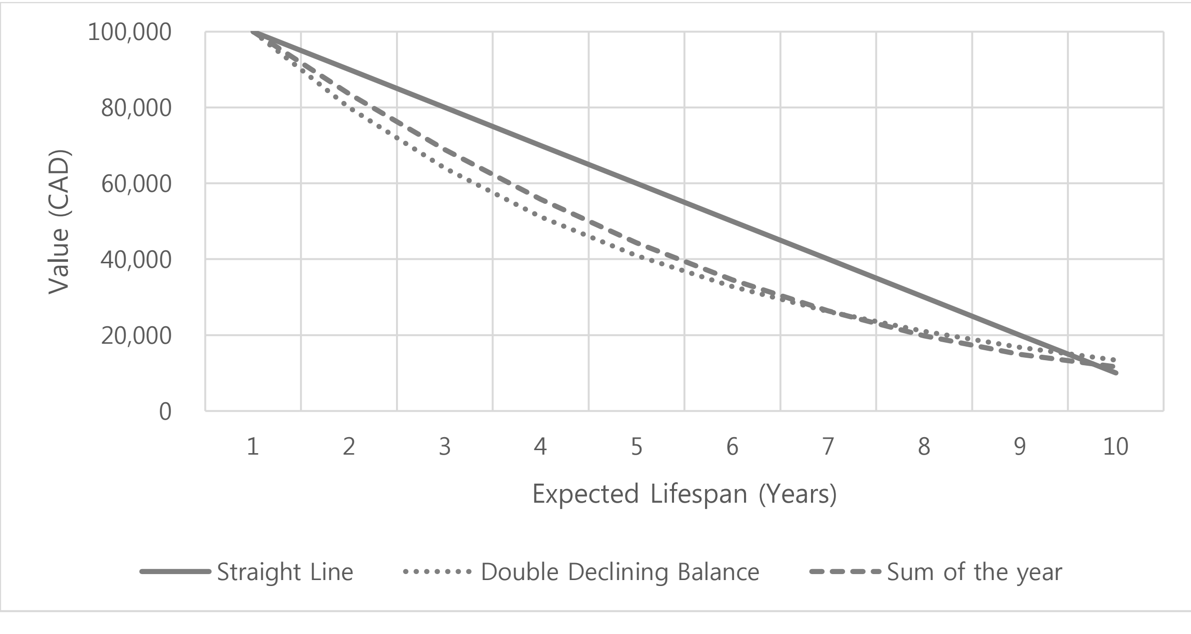


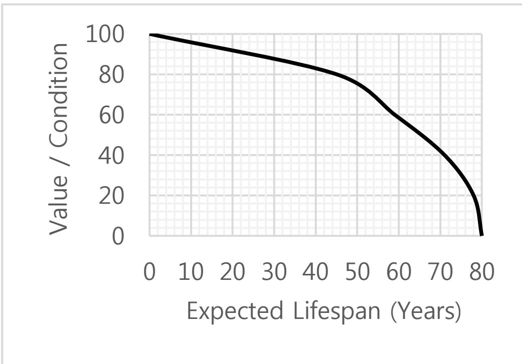
Figure 3-1 Depreciation Curve of Vehicles and machinery

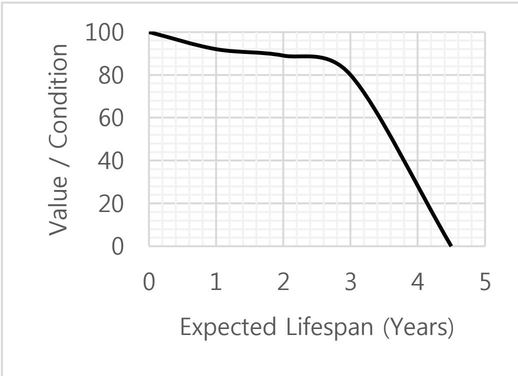
On the other hand, lifespan concept is crucial to asset lifecycle management; methods for guiding asset acquisition, use and disposal. According the relevant works, vehicles and machinery have an expected lifespan of approximately 20 years and 14 years individually. Salvage value is the estimated value that the owner is paid when the asset is sold at the end of its lifespan. The value is used to decide annual depreciation in the accounting data. The value is based on an assumption of the asset's value.

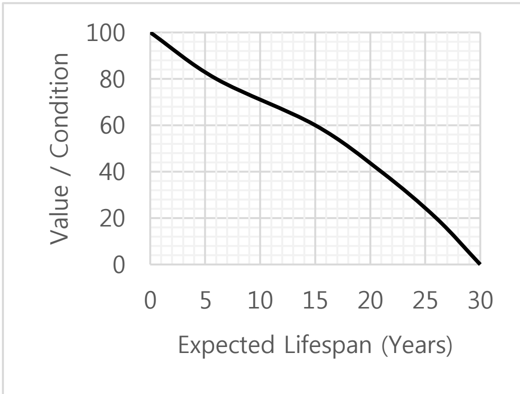
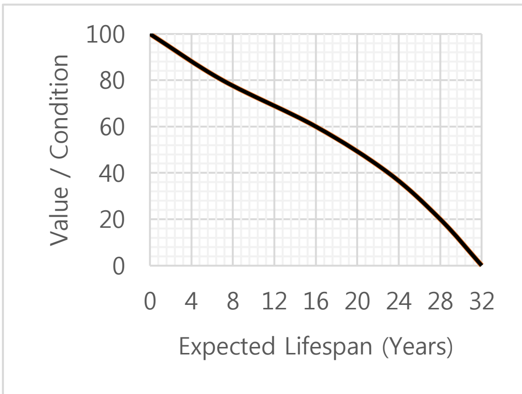
3.2.2 Civil Infrastructures

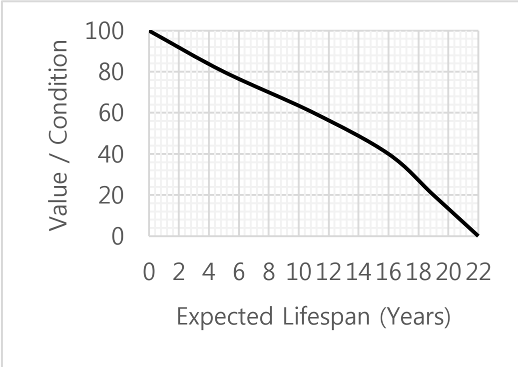
The purpose of this part is to analyze depreciation value of all sorts of assets to be used in the case study of chapter 4 for the municipality of Kindersley. It follows from the proposed value-based approach and is given for street names, hydrants, lighting, signs, sidewalks, roads, sanitary pipes and water mains. For this reason it is necessary to break some assets into their components and develop curves for each of them. Survival probability curves were developed for each asset to reflect the decay on its value. Those replacement costs are calculated prices on the basis of size and materials of assets each type.

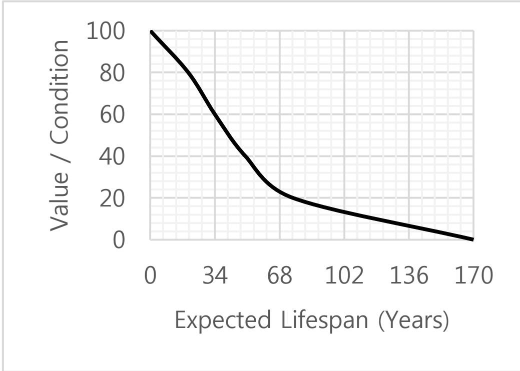
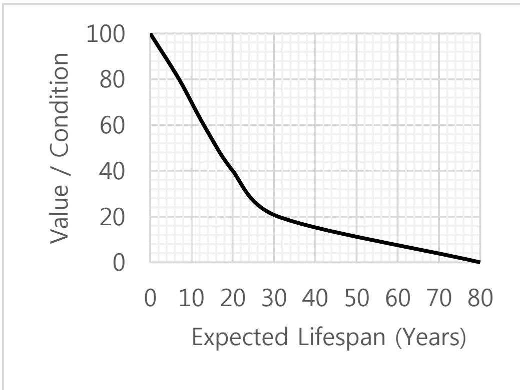
Table 3-2 Civil Infrastructures Deterioration Curves

Asset Type	Unit	Reconstruction or Replacement Value (CAD)	Lifespan (years)	Deterioration Curve	Reference
Street Name	Each	132	20		Rasdorf *et al.* 2006
Hydrants	Each	6,383	100		The Federation of Canadian Municipalities. 2002
Lighting (Steel Pole)	Each	1,882	80		Steel Times International. 2014 W. Richard Lovelace. 2005

Lighting (Wood Pole)	Each	1,957	50		Lebow *et al.* 2015
Lighting (Bulb)	Each	162	4~5		Minnesota Department of Commerce. 2012
Sidewalk	㎡	70	80		The Federation of Canadian Municipalities. 2004

Road (Strong Structure High ESALs)	m²	42	28		Mariam Méité. 2015
Road (Strong Structure Medium ESALs)	m²	42	30		Mariam Méité. 2015
Road(Strong Structure Low ESALs)	m²	42	32		Mariam Méité. 2015

Road (Weak Structure Medium ESALs)	m²	42	22		Mariam Méité. 2015
Road (Weak Structure Low ESALs)	m²	42	21		Mariam Méité. 2015
Sanitary (PVC)	m	210	200		Mariam Méité. 2015

Sanitary (Concrete)	m	210	170		Mariam Méité. 2015
Water main (Steel)	m	210	130		Mariam Méité. 2015
Water main (Clay)	m	210	80		Mariam Méité. 2015

3.2.3 Buildings

There is very little literature available on the subject of expected service life of structures. The lifespan of building generally is taken as 100 years. However, in W.P.S. Dias research (2013), there are several expected as well as normal conventions about design life span, which are given as follow:

- Monumental Structures like temple, mosque or church, etc. - 500 to 1000 years
- Steel Bridges, Steel Building or similar structures - 100 to 150 years
- Concrete bridges or High rise building or Stone bridges, etc. - 100 years
- Residential houses or general office/commercial buildings, etc. - 60 to 80 years
- Roads - 25 to 30 years (Concrete pavements: 30 to 35 years)
- Pipes - 75 to 100 years (PVC 150 years)

Most of Buildings might be expected to have an approximately 10% remaining salvage value when fully depreciated. According to the "Life Expectancy Guidelines" for furniture, fixtures and equipment (2007), average salvage value of structures is around 10 %; in detail, apartment, bank, hotel and school show approximately 10%, meanwhile dwelling and hospital represent 12%. According to the previous tasks, depreciation value can be known as following formula.

$$D = P\,[(100 - r \cdot d) / 100]^n \qquad (10)$$

Where:

D = Depreciated value

P = Cost at present market rate

$r \cdot d$ = fixed percentage of depreciation ("*r*" stands for rate and "*d*" stands for depreciation)

n = A number of years the building had been constructed

To find the total valuation of the property, the present value of land, water supply, electric and sanitary fitting, etc; should be added to the above value.

(Yiu Chung Yim, 2007) explained there are some useful researches about lifespan of structures; they explain depreciation value of building can be identified and inspected empirically as follows:

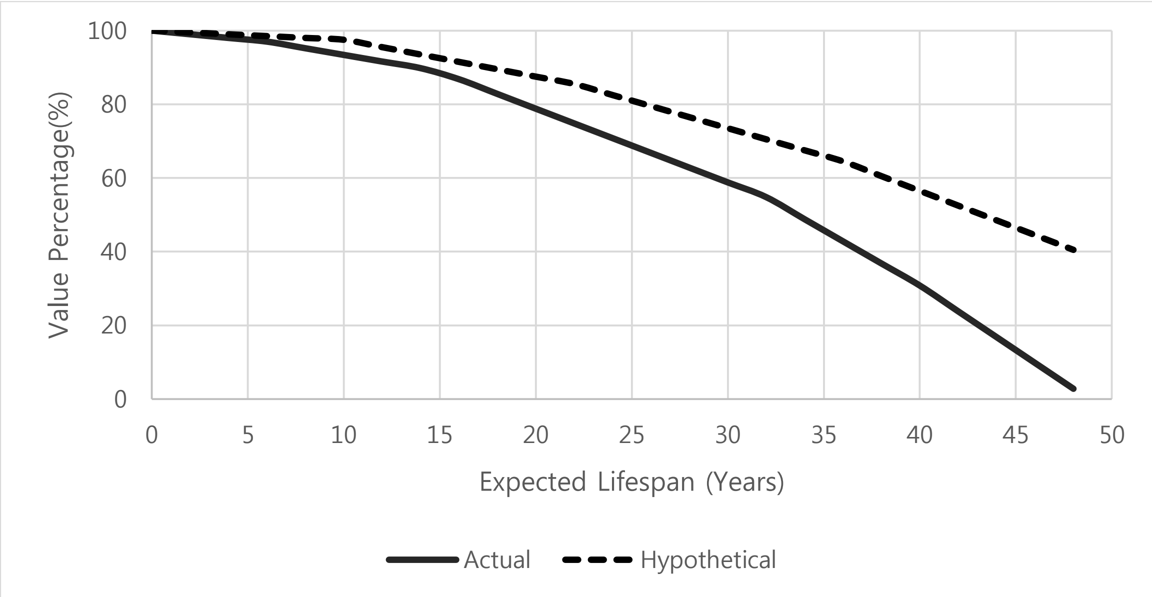


Figure 3-2 Depreciation Curves of building

[Adapted from: Yiu Chung Yim, Journal of Building Appraisal (2007) 3, 97 – 103]

3.3 Case Study of the Town of Kindersley

3.3.1 Database

The data used in chapter 4, which is a self-contained paper, was provided by the municipality of Kindersley in Saskatchewan, Canada. The data were identified as spatial data with the location of all assets. The database had been extracted from shapefiles with the aid of ARCGIS software. The condition assessment of roads is based on visual inspections of the pavements. The condition data had been prepared to develop a pavement management system. The town, Kindersley takes care of approximately 50km of local roads and several arterials roads. This municipality also owns the airport with a 1.2km runway and they were built over a 25cm gravel base. The town faces the daunting task of dealing with a wide variety of assets such as street names, signs, hydrants, lighting, sidewalks, roads, sanitary pipes and water mains and so on with a limited budget. In terms of data, the government has spatial data with the location of all assets, but the condition assessment is based on visual inspections, which is called Visual Inspection Ratio (VIR) (Table 3.3).

Table 3-3 VIR Data of Municipality Kindersley

Type1	Theme1	Theme2	Theme3	VIR	Age	Area	Theme5
Kindersley	Road	Weak	light	7	9	1286	downtown
Kindersley	Road	strong	light	10	1	1675	downtown
Kindersley	Road	Weak	light	4	15	103	downtown
Kindersley	Road	Weak	light	6	11	3680	downtown
Kindersley	Road	Weak	light	6	11	2157	downtown
Kindersley	Road	strong	light	8	7	2077	downtown
Kindersley	Road	strong	light	8	7	942	downtown
Kindersley	Road	strong	light	8	9	3031	downtown
Kindersley	Road	strong	light	7	9	5490	Rosedale
Kindersley	Road	strong	light	8	7	2816	Rosedale
Kindersley	Road	Weak	light	9	5	262	Rosedale
Kindersley	Road	Weak	light	9	5	262	Rosedale

3.3.2 Analysis tools

Solver risk platform was used as a plug in to Excel in order to set up the optimization problem. Solver is part of a suite of commands sometimes called what-if analysis tools. With Solver, people can find an optimal (maximum or minimum) value for a formula in one cell - called the objective cell - subject to constraints, or limits, on the values of other formula cells on a worksheet (Figure 3.3). Solver works with a group of cells, called decision variables or simply variable cells that participate in computing the formulas in the objective and constraint cells. Solver adjusts the values in the decision variable cells to satisfy the limits on constraint cells and produce the result people want for the objective cell. The objective, constraint and decision variable cells and the formulas interrelating them form a Solver model; the final values found by Solver are a solution for this model. Solver uses a variety of methods, from linear programming and nonlinear optimization to genetic and evolutionary algorithms, to find solutions. The results of Treatment Effectiveness Actions (TEA) can be found on Table 3-4.

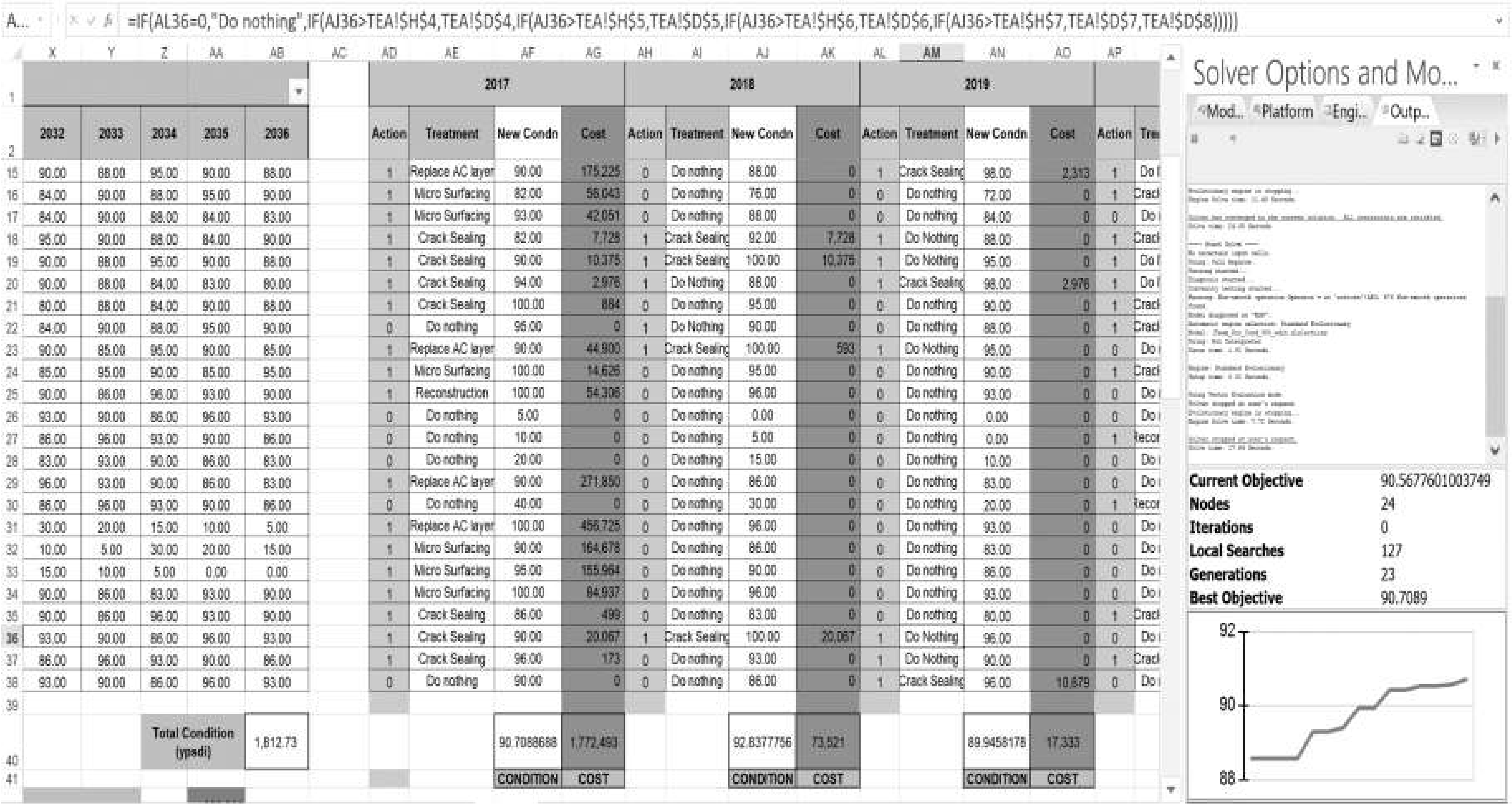


Figure 3-3 Excel spreadsheet with Solver Risk Platform Add-in

In order to define an optimization model in Excel, engineers will follow these essential steps:

a. Organize the data for your problem in the spreadsheet in a logical manner.
b. Choose a spreadsheet cell to hold the value of each decision variable in one's model.
c. Create a spreadsheet formula in a cell that calculates the objective function for one's model.
d. Create formulas in cells to calculate the left hand sides of each constraint.
e. Use the dialogs in Excel to tell the Solver about one's decision variables, the objective, constraints, and desired bounds on constraints and variables.
f. Run the Solver to find the optimal solution.
g. When there is no optimal solutions from solver, people should judge an appropriate decision-making.

The five built–in engines of the Solver Platform are able to solve linear programming, quadratic programming and mixed integer programming problems of up to 8,000 variables (2,000 integers) and 8,000 constraints; quadratic ally constrained programming problems of up to 2,000 decision variables and 8,000 constraints; smooth nonlinear programming problems of up to 1,000 variables and 1,000 constraints; and non-smooth optimization problems of up to 500 decision variables and 250 constraints (in addition to bounds on the variables).

3.3.3 Data Inspection

This section describes related process to analyze an optimal decision of asset management in town, Kindersley through the establishment basic data. There are five kinds of steps to investigate fundamental data; raw data collection, making an asset maintenance actions table, making a treatment table, condition survey and making an excel sheet and implementation of an optimal analysis.

Firstly, it is needed to collect raw data to analysis optimum decision from Kindersley municipality that manages a wide range of assets in their sectors; street name, hydrants, lighting, sidewalk, road, sanitary, storm and water main. Those assets run to approximately more than 4,200 with different ages and conditions (Figure 3.4). The town of Kindersley is not very big though, the engineer in municipality is in control of many assets within restricted budget.

OBJECTI	AdMapKey	THEME1	THEME2	THEME3	THEME4	AGE	AREA	AAUNIT
1	1.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	STEWART CR
2	2.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	THOMSON DRIVE
3	3.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	HAHN CR
4	4.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	THOMSON DRIVE
5	5.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	HAHN CR
6	6.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	THOMSON DRIVE
7	7.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	WEST ROAD
8	8.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	THOMSON DRIVE
9	9.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	WEST ROAD
10	10.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	McEWEN CR
11	11.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	WEST ROAD
12	12.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	RUTLEY CR
13	13.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	RUTLEY DRIVE
14	14.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	RUTLEY CR
15	15.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	RUTLEY CR
16	16.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	RUTLEY DRIVE
17	17.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	WEST ROAD
18	18.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	RUTLEY CR
19	19.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	WEST ROAD
20	20.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	McEWAN GATE
21	21.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	DITSON DRIVE
22	22.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	WEST ROAD
23	23.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	E STREET
24	24.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	12th AVENUE
25	25.00000000000	Streetname	Aluminium	Regularsize	Municipal	1	1	E STREET

signal | WM | storm | sanitory | road | sidewalk | lighting | hydrant | street name | Data-1 | Data-2 | term

Figure 3-4 Municipality Kindersley Assets Status

For the next stage, we require to make a table namely, "assets maintenance actions and cost" included various important data by assets such as asset name, types, age (years), condition state, maintenance actions, new stage after treatment, cost and life expectancy. The purpose of making this table is to utilize at the next stages of a treatment table, an excel sheet and implementation of an optimal analysis.

According to the survey, street name contained sign and brackets as major components is divided by three maintenance actions such as Do Nothing, Maintenance and Replacement. When asset condition is over 80% of new one, it signifies that there is no need to treat at all and followed by state between 40% and 79.99% is for maintenance such as sign cleaning, vegetation control, anti-theft measures and sign support adjustments and lastly, below the condition 39.99% is for replacement or reconstruction; it usually caused by vandalism, hit by vehicle, damage by weather or other natural factors and reached its useful life. The mean cost of replacement is expected to 132 CAD based on price in 2016 and expected life span is 20 years.

In the meanwhile, hydrant is divided by five maintenance actions such as Do Nothing, Minor Maintenance, Major Maintenance, Rehabilitation and Replacement. Asset phase from 60% to 80% is for minor maintenance which is maintained at approximately 50% of total life span include following actions; cleaning, painting, lubricating and minor repair. The average cost of replacement is expected to 32 CAD per unit. Asset condition between 40% and 59.99% is for major maintenance which is maintained at approximately 60% of total life span contained next actions; fixing leaks, broken mains, replacing motors and pumps, unscheduled or unplanned emergency activities. The average cost of replacement is expected to 96 CAD per unit. Costing 4,149 CAD, rehabilitation phase is just one time event such as lining and cathodic protection. Replacement which applies in case of lifespan comes to end is reported to 6,383 CAD per unit and total life span is 100 years (Guide to sustainable asset management for Canadian municipalities, 2002).

The main goal of treatment (Table 3.4) is to apply at the analysis stage; this table is composed of several items such as asset name, unit, treatment, new state, gain, cost and range.

Most important part in this stage is that not only to discover data of gain telling amount of improvements after treatment but to decide lower and upper boundaries.

Generally, lighting is divided by steel pole, wood pole and bulb; it can go up equally 40% of assets condition after minor, major maintenance and rehabilitation while, replacement guarantees 100% as a new. On the other hand, bulb of lighting has separately different data; only two step of treatment such as Do Nothing and Replacement on condition changing with High Pressure Sodium Vapour (HPSV).

Sidewalk is also divided by three step for treatment: Do Nothing, Maintenance and Replacement. After treatment maintenance, it can be improved 60% of assets condition in case of range between 40% and 79.99% while, replacement offers 100% as a new. Whereas in road part, these can be classified roughly into five types such as Do Nothing, Minor Maintenance, Major Maintenance, Rehabilitation and Replacement. This can increases uniformly 40% of assets state after minor, major maintenance and rehabilitation but, replacement supplies 100% as a new. The required cost per square meter of each treatment is expected to respectively 0.33CAD for minor maintenance, 7 CAD for major maintenance, 25 CAD for rehabilitation and 42 CAD for replacement.

Table 3-4 Interventions and operational windows used network-level trade-off analysis

Assets		Unit	Action	Up To (Level)	Gain (%)	Cost (CAD)	Lower (%)	Upper (%)
Street name		each	Do Nothing	1	0	0	80.00	100.00
			Maintenance	1	60	6	40.00	79.99
			Replacement	1	100	132	0.00	39.99
Hydrants		each	Do Nothing	1	0	0	80.00	100.00
			Minor Maintenance	1	40	32	60.00	79.99
			Major Maintenance	1	40	96	40.00	59.99
			Rehabilitation	2	40	4,149	20.00	39.99
			Replacement	1	100	6,383	0.00	19.99
Lighting	Steel Pole	each	Do Nothing	1	0	0	80.00	100.00
			Minor Maintenance	1	40	14	60.00	79.99

Assets		Unit	Action	Up To (Level)	Gain (%)	Cost (CAD)	Lower (%)	Upper (%)
			Major Maintenance	1	40	21	40.00	59.99
			Rehabilitation	2	40	35	20.00	39.99
			Replacement	1	100	1,882	0.00	19.99
	Wood Pole	each	Do Nothing	1	0	0	80.00	100.00
			Minor Maintenance	1	40	350	60.00	79.99
			Major Maintenance	1	40	525	40.00	59.99
			Rehabilitation	2	40	876	20.00	39.99
			Replacement	1	100	1,957	0.00	19.99
	bulb	each	Do Nothing	1	0	0	70.00	100.00
			Replace(HPSV)	1	100	162	0.00	69.99
Sidewalk		m^2	Do Nothing	1	0	0	80.00	100.00
			Maintenance	1	60	11	40.00	79.99
			Replacement	1	100	70	0.00	39.99
Road		m^2	Do Nothing	1	0	0	80.00	100.00
			Minor Maintenance	1	40	0.33	60.00	79.99
			Major Maintenance	1	40	7	40.00	59.99
			Rehabilitation	2	40	25	20.00	39.99
			Replacement	1	100	42	0.00	19.99
Sanitary		m	Do Nothing	1	0	0	80.00	100.00
			Maintenance	1	60	131	40.00	79.99
			Replacement	1	100	210	0.00	39.99
Storm		m	Do Nothing	1	0	0	80.00	100.00

Assets		Unit	Action	Up To (Level)	Gain (%)	Cost (CAD)	Lower (%)	Upper (%)
			Maintenance	1	60	500	40.00	79.99
			Replacement	1	100	1,200	0.00	39.99
Watermain		m	Do Nothing	1	0	0	80.00	100.00
			Maintenance	1	60	131	40.00	79.99
			Replacement	1	100	210	0.00	39.99

It is obviously necessary to confirm present condition of each asset which have different capability of lifespan. Infrastructures in municipality are installed in different time and place; all asset has their characteristic features like condition. This is principal reason why municipalities have to inspect each condition of asset. As can be seen in (Figure 3.5), it is just a sample of all assets that Kindersley municipality owns; and also can calculate an expected life expectancy of wood pole in lighting through the whole period based on deterioration curve noted previous works. An average age of wood pole, town of Kindersley is between fourteen and twenty-six, which is recorded approximately from eighty-six to ninety-two. It also can be assumed, for example, that an expected condition of wood pole asset will be 33% out of 100% in 45 years of total lifespan.

For the next stage, it is needed to form several compacted groups; “A” as a street name sign, “B” as a hydrant, “C-1” as a steel pole, “C-2” as a wood pole, “C-3” as a bulb in lighting, “D” as a sidewalk, “E” as a road, “F” as a sanitary, “G” as a storm and “H” as a water main. It also required to divide asset E (Road), asset F (Sanitary) and H (Water main) which are composed of differential lifespan and similar materials. Thus, it can be classified asset E (Road) into E-1 (Strong High Road), E-2 (Strong Medium Road), E-3 (Strong Light Road), E-4 (Weak Medium Road) and E-5 (Weak Light Road). Next, it also can be divided asset F (Sanitary) into F-1, F-4 (PVC Sanitary), F-2, F-3, F-5, F-7 (Concrete Sanitary) and F-6 (Steel Sanitary). It also required to classify asset G (Storm) into G-1 (PVC Storm), G-2, G-4, G-5, G-6 (Concrete Storm) and G-3 (Steel Storm). Lastly, it is needed divide H (Water main) into H-1, H-7, H-8, H-9 (PVC Water main), H-2 (Clay Water main), H-3, H-5, H-10, H-11 (Concrete Water main) and H-4, H-6 (Steel Water main). It is necessary to utilize a long-term strategy analysis (20 years); engineers in Kindersley can make effective and informed decisions, and plan financially for the renewal and replacement of their infrastructure.

Group	Annual Condition																			
	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**
A	96.00	94.00	90.00	86.00	83.00	80.00	76.00	96.00	94.00	90.00	86.00	83.00	80.00	76.00	96.00	94.00	90.00	86.00	83.00	80.00
A	96.00	94.00	90.00	86.00	83.00	80.00	76.00	96.00	94.00	90.00	86.00	83.00	80.00	76.00	96.00	94.00	90.00	86.00	83.00	80.00
A	96.00	94.00	90.00	86.00	83.00	80.00	76.00	96.00	94.00	90.00	86.00	83.00	80.00	76.00	96.00	94.00	90.00	86.00	83.00	80.00
A	96.00	94.00	90.00	86.00	83.00	80.00	76.00	96.00	94.00	90.00	86.00	83.00	80.00	76.00	73.00	96.00	94.00	90.00	86.00	83.00
B	80.50	80.00	79.50	98.80	98.60	98.40	98.20	98.00	97.50	97.00	96.50	96.00	95.70	95.30	95.00	94.70	94.30	94.00	93.50	93.00
B	80.50	80.00	79.50	98.80	98.60	98.40	98.20	98.00	97.50	97.00	96.50	96.00	95.70	95.30	95.00	94.70	94.30	94.00	93.50	93.00
B	80.50	80.00	79.50	79.00	78.50	98.80	98.60	98.40	98.20	98.00	97.50	97.00	96.50	96.00	95.70	95.30	95.00	94.70	94.30	94.00
C-1	88.00	87.50	87.00	86.00	85.70	85.30	85.00	84.50	84.00	83.50	83.00	82.70	82.30	81.60	80.50	80.00	79.00	78.00	77.00	98.60
C-1	92.50	92.15	91.80	91.45	91.10	90.75	90.50	90.30	90.10	89.90	89.70	89.50	89.30	89.10	88.90	88.00	87.50	87.00	86.00	85.70
C-1	92.15	91.80	91.45	91.10	90.75	90.50	90.30	90.10	89.90	89.70	89.50	89.30	89.10	88.90	88.00	87.50	87.00	86.00	85.70	85.30
C-2	85.00	84.00	83.80	83.70	82.90	82.00	81.00	80.00	78.00	98.00	97.50	97.00	96.50	96.00	95.50	95.00	94.50	94.00	93.50	93.00
C-2	90.00	89.50	89.00	88.50	88.00	87.50	87.00	86.50	86.00	85.00	84.00	83.80	83.70	82.90	82.00	81.00	80.00	78.00	76.00	98.00
C-2	85.00	84.00	83.80	83.70	82.90	82.00	81.00	80.00	78.00	76.00	98.00	97.50	97.00	96.50	96.00	95.50	95.00	94.50	94.00	93.50
C-2	91.50	91.00	90.50	90.00	89.50	89.00	88.50	88.00	87.50	87.00	86.50	86.00	85.00	84.00	83.80	83.70	82.90	82.00	81.00	80.00
C-2	85.00	84.00	83.80	83.70	82.90	82.00	81.00	80.00	78.00	98.00	97.50	97.00	96.50	96.00	95.50	95.00	94.50	94.00	93.50	93.00
C-2	85.00	84.00	83.80	83.70	82.90	82.00	81.00	80.00	78.00	98.00	97.50	97.00	96.50	96.00	95.50	95.00	94.50	94.00	93.50	93.00

Figure 3-5 Deterioration and Condition Data of Assets

Chapter 4 Municipal Asset Management: A value-based approach to optimal facilities, infrastructure, equipment and machinery

ABSTRACT

Civil Infrastructure Asset Management is a philosophical approach typically implemented through tools and techniques used by governments to preserve and maintain all assets at good levels of condition. Municipalities face the daunting task of dealing with a wide variety of assets (roads, vehicles, pipes, buildings, parks, airports, fire equipment and so on) with a limited budget, which is required to be economically distributed across all the assets within their jurisdiction. One of the main disquiets of municipal assets management is the long term prediction of capabilities to deliver sufficient levels of service while restricted by limited budgets. There is a lack of an approach to handle long term investments across all the asset types: to optimize scheduling of interventions. There is a disconnection between the effectiveness of the budget and its ability to upkeep the value of the assets: interventions are typically analyzed in terms of their ability to rejuvenate (extend) the service life of an asset. In addition to that, previous attempts to handle multiple assets face problems in budget balancing given the dissimilar units of measurement of condition for each network. Up to now, all such decision on budget allocation use a condition-based model. This research proposes value decay curves which are calibrated from deterioration curves, and treatment effectiveness that is matched to value increase of any asset. A case study of the municipality of Kindersley is presented, it aims to propose a value-based optimization for maintenance and rehabilitation treatments in order to choose more financially-sustainable, yet cost-effective actions. The approach is flexible enough to accommodate traditional physical assets and equipment and vehicles along the mix, the case study considers: street names, signs, hydrants, lighting, sidewalks, roads, sanitary pipes and water mains. We use excel as a platform to define the problem and its mechanisms and a plug in to another commercial optimization software called solver risk platform to solve the dynamic binary programming. Results from the software demonstrate a more stable long term progression for the value of assets than for their condition. Meanwhile budget levels remain at very similar levels.

4.1 Literature Review

Asset Management System supports the mission of the municipal agencies to meet their requirements of delivering customer-oriented service within an aging infrastructure and ever more constrained resources. One of the key tasks in the asset management process is an improved and optimized coordination of all influencing engineering parameters together with the asset value to the expectations and requirements of the public (Deix, Alten and Weninger-Vycudil 2012). Asset management has evolved over the past decades, assets systems were increasingly added as well as objectives. Today the frontier in asset management pushes towards having resilient systems to natural hazards, integrated infrastructure analysis that account for cross interactions, policy oriented systems that can support government's decisions and infrastructure that supports sustainability goals.

Municipalities have an increasing focus on ensuring effective operation and optimal investment in their civil infrastructure assets. However, few municipalities have a management system in place that ensures factual decision-making and stringent implementation. Most municipalities are realizing that an asset management process is required to address the rising costs for, and competing priorities associated with, infrastructure aging and the need for better services (National Guide to Sustainable Municipal Infrastructure 2003). Effective asset management planning enables a decision making process that balance engineering and economic approaches to deliver a better value for money. As many organizations develop an understanding of the physical condition of their assets, it is inevitably required to reflect and transform this condition with the service that the asset provides. This will lead to asset management processes that focus on managing services and how investment decisions may be used to best support the delivery of these services (Canada Infrastructure Report Card 2014).

Most of municipal agencies deal with different assets such as pavements, bridges, street light, signs, building, rails, vehicles and equipment to perform their asset management planning. In fact, all these assets use different criteria's in determining an optimal long term planning. In addition to that, previous attempts to handle multiple assets face problems in budget balancing given the dissimilar units of measurement of condition for each network. Many agencies are focused on managing a single asset type and very few are making cross-asset analysis. However, the main challenge facing the industry today is how to distribute available limited budget among different asset types to achieve the best overall asset value performance (Laumet and Bruun 2016).

Based on ISO 55000 - International Standard for Asset Management encourages organizations to foster a consistent understanding and approach to asset management so as to ensure an optimal service deliverables. This raises a need for cross asset optimization with a key question of how to achieve a better value for money, especially in this era where the infrastructure gap keeps increasing with shrinkage of budget. It is clear that, the asset value may be different for different organizations and it may vary as the assets age, but by using a value-based approach the investment can be optimized and well managed over time.

However, it is not common for the asset management practitioners to integrate asset value and engineering deterioration of the asset as part of the optimization and benefit parameters. Most agencies often consider asset value as a parameter to calculate and seek funds for their maintenance and operation budget. It is therefore necessary to consider asset values together with or as a supplement to the normally applied asset management optimization parameters, in order to realize the full economic benefits of different funding scenarios.

In other words, it is important for the agencies consider financial performance and engineering deterioration criteria’s for their asset management planning. This paper considers the use of value decay curves which is calibrated from assets deterioration curves, and treatment effectiveness to improve the financial performance and the level of service of the assets with an ultimate goal of ensuring maximum returns of an investment.

A comprehensive asset optimization requires continuous improvement in the effectiveness of the overall asset management by providing more holistic adjustments across different asset types (CGI 2015). Due to the facts that, often assets are different, the need to analyze assets based on its adjustable value is paramount. Combination of asset cost and its engineering deterioration model can scientifically support decision making processes to better justify the allocation of limited resources (budget) across the organization. The core basis of adopting a value-based optimization model is to shift the focus of the asset itself and onto the value that the asset provides to the organization. The goals of reducing costs and risk, and increasing performance, are neither mutually exclusive nor interdependent, but they are interrelated.

Obviously, business as usual is not an option in today's economy with increasing pressure on the budget while aging infrastructure gap widening. Any assets planning decision which is not well optimized with its associate asset value performance, its potential impacts of those decisions remain unknown and indefensible. The value-based optimization is centered on a balanced routing model in order to frame decision-making of the organization. Furthermore, the value-based model provides the foundation for an efficient and structured approach to ensure that all parameters of asset management information's are part of the process and those resources are used prudently. This paper will demonstrate how asset values are part of the optimization algorithms process.

It is true that, infrastructure assets require ongoing investment to sustain it. In other words, infrastructure assets have monetary value (financial) and it does deteriorate over its useful life (engineering). Integrating asset value in asset management is essential as it offers the most optimized, cost-effective ways while maintaining or enhancing the value of those assets (Alyami and Tighe 2016). The value-based optimization approach will help the organization to make informed, proactive infrastructure and budget decisions based on their priorities and needs. The menace in decision-making will be lower as the decision maker will be scientifically informed of the probability of making the right decision at the right time. In addition, there will be a better understanding of the relationship between the budget, asset condition deterioration and service levels.

Generally, the value-based optimization focuses on identifying what is important and adds value to the organization considering its strategic objectives. This is backed up by the recent initiation requirements by the government and public sector in Canada to apply cost based accounting systems in the public sector (Government Accounting Standard Board 1999).

Availability of a proper tool in decision-making and investment planning best practices can transform complex and technical information into non-technical principles and guidelines for decision making, and facilitate the realization of high level service with minimum budget over the life cycle of the assets (National Guide to Sustainable Municipal

Infrastructure 2004). The integration between engineering condition and financial performance of an asset provides a systematic approach to prioritize and maintain an asset level of service, in an economical and proactive manner. In summary, it is a significant to demonstrate a proper management of infrastructure assets and effective utilization of tax payer's money. The value-based optimization takes place over the entire lifecycle of the assets, and value is optimized through the coherent management of costs, risks and performance.

By shifting from an engineering-driven asset management model to the one driven by both engineering and value asset management, an organization will expand the benefits of asset management beyond the physical to encompass all its business objectives such as higher performance, minimum cost, less risk and more customer focus (Sidney 2014).

4.1.1 Research Objective

The overall goal of this research is to propose a combined engineering-driven and value asset management framework to conduct optimal allocation of maintenance of vehicles, machinery and equipment and interventions of facilities and infrastructure.

4.2 Methodology

This study has been executed in three main steps: first the estimation of depreciation or deterioration trends for each asset (vehicle, equipment, infrastructure, or building), second the estimation of performance in terms of value and third the optimization of long term budget allocation and scheduling of annual actions (Figure 4-1). Results are reported through financial statements which respond to best practices by incorporating optimal asset management.

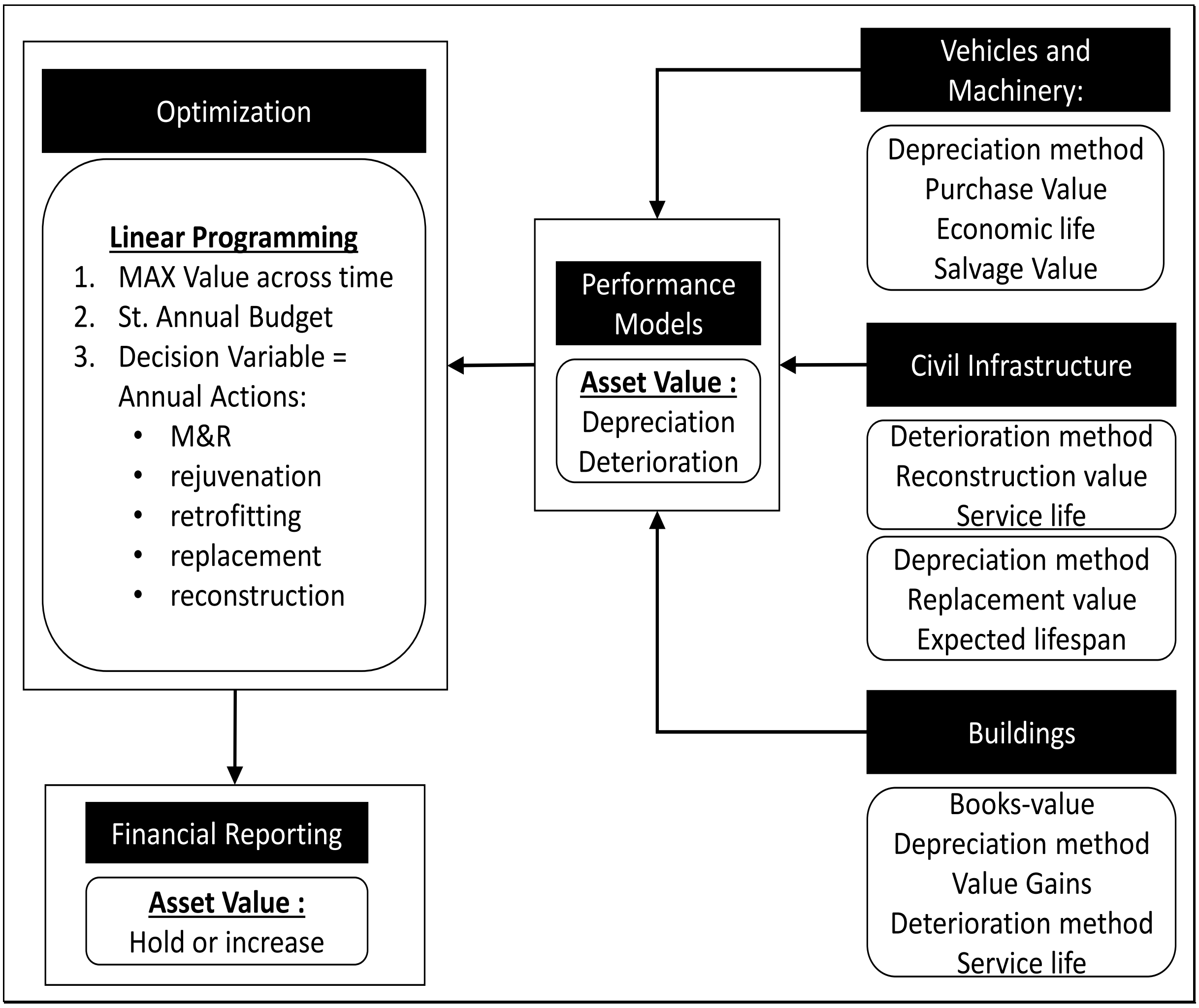


Figure 4-1 Proposed Methodology

4.2.1 Value Curves and Operational Windows

Value Curves have been developed for a sample of available assets to illustrate the approach based on locally observed performance and valuation of assets. These curves are later used on a case study. The development of each curve matched those found in the literature. Appendix A contains the curves estimated for the case study on this paper. Operational windows were defined for various assets (Table 4-1)

Table 4-1 Interventions and operational windows used in network-level trade-off analysis

Assets		Unit	Action	Up To (Level)	Gain (%)	Cost (CAD)	Lower (%)	Upper (%)
Street name		each	Do Nothing	1	0	0	80.00	100.00
			Maintenance	1	60	6	40.00	79.99
			Replacement	1	100	132	0.00	39.99
Hydrants		each	Do Nothing	1	0	0	80.00	100.00
			Minor Maintenance	1	40	32	60.00	79.99
			Major Maintenance	1	40	96	40.00	59.99
			Rehabilitation	2	40	4,149	20.00	39.99
			Replacement	1	100	6,383	0.00	19.99
Lighting	Steel Pole	each	Do Nothing	1	0	0	80.00	100.00
			Minor Maintenance	1	40	14	60.00	79.99
			Major Maintenance	1	40	21	40.00	59.99
			Rehabilitation	2	40	35	20.00	39.99
			Replacement	1	100	1,882	0.00	19.99
	Wood Pole	each	Do Nothing	1	0	0	80.00	100.00
			Minor Maintenance	1	40	350	60.00	79.99
			Major Maintenance	1	40	525	40.00	59.99
			Rehabilitation	2	40	876	20.00	39.99
			Replacement	1	100	1,957	0.00	19.99

Assets		Unit	Action	Up To (Level)	Gai n (%)	Cost (CAD)	Lower (%)	Upper (%)
	bulb	each	Do Nothing	1	0	0	70.00	100.00
			Replace(HPSV)	1	100	162	0.00	69.99
Sidewalk		㎡	Do Nothing	1	0	0	80.00	100.00
			Maintenance	1	60	11	40.00	79.99
			Replacement	1	100	70	0.00	39.99
Road		㎡	Do Nothing	1	0	0	80.00	100.00
			Minor Maintenance	1	40	0.33	60.00	79.99
			Major Maintenance	1	40	7	40.00	59.99
			Rehabilitation	2	40	25	20.00	39.99
			Replacement	1	100	42	0.00	19.99
Sanitary		m	Do Nothing	1	0	0	80.00	100.00
			Maintenance	1	60	131	40.00	79.99
			Replacement	1	100	210	0.00	39.99
Storm		m	Do Nothing	1	0	0	80.00	100.00
			Maintenance	1	60	500	40.00	79.99
			Replacement	1	100	1,200	0.00	39.99
Watermai n		m	Do Nothing	1	0	0	80.00	100.00
			Maintenance	1	60	131	40.00	79.99
			Replacement	1	100	210	0.00	39.100

4.2.2 Mathematical Algorithm - Linear Binary Programming

Lifecycle optimization to maximize assets condition with a given budget was used to find the results of traditional civil infrastructure management (Equation 1 and 2). This formulation relied on a transfer function that connects recursively all periods of time (Equation 3). Each asset carried indexed characteristics: (1) type of asset, (2) material, (3) capacity, (4) last intervention received, to limit the number of interventions and to control the effectiveness of the intervention by switching to a new performance curve.

$$\text{MAXIMIZE } \sum_{t=1}^{T}\sum_{i=1}^{a} L_i(\mathrm{Q}_{tij}) \text{, where } Q_{tii} \text{ is defined by Equation 3} \tag{1}$$

$$\text{Subject to: } \sum_{t=1}^{\mathrm{T}}\sum_{i=1}^{a}\sum_{j=1}^{k} C_{t,j} x_{t,i,j} L_i \leq \mathrm{B}_\mathrm{t} \tag{2}$$

$x_{t,i,j} \in [0 \text{ or } 1]$, binary decision variable for asset i

$$Q_{tij} = X_{tij}\ (Q_{(t-1)ij} - E_{ij}) + (1 - X_{tij})\ (Q_{(t-1)ij} + D_{it}) \tag{3}$$

Where X_{tij} is 1 if action j is applied on asset i at year t, zero otherwise; Q_{ti} is condition Index for asset i at year t; C_{tj} is cost ($) of action j at year t; L_i is size of asset i (see Table 1 for units); E_{ij} is improvement of asset i after receiving action j, D_{it} is depreciation on the value of asset i at time t, B_t is budget at year t. The formulation was slightly modified to achieve optimal levels of asset valuation with the same budget levels as before. Asset value (V) replaced Condition (Q).

$$\text{MAXIMIZE } \sum_{t=1}^{T}\sum_{i=1}^{a} L_i(\mathrm{V}_{tij}) \text{, where } V_{tii} \text{ is defined by Equation 6} \tag{4}$$

$$\text{Subject to: } \sum_{t=1}^{\mathrm{T}}\sum_{i=1}^{a}\sum_{j=1}^{k} C_{t,j} x_{t,i,j} L_i \leq \mathrm{B}_\mathrm{t} \tag{5}$$

$x_{t,i,j} \in [0 \text{ or } 1]$, binary decision variable for asset i

$$V_{tij} = X_{tij}\ (V_{(t-1)ij} - E_{ij}) + (1 - X_{tij})\ (V_{(t-1)ij} + D_{it}) \tag{6}$$

An excel spreadsheet was developed to capture the inventory of assets, their performance curves, operational windows and available actions. An add-in for Excel called Solver-Risk Platform was used to define the linear integer programming problem (Figure 4-2). External Solver MOSEK was used to find a solution to the decision variables within the optimization.

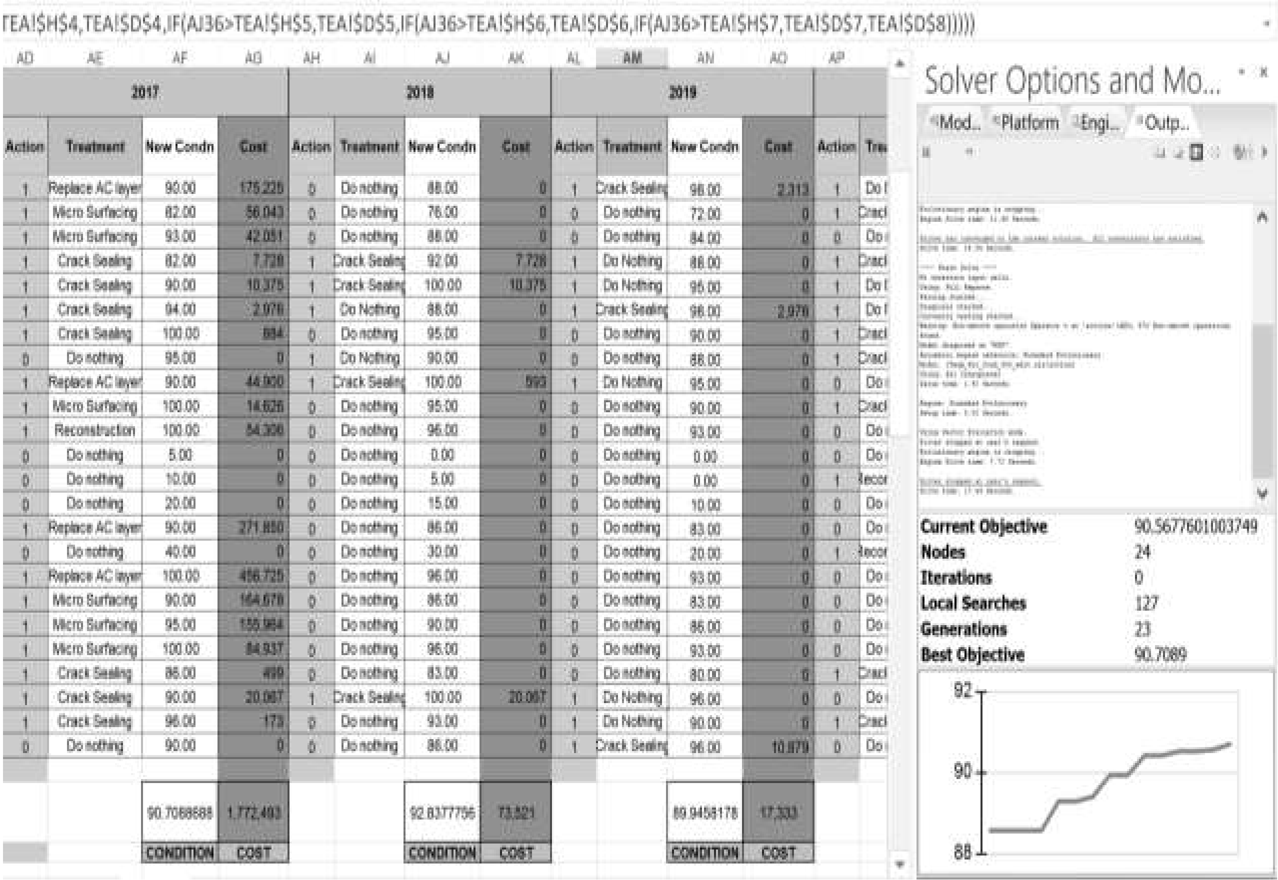


Figure 4-2 Excel spreadsheet with Solver Risk Platform Add-in

4.3 Results and discussion

4.3.1 Optimization of Assets' Condition

The first analysis was devoted to optimize assets' condition with one million dollar budget (CAD$), the results of such optimization can be found on Table (4-2). The top portion of Figure (4-3) provides a graphical representation of Table (4-2) and is used to facilitate the comparison versus the results obtained for the value-based optimization presented in the next section.

Table 4-2 Average-Asset Group Annual Condition from a Condition-based approach

	Street Name (%)	Hydrants (%)	Lighting (%)	Sidewalks (%)	Roads (%)	Sanitary (%)	Storm (%)	Water main (%)	Overall (%)
2017	96.00	80.50	77.65	92.00	78.39	57.00	55.13	57.86	74.32
2018	94.00	80.00	74.93	91.90	75.64	62.30	54.02	57.00	73.72
2019	90.00	99.12	75.71	91.80	82.33	62.01	55.76	56.00	76.59
2020	86.00	97.95	75.46	91.60	77.52	68.30	54.56	55.04	75.80
2021	83.00	98.66	77.49	91.40	75.22	69.52	56.14	54.05	75.69
2022	80.00	98.42	74.72	91.20	83.18	69.98	54.99	53.11	75.70
2023	80.00	98.42	74.72	91.20	83.18	69.98	54.99	53.11	75.70
2024	96.00	98.02	73.66	90.00	77.48	84.01	52.72	51.21	77.89
2025	94.00	97.53	82.95	89.50	82.34	83.44	51.54	52.45	79.22
2026	90.00	97.04	81.79	89.00	84.86	85.06	52.26	51.43	78.93
2027	86.00	96.54	82.01	88.50	84.25	90.25	51.15	50.48	78.65
2028	83.00	96.04	80.57	88.00	83.66	90.31	51.91	49.53	77.88

	Street Name (%)	Hydrants (%)	Lighting (%)	Sidewalks (%)	Roads (%)	Sanitary (%)	Storm (%)	Water main (%)	Overall (%)
2029	80.00	95.73	84.41	87.00	82.00	91.93	53.56	48.64	77.91
2030	96.11	95.33	93.03	86.50	81.52	90.87	54.20	52.22	81.22
2031	96.65	95.03	80.06	86.00	83.35	90.03	54.45	51.30	79.61
2032	94.32	94.73	68.98	85.50	86.18	89.98	56.57	50.38	78.33
2033	90.65	94.33	84.71	85.00	87.08	89.09	55.51	54.61	80.12
2034	86.65	94.03	92.00	84.50	86.78	88.13	54.56	60.59	80.90
2035	83.49	93.53	79.32	84.00	88.54	87.23	54.99	62.45	79.19
2036	80.49	93.04	68.23	83.50	85.28	86.32	55.10	66.88	77.36

As seen on Table (4-2), the optimization is unable to achieve non-declining levels of condition: some assets do obtain significant gains in condition (roads, water-mains, hydrants, sanitary-sewage), others observe cycles of gain and loses on their condition (street-name signs, lighting), some assets experience stagnation or even decay (storm-sewage or sidewalks, correspondingly).

4.3.2 Optimization of Assets' Valuation

The second analysis was devoted to optimize assets' valuation with a budget of one million dollars (CAD$), the results of such optimization can be found on Table (4-3). The results show in general increasing values for all assets, which translates to increasing levels of condition as well as better ability to serve the population.

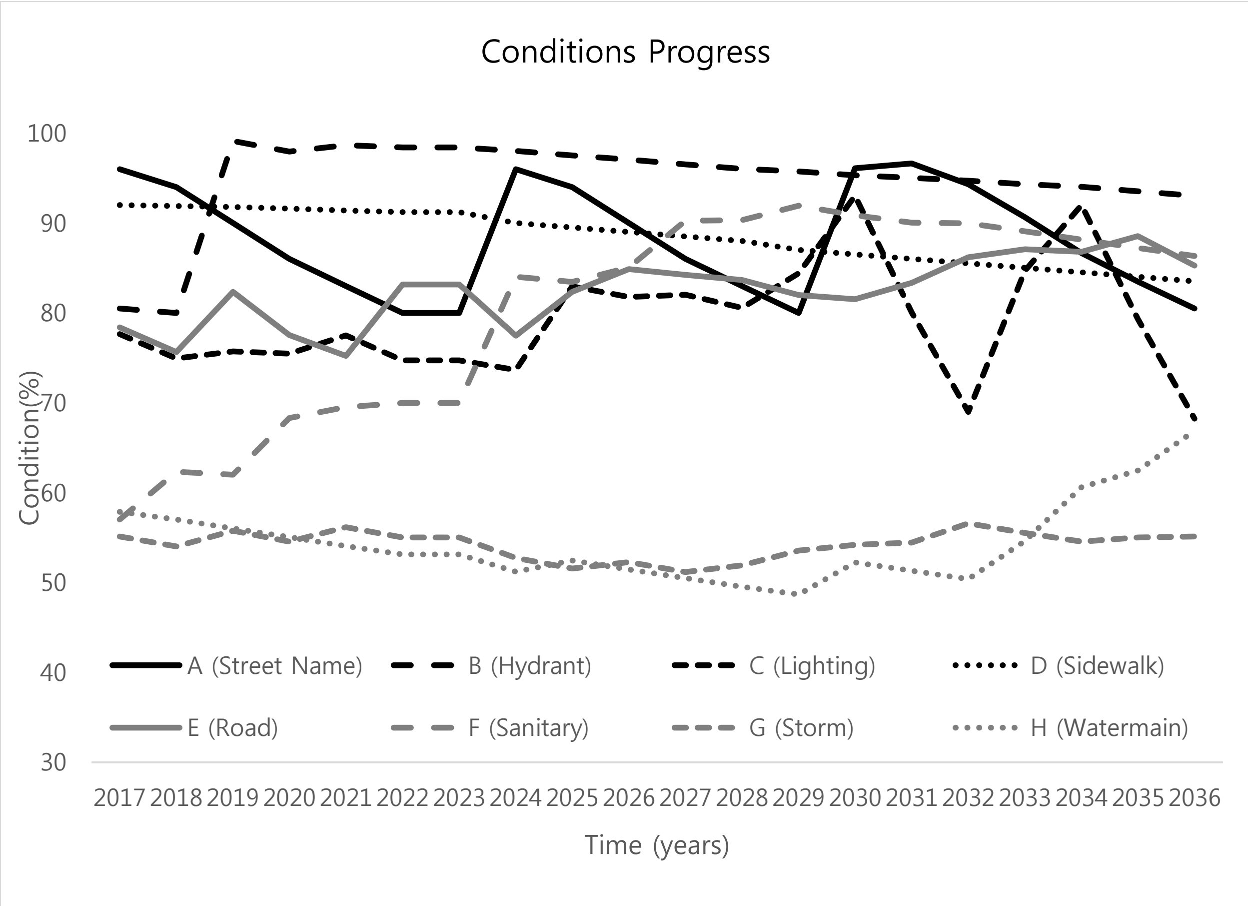
Table 4-3 Average-Asset Group Annual Value (thousands) from a Value-based approach

	Street Name CAD(thousands)	Hydrants CAD(thousands)	Lighting CAD(thousands)	Sidewalks CAD(thousands)	Roads CAD(thousands)	Sanitary CAD(thousands)	Storm CAD(thousands)	Water main CAD(thousands)	Overall CAD(thousands)
2017	45	1,074	1,000	3,565	16,409	4,447	11,532	6,055	5,516
2018	44	1,067	965	3,561	16,143	4,392	12,474	5,967	5,577
2019	43	1,191	943	3,557	15,271	4,317	13,285	6,010	5,577
2020	41	1,326	921	3,550	15,790	4,573	13,070	5,913	5,648
2021	39	1,317	915	3,542	15,820	4,715	13,228	6,074	5,706
2022	38	1,314	948	3,534	15,409	4,758	13,717	6,055	5,722
2023	42	1,311	956	3,526	15,622	4,792	14,119	5,957	5,791
2024	46	1,309	940	3,488	16,882	5,164	13,882	6,116	5,978
2025	45	1,304	880	3,468	16,675	5,710	13,648	6,138	5,984
2026	43	1,298	886	3,449	16,090	5,802	13,774	6,355	5,962
2027	41	1,291	1,064	3,429	15,497	5,717	13,761	6,764	5,946
2028	40	1,284	1,118	3,410	15,455	5,910	13,881	6,654	5,969

	Street Name CAD(thousands)	Hydrants CAD(thousands)	Lighting CAD(thousands)	Sidewalks CAD(thousands)	Roads CAD(thousands)	Sanitary CAD(thousands)	Storm CAD(thousands)	Water main CAD(thousands)	Overall CAD(thousands)
2029	38	1,279	1,150	3,371	16,313	6,363	13,757	6,550	6,103
2030	40	1,274	1,138	3,352	16,342	7,048	13,557	6,449	6,150
2031	47	1,269	1,091	3,333	16,280	7,197	13,920	6,416	6,194
2032	45	1,265	1,072	3,313	16,149	7,608	13,908	6,323	6,210
2033	44	1,261	1,069	3,294	16,031	7,536	13,705	6,799	6,217
2034	42	1,256	1,063	3,274	15,923	7,705	13,937	6,756	6,244
2035	40	1,251	1,083	3,255	15,734	7,627	13,737	7,330	6,257
2036	39	1,244	1,117	3,236	16,168	7,563	13,570	7,929	6,358

4.3.3 Comparison of Approaches

Figure (4-3) shows the same results from the tables before but serves to compare the condition base with the value base approaches. As seen the value-based approach results in either assets holding constant or increasing levels of valuation. Such trends are more stable than those observed at the condition-based approach results: in which strong cycles of increase and drop in condition (and value as well) can be observed for various assets, and for others declining trends.



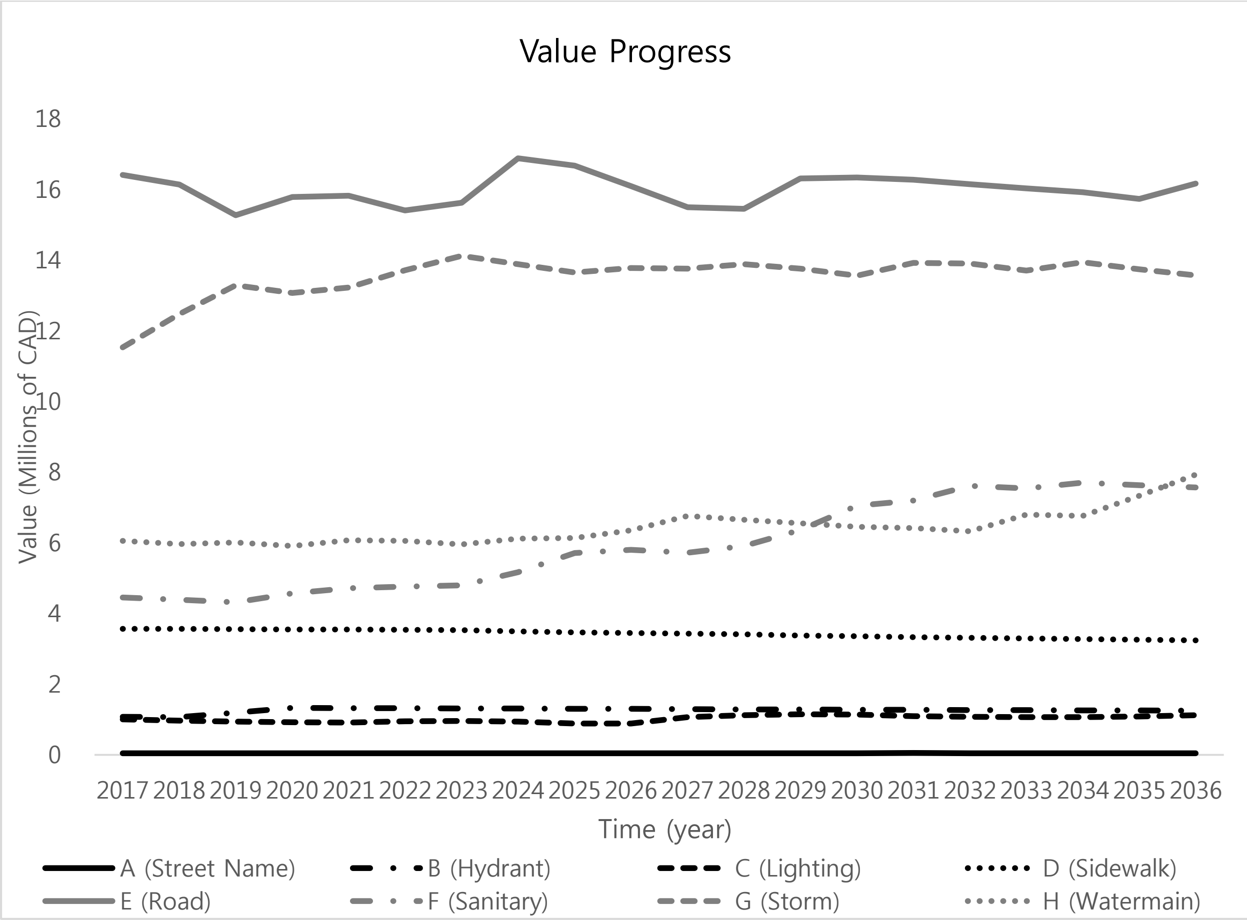


Figure 4-3 Comparison of Condition-based versus Value-Based approaches.

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

Municipal asset management is a philosophical approach typically implemented through tools and techniques used by municipalities to preserve and maintain all assets at good levels of condition.

This research is mainly focused on two different approaches: traditional condition-based approach and proposed value-based approach to get appropriate decisions to maintain and rehabilitate municipal assets. The condition-based is achieved through accurate data inspection, reliable deterioration models and good resource analysis through optimization techniques.

On the contrary, the value-based approach is supported over similar data, but the deterioration modeling is replaced by depreciation models and survival curves that are linked to the drop in asset value through time: performance curves can be transformed into valuation curves by considering either the replacement or reconstruction value of the asset, its expected life span and residual value (if any). In addition, the value-based approach can be employed for all types of assets including: equipment, vehicles and machinery, as well as for all types of civil infrastructures and buildings. Hence, asset valuation can be used to guide municipal asset infrastructure decisions; the approach provides a common unifying platform, where the units of measurement do not impact the results and hence no weighting is required.

A case study of the municipality of Kindersley was presented, it aimed to propose a more financially-sustainable, yet cost-effective framework. The proposed approach (value-based) proved flexible enough to accommodate street names, signs, hydrants, lighting, sidewalks, roads, sanitary pipes and water mains. Excel was used as a platform to define the problem and its mechanisms and a plug-in to commercial optimization-platform software, solver risk platform, was used to define the problem. An external solver (MOSEK, LPABO, and etcetera) was used to solve the dynamic binary programming.

A comparison of the traditional, condition-based optimization, and the proposed value-based optimization showed more stable results for the value-based approach, with asset values either holding at good levels or increasing over time. A detailed view of budget allocation per year revealed that the condition-based approach was overfunding roads and underfunding other assets. The value-based approach provided more budget to water mains and storm pipes at earlier years, it delayed slightly the budget for sanitary pipes and increased the level of expenditure for lighting systems.

Ultimately, this research suggests that a value-based decision making support system is better suited to handle municipal assets.

5.2 Recommendations for Future Research

Future research must test the approach herein proposed with other databases that include vehicles and machinery in order to confirm the findings. Future research may incorporate risk of collapse or failure as a random effect coming from unobserved characteristics of the assets, and hence enable budgeting for such unforeseen events.

Future research must add additional constraints to prevent specific individual asset to go below critical levels. Future research must expand the array of assets to include vehicles and machinery commonly under municipal jurisdiction and test the suitability of the current approach through a similar analysis.

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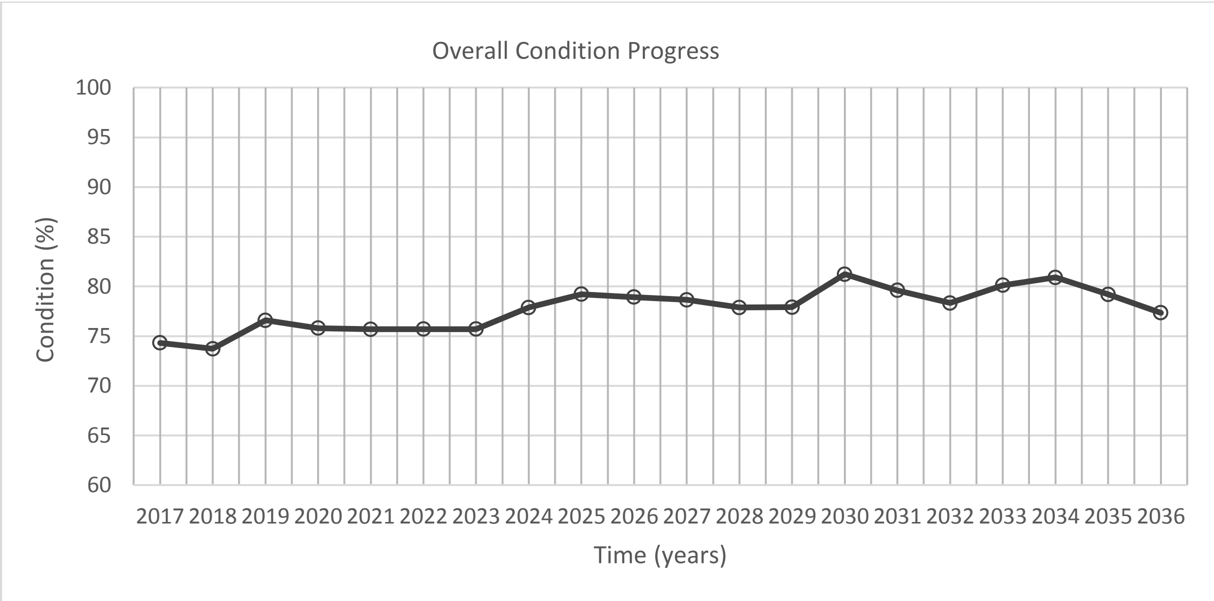
APPENDIX A: Overall Outcomes

The following table and figure show the expected mean condition and annual budget for the condition-based approach method during 20 analysis years. As seen, in general, the trend fluctuates very slightly up and down, remaining significantly stable with the same pattern from about 74% to nearly 81% over the period between starting point and ending point for analysis.

Average Condition and Budget (Condition-based)

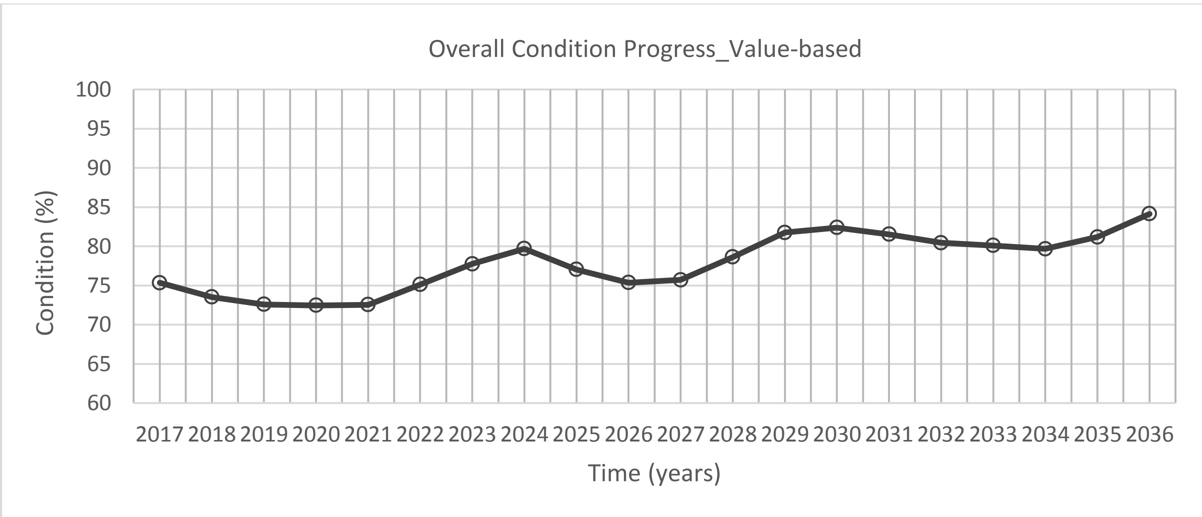
Year	Condition (%)	Cost (CAD)
2017	74.318	992,608
2018	73.724	982,616
2019	76.590	999,533
2020	75.804	843,931
2021	75.685	928,912
2022	75.698	988,316
2023	78.494	996,205
2024	77.886	873,859
2025	79.219	898,359
2026	78.930	957,774
2027	78.647	925,539
2028	77.877	977,059
2029	77.910	975,304
2030	81.224	872,067
2031	79.607	946,509
2032	78.331	808,963
2033	80.121	947,899
2034	80.905	978,836
2035	79.192	980,997
2036	77.355	932,809

Overall Condition Change (Condition-based)



The following table and figure explain expected average condition of each year for the value-based approach method from 2017 to 2036. According to the graph, the trend remains steady through all periods having from approximately 72% to about 84% from beginning, 2017 to ending point, 2036. In this figure, we can confirm the condition and cost required for treatment as well as the total value of assets which is obtained by calculation; using the quantity and replacement cost of each asset and their condition. This data wonderfully explains how much assets are worth in each year.

Overall Condition Change (Value-based)



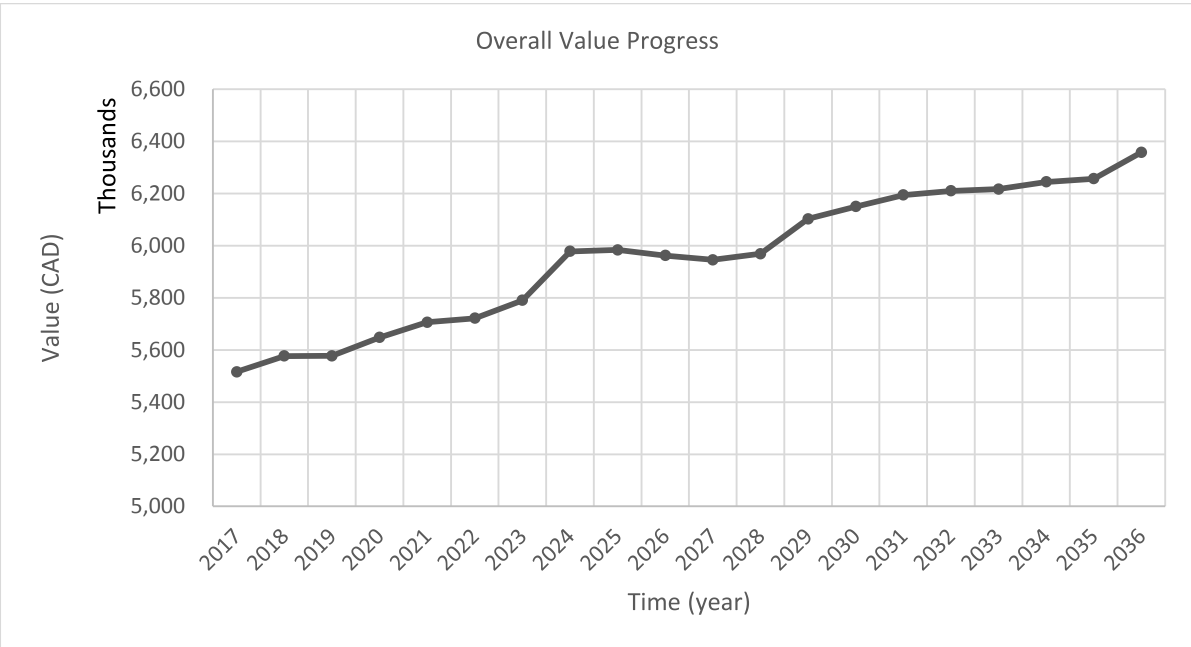
Value, budget and condition (Value-based)

Year	New Value (CAD)	Cost (CAD)	Conditions (%)
2017	44,126,723	999,734	75.353
2018	44,614,880	999,820	73.524
2019	44,616,804	999,280	72.600
2020	45,183,873	999,200	72.466
2021	45,649,543	999,963	72.559
2022	45,773,278	999,617	75.120
2023	46,324,930	998,959	77.749
2024	47,827,056	999,647	79.694
2025	47,869,110	992,883	77.035
2026	47,697,411	999,589	75.379
2027	47,564,627	981,992	75.717
2028	47,752,401	999,958	78.643
2029	48,821,682	999,703	81.764
2030	49,199,709	999,837	82.388
2031	49,552,960	999,859	81.526
2032	49,683,785	997,134	80.452
2033	49,737,832	821,129	80.105
2034	49,955,988	999,725	79.682
2035	50,057,796	995,043	81.191
2036	50,866,042	993,442	84.156

The following figure illustrates an expected average value of each year on the basis of the value-based approach between 2017 and 2036. The mean value come from the summation of the value of all assets divided by sum of all asset types (8 types). As can be seen from the graph and table below, in general, the average value marks steady growth from approximately 5,500,000 CAD to 6,360,000 CAD through the analysis period.

The results show that the highest mean value is 6,358,255 CAD at the end of period, followed by 6,257,225 CAD in 2035 and 6,244,499 CAD in 2034. On the other hand, the lowest is 5,515,840 CAD in 2017, followed by 5,576,860 CAD in 2018 and 5,577,101 CAD in 2019.

Overall Value Change (Value-based)



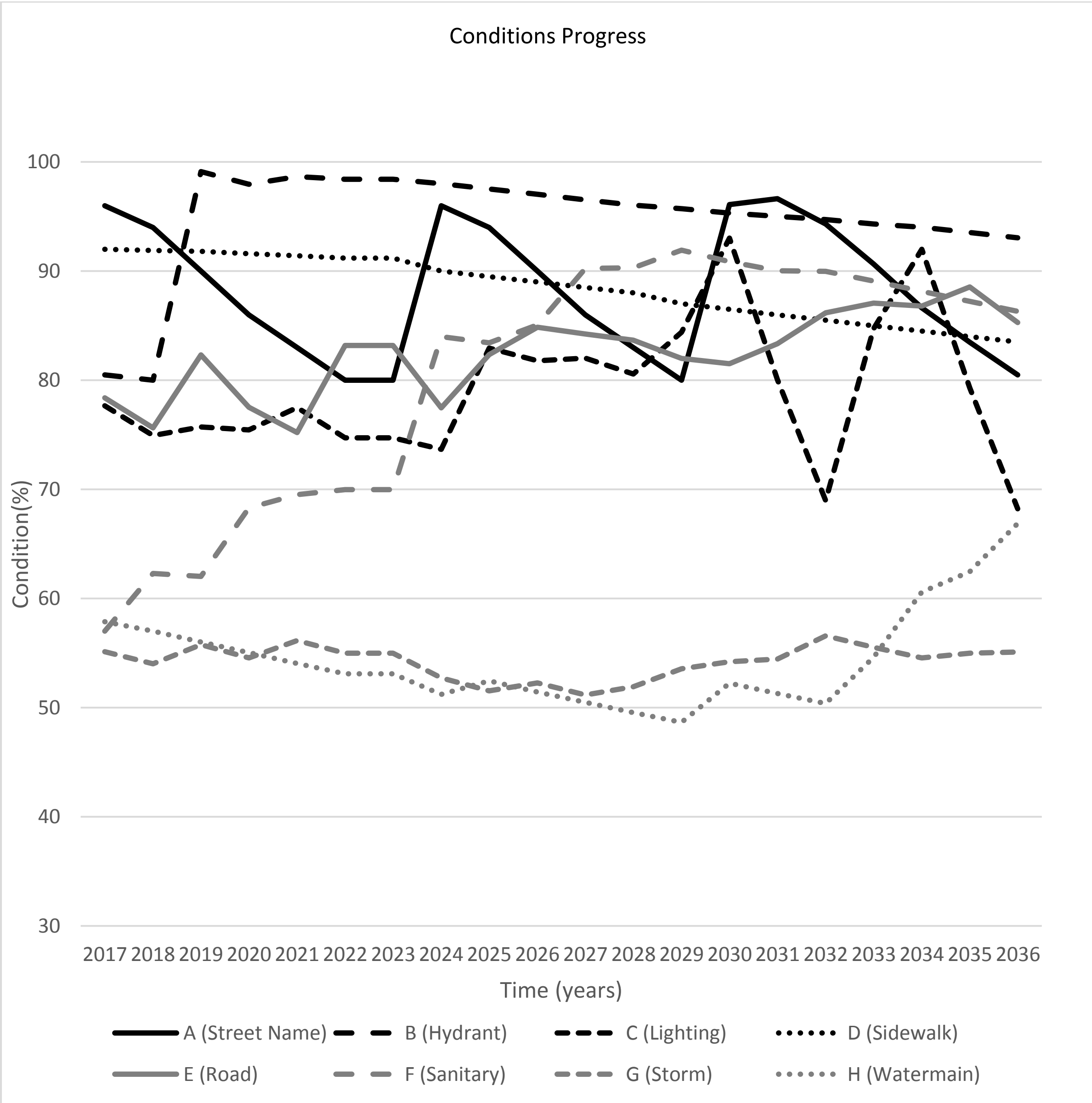
The following table shows a predicted average condition of the condition approach method between 2017 and 2036. The data of each asset type reaches steeply up and down while, an overall marks constantly increase. This table also beautifully explains how an overall condition is differ as compared with each asset type.

To put it in another way, according to the following Figure, we can identify that all assets has a different trend during analysis period; asset "street name" labeled "A" marks the biggest change having repeatedly up and down at the range of about 80% to 100%, asset "Lighting" labeled "C" also represents a huge change as mentioned earlier asset at the range of approximately 70% to 95%. On the other hand, asset "sidewalk" labeled "D" and asset "storm" labeled "G" picture very stable trend over the whole period. It could infer that an optimization decision obtained by condition-based approach can be shown unstably.

Average Condition Each Year (Condition-based)

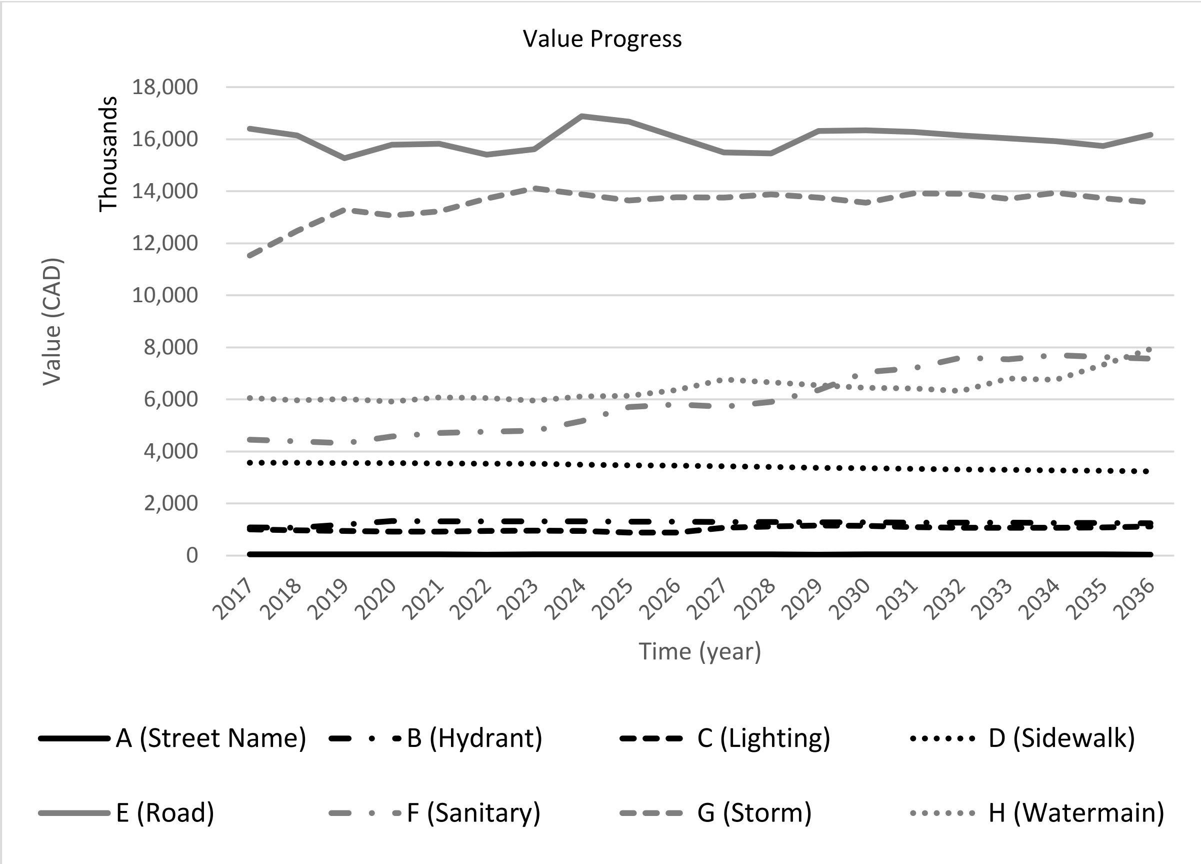
	A	B	C	D	E	F	G	H	OL
2017	96.00	80.50	77.65	92.00	78.39	57.00	55.13	57.86	74.32
2018	94.00	80.00	74.93	91.90	75.64	62.30	54.02	57.00	73.72
2019	90.00	99.12	75.71	91.80	82.33	62.01	55.76	56.00	76.59
2020	86.00	97.95	75.46	91.60	77.52	68.30	54.56	55.04	75.80
2021	83.00	98.66	77.49	91.40	75.22	69.52	56.14	54.05	75.69
2022	80.00	98.42	74.72	91.20	83.18	69.98	54.99	53.11	75.70
2023	80.00	98.42	74.72	91.20	83.18	69.98	54.99	53.11	75.70
2024	96.00	98.02	73.66	90.00	77.48	84.01	52.72	51.21	77.89
2025	94.00	97.53	82.95	89.50	82.34	83.44	51.54	52.45	79.22
2026	90.00	97.04	81.79	89.00	84.86	85.06	52.26	51.43	78.93
2027	86.00	96.54	82.01	88.50	84.25	90.25	51.15	50.48	78.65
2028	83.00	96.04	80.57	88.00	83.66	90.31	51.91	49.53	77.88
2029	80.00	95.73	84.41	87.00	82.00	91.93	53.56	48.64	77.91
2030	96.11	95.33	93.03	86.50	81.52	90.87	54.20	52.22	81.22
2031	96.65	95.03	80.06	86.00	83.35	90.03	54.45	51.30	79.61
2032	94.32	94.73	68.98	85.50	86.18	89.98	56.57	50.38	78.33
2033	90.65	94.33	84.71	85.00	87.08	89.09	55.51	54.61	80.12
2034	86.65	94.03	92.00	84.50	86.78	88.13	54.56	60.59	80.90
2035	83.49	93.53	79.32	84.00	88.54	87.23	54.99	62.45	79.19
2036	80.49	93.04	68.23	83.50	85.28	86.32	55.10	66.88	77.36

Progression of Condition for Each Asset (Condition-based)



As a result, the following Figure represents an expected value of the value approach method from 2017 to 2036. The value of each asset type marks extremely stable in contrast with condition-based method. This truly shows the reason why we need to use value-based approach method instead of condition-based.

Progression of Value for Each Asset (Value-based)

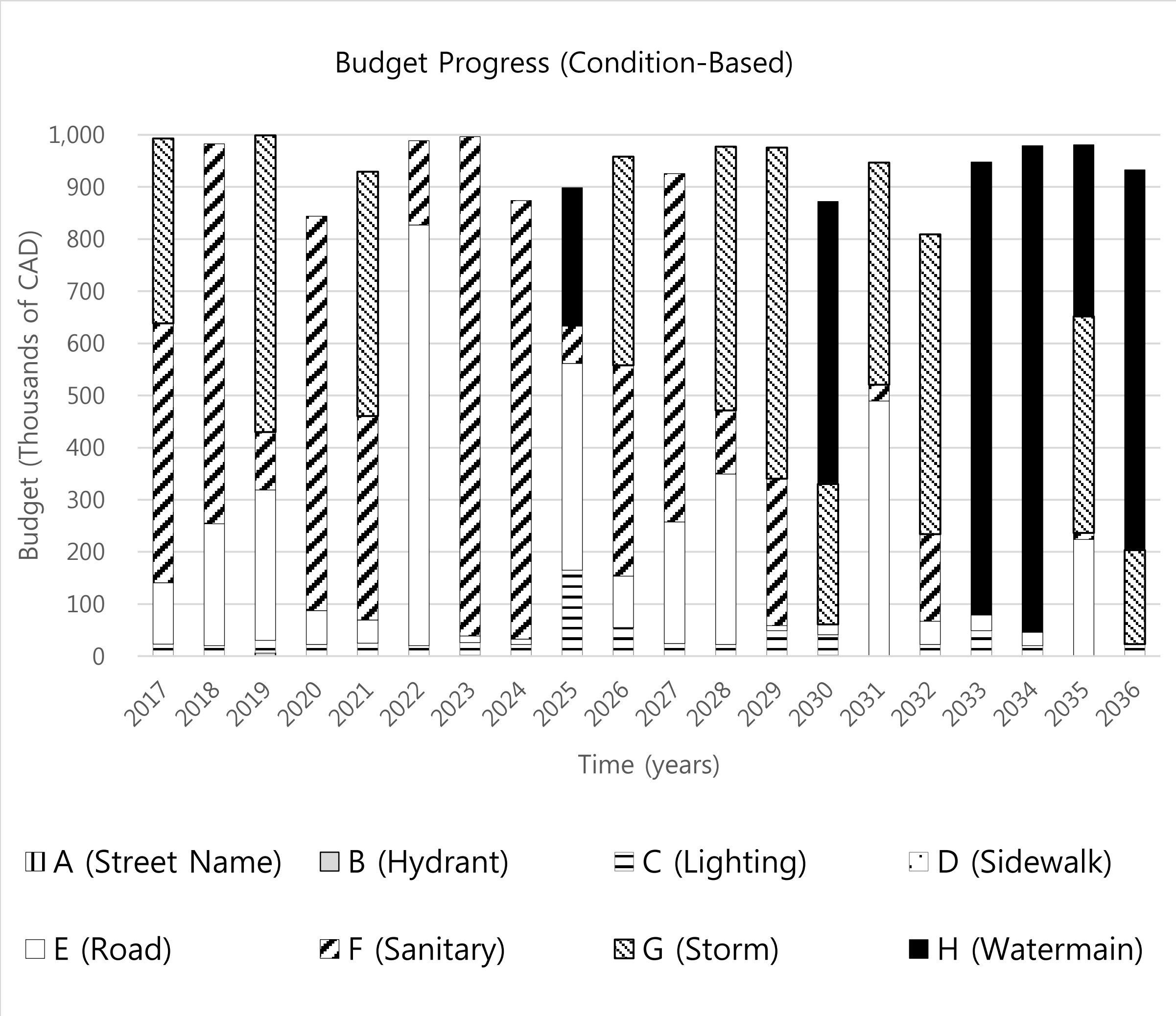


The following Table and Figure show the expected annual budget change for the condition-based approach method during 20 analysis years. As most administrations have limited budgets, this solution was calculated using a one million Canadian dollars per year of available budget in order to treat all kinds of assets within the municipality of Kindersley. As can be seen from the graph and table below, the largest expenditure of 999,533 CAD happens in 2019, followed by 996,205 CAD in 2023 and 992,608 CAD in 2017. On the contrary, the lowest is 808,963 CAD in 2032, followed by 843,931 CAD in 2020 and 872,067 CAD in 2030. In the analysis of sanitary pipes, we can see that the required budget is evenly spread between 2017 and 2030 while, storm pipes uniformly need various levels of budget through all periods. In addition, we also discover that budget for hydrants is distributed equally from 2025 to 2036 and increases between 2033 and 2036 for three years meanwhile, for roads it spreads across all analysis periods with a peak on 2022. Unusually, sidewalks does not receive any budget through the all periods; this is because condition of asset sidewalk is generally very good and has relatively a long expectancy lifespan, eighty years.

Budget Each Year (Condition-based)

	A	B	C	D	E	F	G	H	Total
2017			23,004		117,540	497,564	354,500	0	992,608
2018	0	0	19,764	0	233,910	728,942	0	0	982,616
2019	0	6,400	23,976	0	288,217	111,300	568,800	840	999,533
2020	0	0	22,680	0	64,806	756,445	0	0	843,931
2021	0	288	24,624	0	44,278	391,222	468,500	0	928,912
2022	0	0	19,764	0	807,131	161,421	0	0	988,316
2023	2,148	0	23,976	0	12,388	957,693	0	0	996,205
2024	0	0	22,680	0	9,763	841,416	0	0	873,859
2025	0	0	164,624	0	396,751	71,610	0	265,374	898,359
2026	0	0	54,764	0	98,521	404,589	399,900	0	957,774
2027	0	0	23,976	0	233,133	668,430	0	0	925,539
2028	0	0	22,680	0	326,358	122,421	505,600	0	977,059
2029	0	0	48,600	0	10,023	281,781	634,900	0	975,304
2030	1,800	0	39,189	0	20,067	0	269,000	542,011	872,067
2031	348	0	0	0	489,114	31,047	426,000	0	946,509
2032	0	0	22,680	0	44,358	167,025	574,900	0	808,963
2033	0	0	48,600	0	30,114	0	0	869,185	947,899
2034	0	0	19,764	0	26,042	0	0	933,030	978,836
2035	0	0	532	0	223,199	12,576	415,200	329,490	980,997
2036	0	0	22,680	0	86	0	180,600	729,443	932,809

Budget Change of Each Asset (Condition-based)



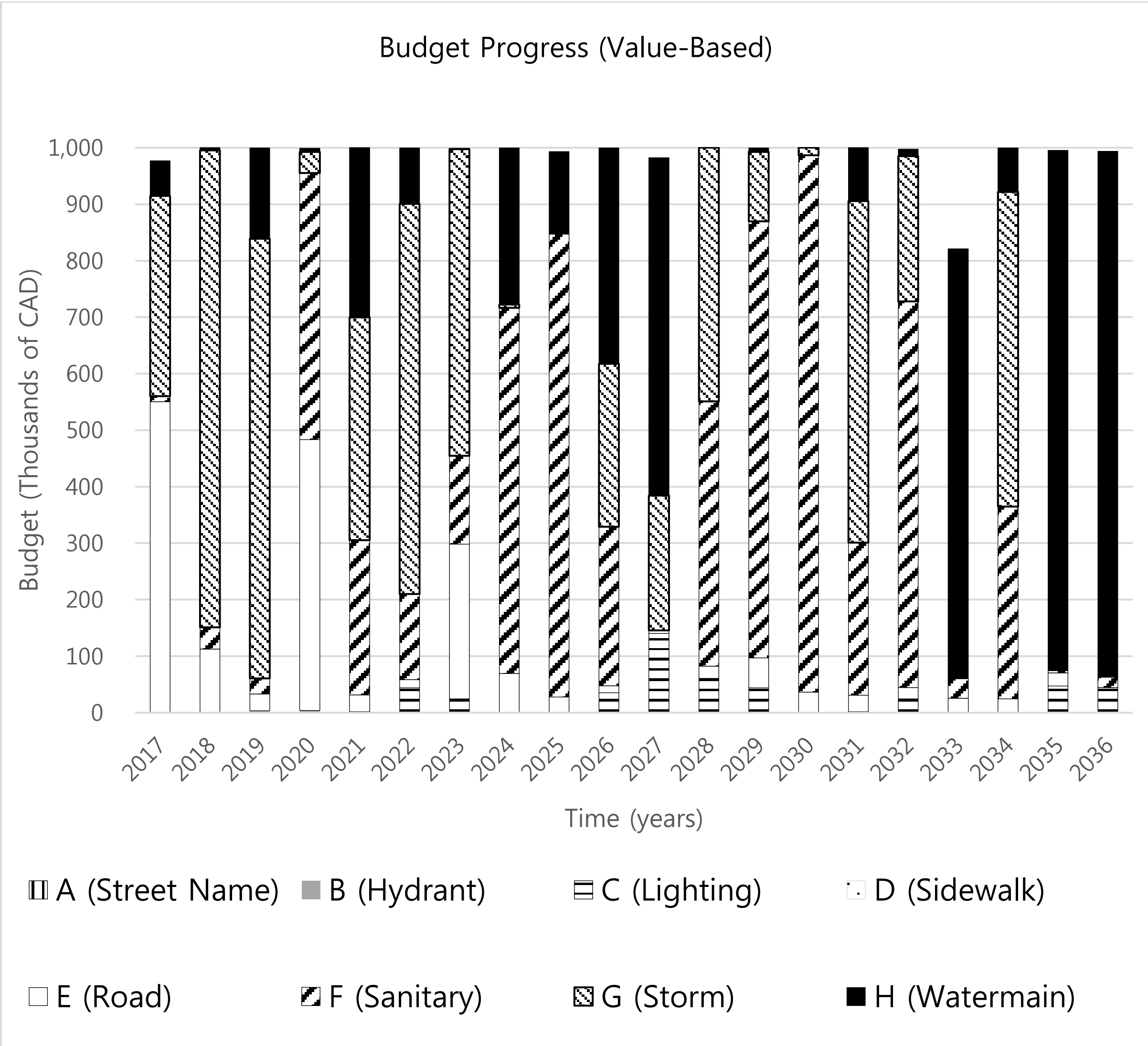
The following Table and Figure present the annual budget progression for the value-based approach across all periods of time. This results also used one million Canadian dollars per year. Sanitary pipes, receive equally distributed amounts through all periods with an increase between 2024 and 2032 while, hydrant budget distributes evenly across all analysis periods and is concentrated on 2026, 2027 and from 2033 to 2036. Budget for roads is distributed during the first half of the analysis period and is concentrated between 2017 and 2020 but, is spread evenly from 2017 to 2036. Interestingly, sidewalks does not need any budget across the analysis times; this is why condition of asset sidewalk is overall very high and has comparatively a long expected lifespan, eighty years.

Budget Each Year, Asset (Value-based)

	A	B	C	D	E	F	G	H	Total
2017			23,004		550,388	9,563	354,500	62,279	999,734
2018	0	0	0	0	112,607	38,383	844,000	4,830	999,820
2019	0	3,200	0	0	29,595	27,510	778,500	160,475	999,280
2020	0	3,488	0	0	479,704	471,827	37,500	6,681	999,200
2021	0	0	1,620	0	29,639	273,790	394,400	300,514	999,963
2022	0	0	43,740	0	14,850	151,129	690,600	99,298	999,617
2023	1,200	0	23,004	0	273,820	156,545	542,500	1,890	998,959
2024	948	0	0	0	68,222	647,269	6,000	277,208	999,647
2025	0	0	0	0	27,282	819,651	0	145,950	992,883
2026	0	0	35,000	0	12,398	281,781	288,000	382,410	999,589
2027	0	0	140,000	0	5,322	0	238,800	597,870	981,992
2028	0	0	60,254	0	21,760	468,844	449,100	0	999,958
2029	0	0	43,740	0	52,928	772,961	123,000	7,074	999,703
2030	600	0	0	0	35,525	950,212	13,500	0	999,837
2031	1,548	0	0	0	29,168	270,253	604,500	94,390	999,859
2032	0	0	24,300	0	20,021	683,414	257,300	12,099	997,134
2033	0	0	182	0	24,919	34,846	0	761,182	821,129

2034	0	0	350	0	23,766	340,584	556,800	78,225	999,725
2035	0	0	46,980	0	23,055	4,192	0	920,816	995,043
2036	0	0	44,064	0	160	18,270	0	930,948	993,442

Progression of Budget for Each Asset (Value-based)

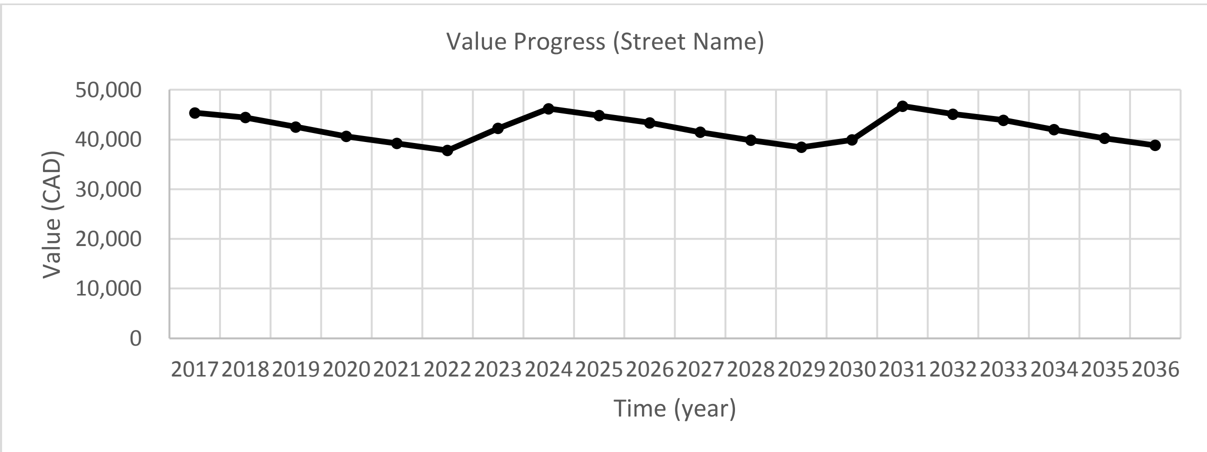


APPENDIX B: Results for Each Asset

The following figures illustrate the condition and value changes for street name signs on the basis of the two methods: condition-based and value-based. The condition of street name signs fluctuated slightly up and down with a regular cycles from approximately 80% to about 100%. From the result, the biggest condition is 96.65% in 2031, followed by 96.11% in 2030 and 96.00% in 2017. On the contrary, the lowest is 80% in 2023 and 2029, followed by 80.49% in 2036. Meanwhile, the value-based approach trend for asset street name signs also fluctuates up and down with a regular interval between about 37,000 CAD and approximately 47,000 CAD. The highest value occur at 46,728 CAD in 2031, followed by 46,200 CAD in 2024, and 45,366 CAD in 2017. On the other hand, the lowest is 37,805 CAD in 2022, followed by 38,430 CAD in 2029.

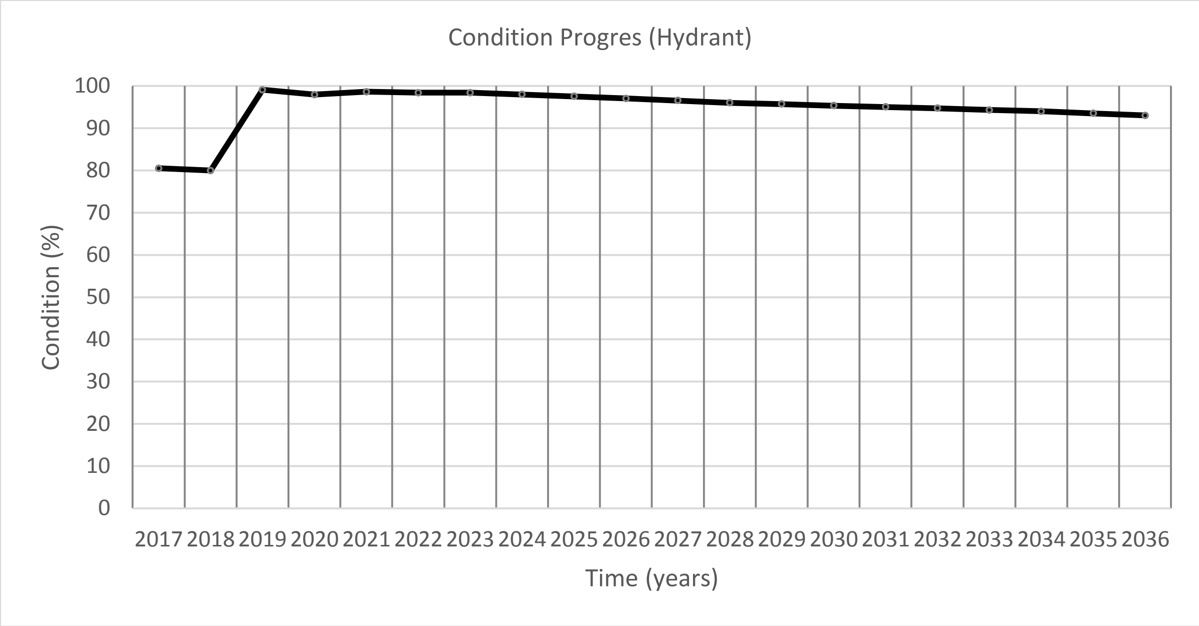
Progression of Condition for Street Name (Condition-based)

Progression of Value for Street Name (Value-based)

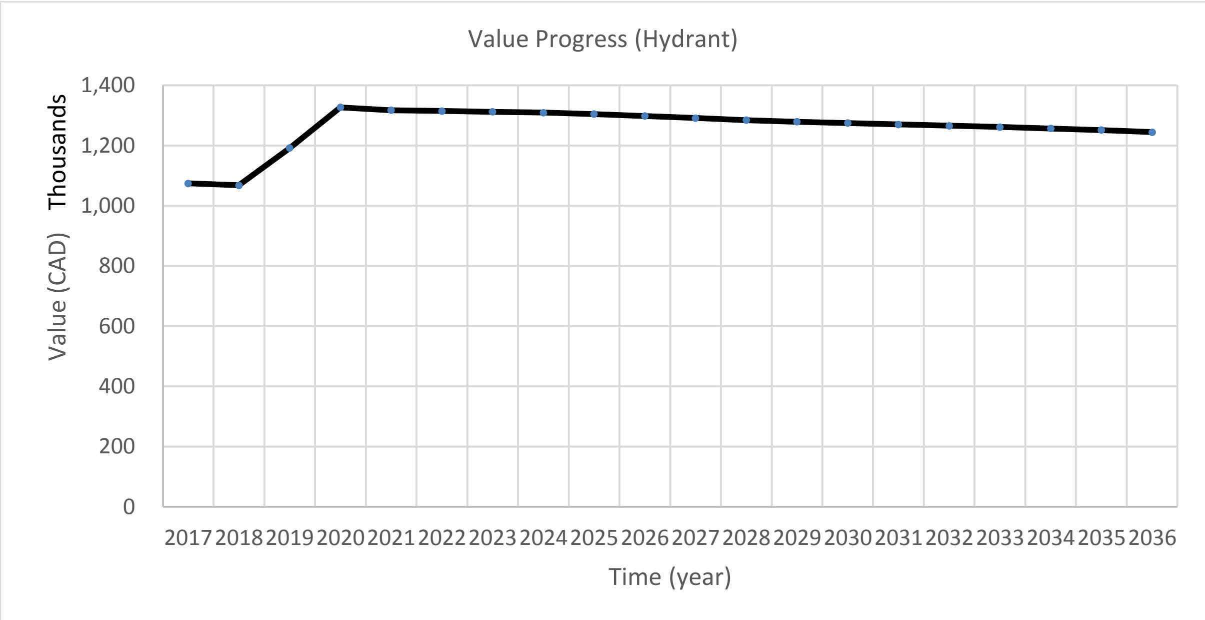


Results for hydrants are shown below. The change in condition revealed a steady state after two-years of interventions all the way to the end of period. As a result, the highest condition is 99.12% in 2019, followed by 98.66% in 2020 and 98.42% in 2021. On the other hand, the lowest is 80.00% in 2018, followed by 80.50% in 2017.

Progression of Condition for Hydrant (Condition-based)

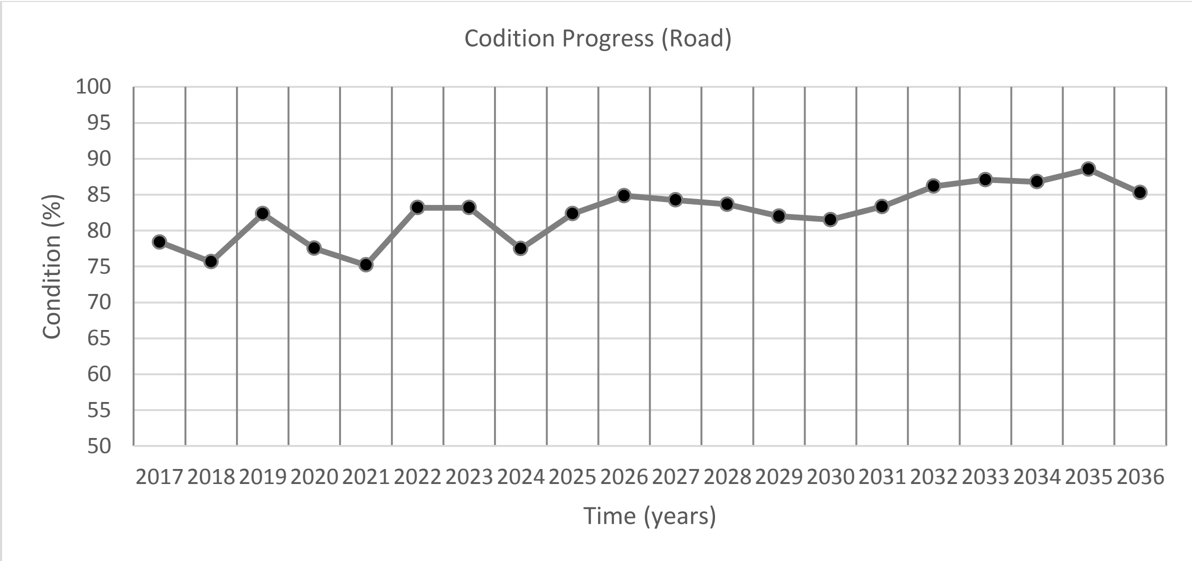


Progression of Value for Hydrant (Value -based)

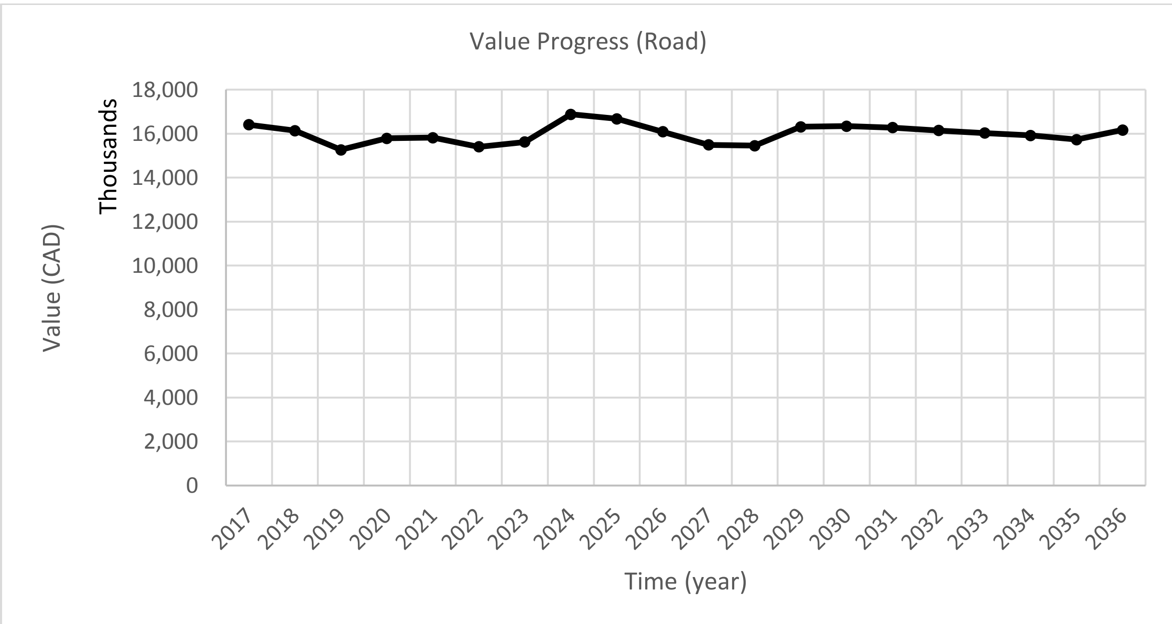


The following figures show the condition and value change of roads. For the condition-based approach the trend fluctuated considerably up and down with a different interval from almost 70% to nearly 90% while, the value's approach remain more stable between about 15,000 CAD and approximately 17,000 CAD.

Progression of Condition for Road (Condition-based)

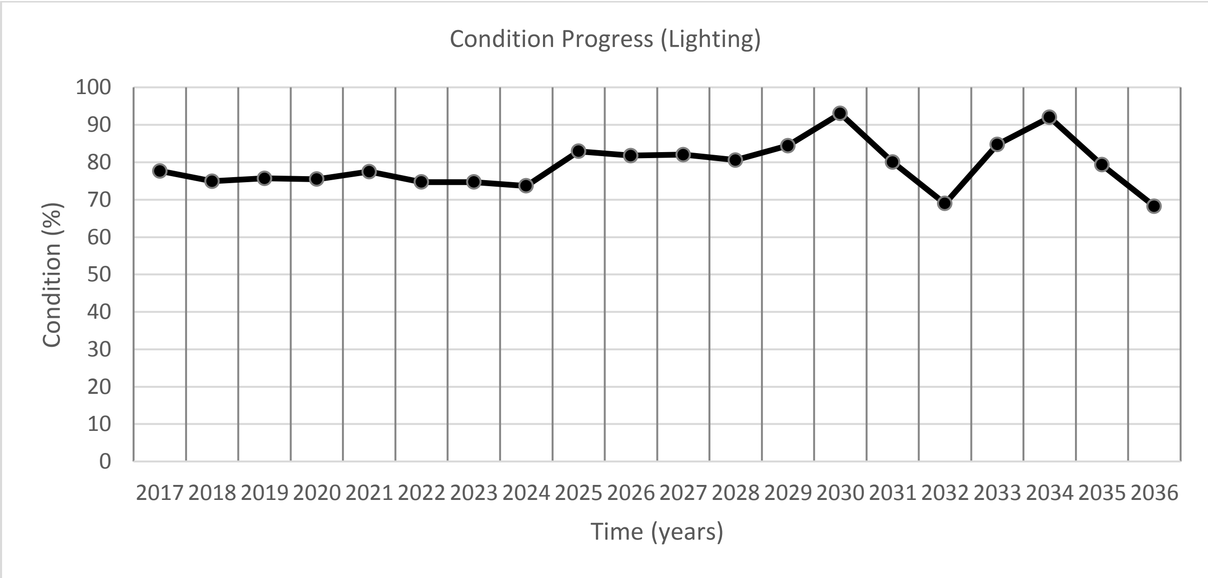


Value Change of Road (Value -based)

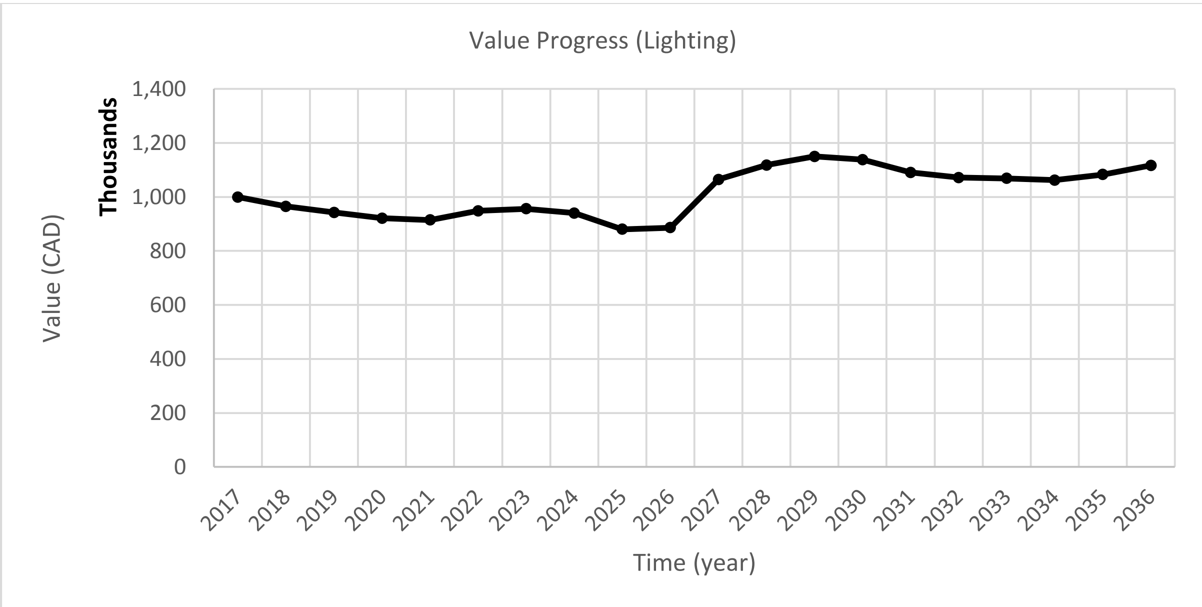


The results for lighting on the basis of different methods such as condition-based and value-based are presented below. The condition-approach shows a trend that remains nearly steady until in 2029 while, fluctuating sharply up and down after this time until at the end of period.

Progression of Condition for Lighting (Condition-based)



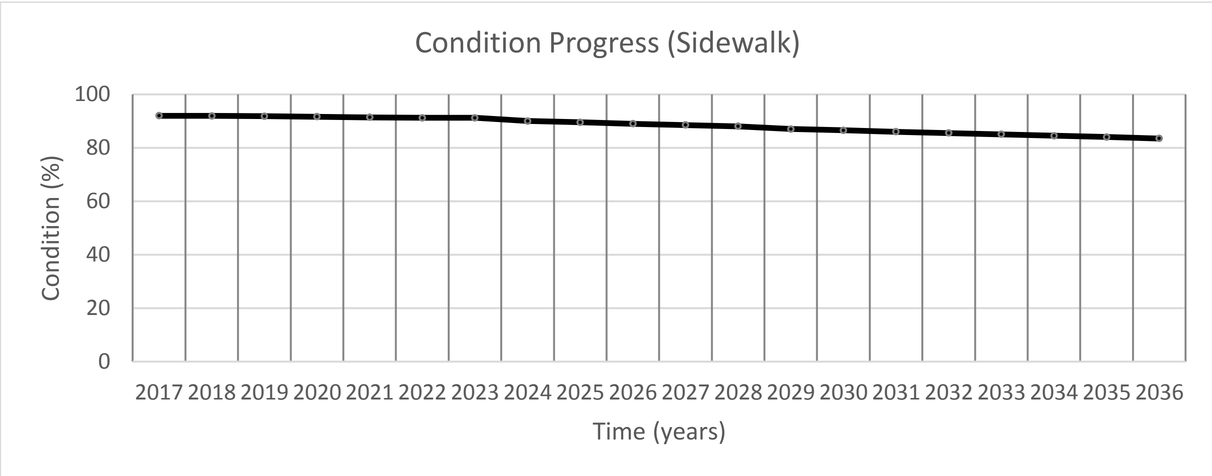
Progression of Value for Lighting (Value-based)



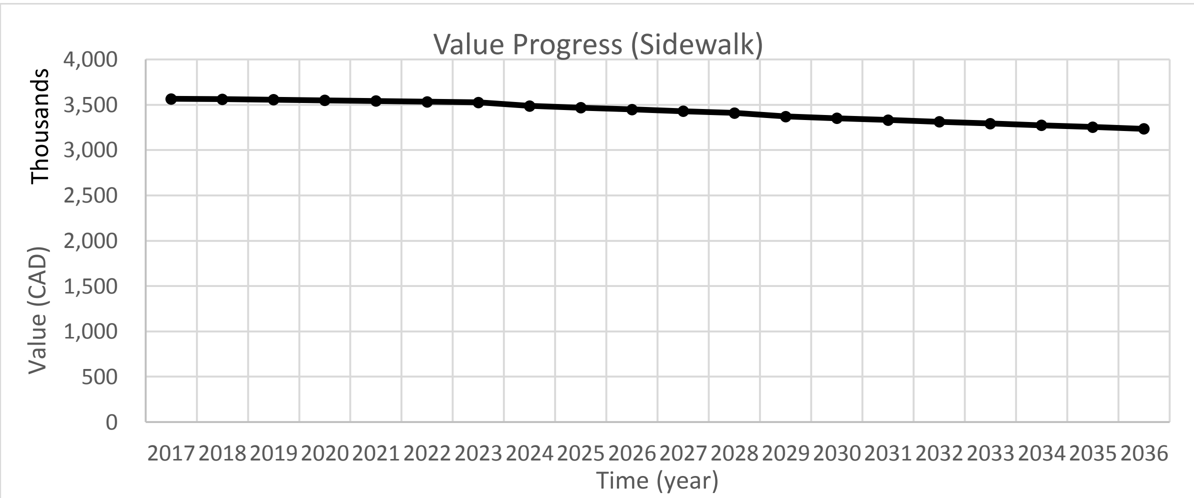
The following figures illustrate the condition and value changes of sidewalks. The condition change of sidewalk showed nearly steady values until at the end of period while, the value’s trend shows gradually going down.

It can be seen in figure that the highest condition is 92.0% in 2017, followed by 91.9% in 2018 and 91.8% in 2019. On the other hand, the lowest is 83.5% in 2036 and followed by 84.0% in 2035 and 84.5% in 2034. In the meantime, the biggest value is 3,565,055 CAD in 2017, followed by 3,561,180 CAD in 2018, and 3,557,305 CAD in 2019. On the contrary, the lowest is 3,235,675 CAD in 2036, followed by 3,235,050 CAD in 2035 and 3,274,426 CAD in 2034.

Progression of Condition for Sidewalk (Condition-based)



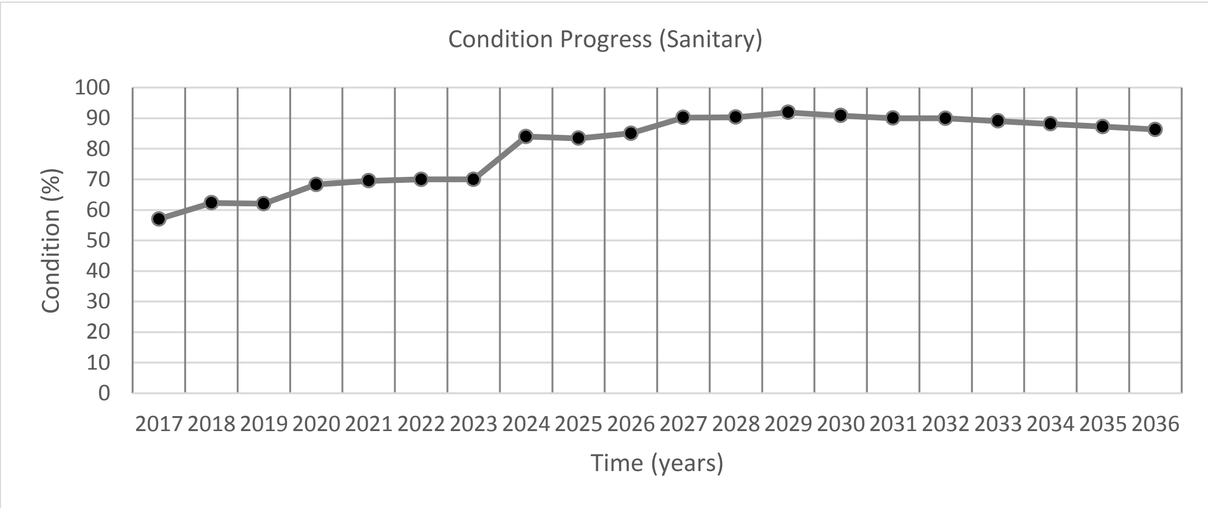
Progression of Value for Sidewalk (Value -based)



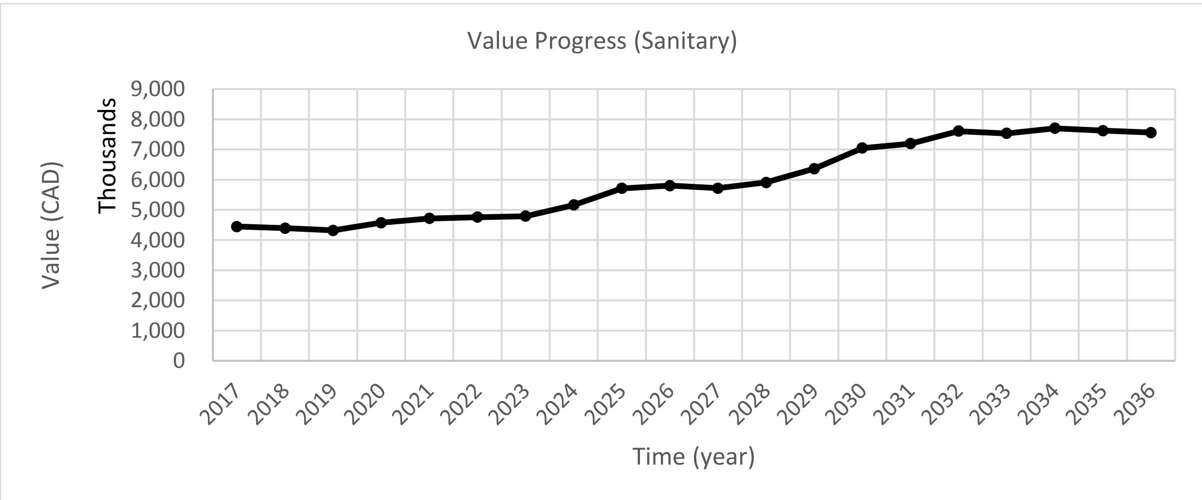
For sanitary pipes the condition-based approach shows a trend that gradually increases from approximately 60% to about 90%. Additionally, the change of value also shows a steady increase until at the end of analysis period with a range of 4,200,000 CAD and 8,000,000 CAD.

As a result, the highest condition is 91.93% in 2029, followed by 90.87% in 2030 and 90.31% in 2028. On the contrary, the lowest is 57.00% in 2017, followed by 62.01% in 2019 and 62.30% in 2018. However, the highest value is 7,705,082 CAD in 2034, followed by 7,626,594 CAD in 2035, and 7,607,828 CAD in 2032. On the other hand, the lowest is 4,316,938 CAD in 2019, followed by 4,392,228 CAD in 2018 and 4,573,271 CAD in 2020.

Progression of Condition for Sanitary (Condition-based)



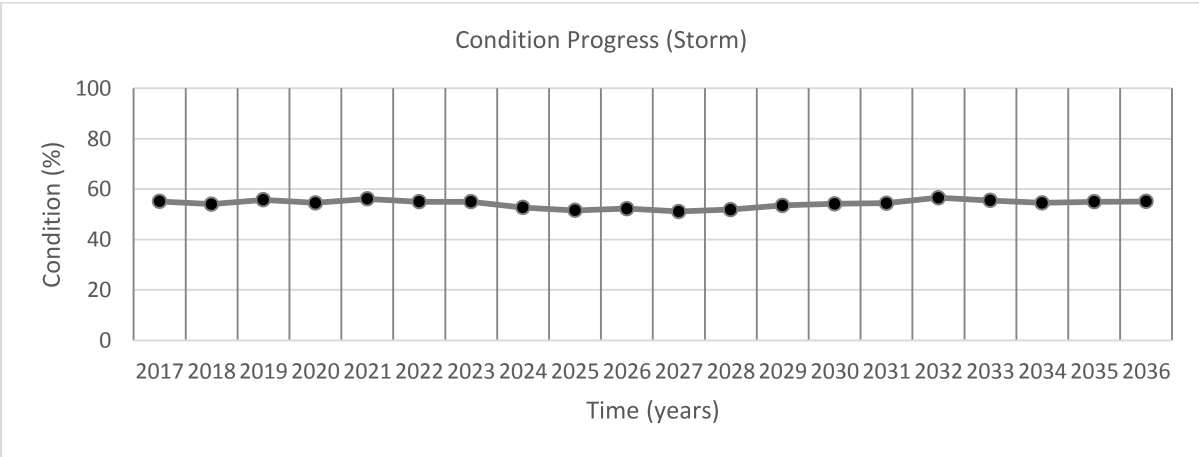
Progression of Value for Sanitary (Value -based)



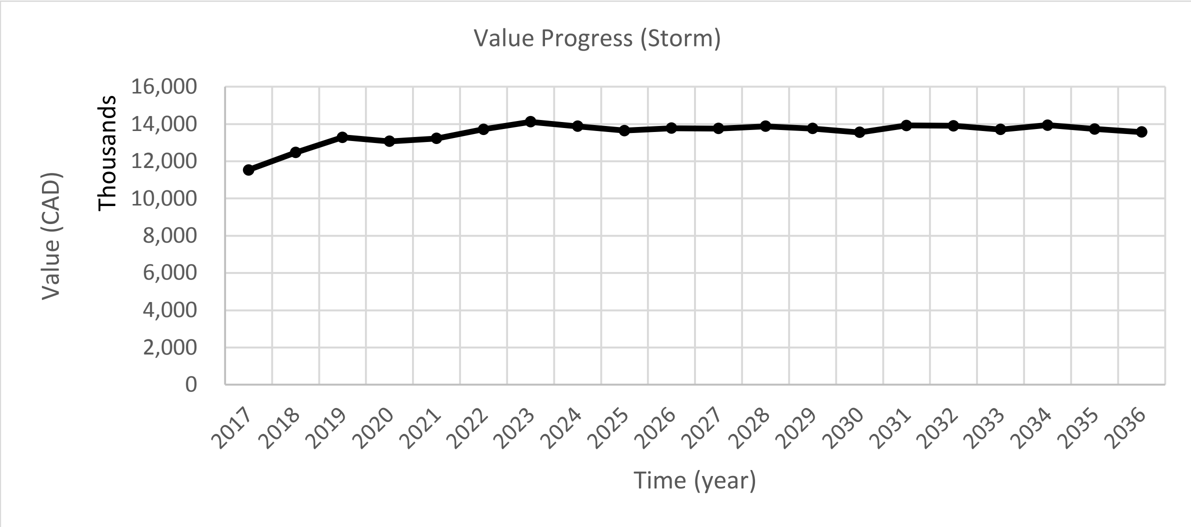
For storm pipes, the condition-based approach showed a near constant trend that remains from approximately 55% to about 60%. The value-based approach showed consistent increases until at the final analysis time with a range of 11,000,000 CAD and 14,000,000 CAD.

The results show that the highest condition is 56.57% in 2032, followed by 56.14% in 2021 and 55.76% in 2019. On the contrary, the lowest is 51.15% in 2027, followed by 51.54% in 2025 and 51.91% in 2028. In the meantime, the highest value is 14,118,536 CAD in 2023, followed by 13,936,796 CD in 2034, and 13,920,197 CAD in 2031. On the other hand, the lowest is 11,531,957 CAD in 2017, followed by 12,474,290 CAD in 2018 and 13,069,704 CAD in 2020.

Progression of Condition for Storm (Condition-based)



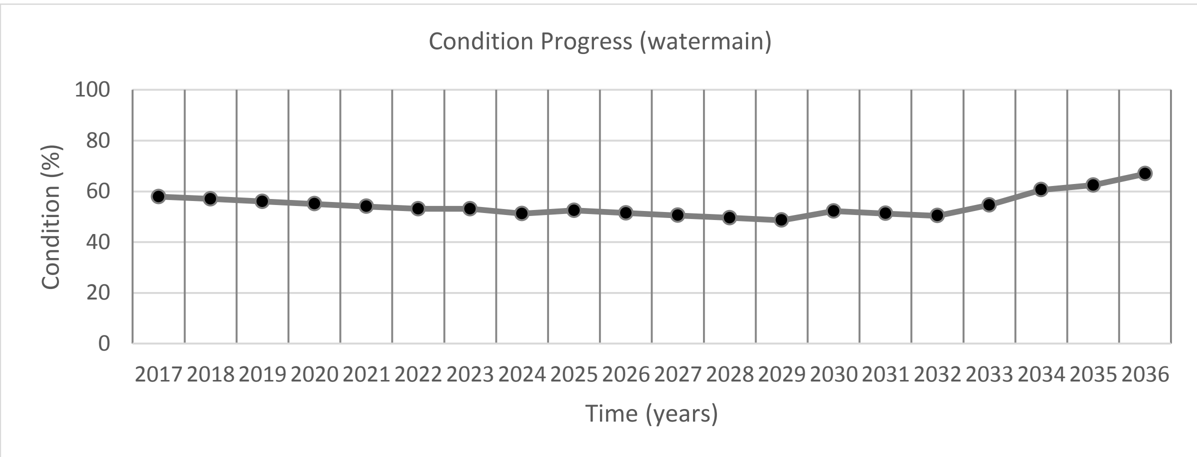
Progression of Value for Storm (Value -based)



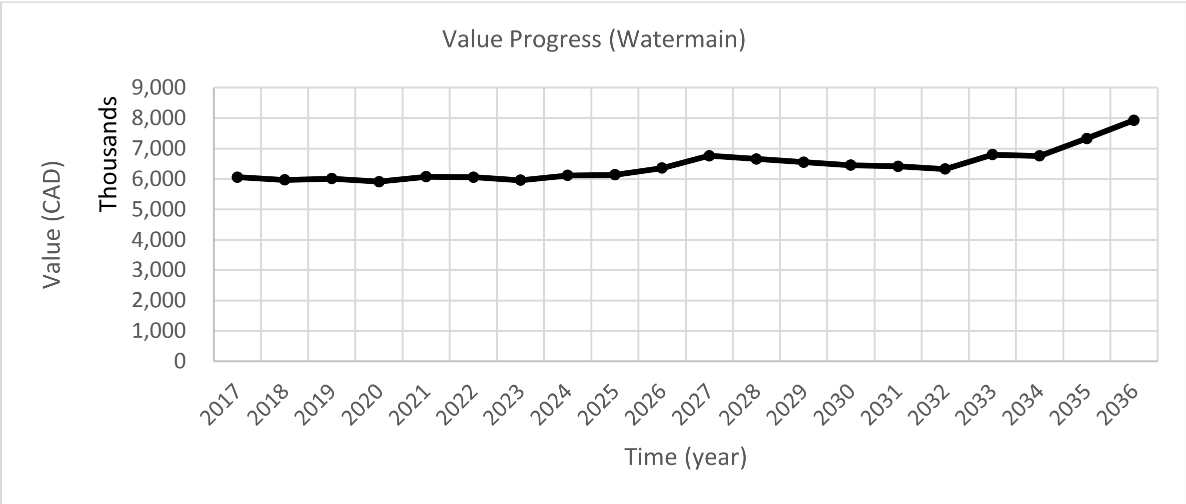
For water mains the condition-based approach shows a drop from nearly 60% to about 50%. For the value-approach the value remains almost constant until 2032 with a very light fluctuation but, it rises constantly during rest of the time with a range of 6,000,000 CAD and 8,000,000 CAD.

As a result, the highest condition is 66.88% in 2036, followed by 62.45% in 2035 and 60.59% in 2034. On the contrary, the lowest is 48.64% in 2029, followed by 49.53% in 2028 and 50.38% in 2032. The highest value is 7,929,381 CAD in 2036, followed by 7,330,344 CAD in 2035, and 6,799,010 CAD in 2033. On the other hand, the lowest is 5,912,520 CAD in 2020, followed by 5,967,461 CAD in 2018 and 5,959,969 CAD in 2023.

Progression of Condition for Water main (Condition-based)



Progression of Value for Water main (Value -based)


Value Progress (Watermain)
Value (CAD)
Thousands
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
Time (year)