An integrated approach for municipal infrastructure interventions management

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ABSTRACT

One of the main concerns of municipal infrastructure management is the long term estimation of capabilities to deliver adequate levels of service while restricted by limited resources. Modeling of such problems requires dynamic optimization techniques to identify an optimal set of decision variables related to interventions at different planning periods and scattered across the territory. Although some municipalities count on such strategic analysis tools, most do not consider measures of coordination resulting in repeated service disruptions and premature infrastructures damage. This thesis develops an integral approach to support decision making by connecting all levels of planning through the adaptation of commercial software from forestry. As such it proposes a hierarchical approach in which results from strategic plans are translated into tactical projects leading to operation programs of works. Such a connection requires the allocation of projects and interventions to private contractors by considering their qualifications and quoted cost within an optimization approach. It was found that commercial forestry software *REMSOFT* is suitable for hierarchical analysis of municipal infrastructure. Results from the software demonstrated the potential to identify the most optimal set of decisions and then to advance or defer them to form projects along corridors or zones. Projects were then allocated to private contractors by considering their capabilities and quoted cost. A case study illustrates the proposed approach.

DEDICATION

To

My Parents for their support and encouragement throughout this journey.

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I would like to express my very deep gratitude to my research supervisor Dr. Luis Amador, for his patient guidance, his willingness to give his time so generously and his constructive critiques during this research work.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AO	Allocation Optimizer
APCC	Australian Procurement and Construction Council
AM	Asset Management
BCA	Benefit-Cost Analysis
BSI	British Standards Institution
CCTV	Closed-Circuit Television
CERF	Civil Engineering Research Foundation
CIEAM	Centre for Integrated Engineering Asset Management
CIS	Civil Infrastructure Systems
DOT	Department of Transportation
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
IBC	Incremental Benefit Cost
LCA	Life Cycle Analysis
LCCA	Life-Cycle Cost Analysis
LRS	Linear Referencing System
LOS	Level-Of-Service
NRC	National Research Council Canada
OECD	Organization for Economic Cooperation and Development's
PCI	Pavement Condition Index
PCR	Pavement Condition Rating
PSI	Present Serviceability Index
VIR	Vehicle In Road

CHAPTER 1 INTRODUCTION

1.1 Background

Governments around the world face the challenging task of managing civil infrastructure with limited resources. This implies a need to identify the most cost-effective interventions to maintain and/or rehabilitate those infrastructures at the best timing. According to Vanier (2001), many municipalities focus on corrective actions (worst first approach) when a problem occurs instead of having an integrated program capable of taking into account preventive maintenance needs of their assets in an effective and efficient way over their life cycle.

Three levels of planning (strategic, tactical and operational) are commonly used to optimize allocation of treatment. They follow a hierarchical approach that starts with a long term planning that estimates overall networks need on an annual basis. The primary objective of long term planning is to identify budget needs capable of achieving target levels of service typically through an optimal mix of assets that effectively meet users' needs and therefore the organisation's strategic goals. Hence, strategies identify feasibility and prioritize the objectives of the organization. This plan also allows organization to establish long-term direction of the most important activities to be conducted. Long term planning is also known as strategic planning and looks at a period beyond 5 years, more commonly 10 to 20 years.

Strategic planning is a difficult task addressed by municipalities because they experience resources shrinkage constraint combined with conflicting political and administrative agendas, as well as rapidly changing targets. (Vanier and Rahman 2004)

Tactical planning is used to schedule project based on a political cycle. Tactical planning looks at the time horizon between two to five years. Project timing is coordinated to avoid user cost and utility cuts. In theory, tactical planning serves as a connection between a strategic plan and operational programs of work. In practice however, tactical plans are often disconnected from the strategic plans.

Operational plans identify the order in which intervention on assets is scheduled on a yearly basis along with the corresponding resources allocation. (Halfawy, 2008)

According to the literature (Amador and Magnuson, 2011), operational plans are often based on engineers' and managers' criteria yet, most of the time there is a disconnection between operational and tactical plans, and even further to strategic planning. Breaking down tactical plans into operational programs of work is a less explored field (Infra-guide 2003). Such a connection requires several practical considerations related to managing resources needed to undertake interventions. The creation of programs of works entails the consideration of operational constraints from the perspective of both the government and the contractor.

In order to transfer long term needs into programs of work, there is a need for the coordination of maintenance and rehabilitation works across different infrastructure types. (Amador and Magnuson, 2011).

1.2 Problem Statement

There is a lack of an integrated decision making support approach capable of planning maintenance and rehabilitation of municipal infrastructure at different time horizons.

1.3 Research Objectives and Tasks

1.3.1 Main Objective

To propose an approach that connects all levels of municipal infrastructure planning capable of supporting the allocation of maintenance and rehabilitation works.

1.3.2 Specific Objectives

Specific objectives of this thesis are to:

(1) Propose an approach capable of supporting the decision making process for allocating maintenance and rehabilitation works in the long, medium and short terms.

(2) Identify and adapt a commercial software suitable to support such decision making processes in the long, medium and short terms.

(3) Test the approach through a case study.

1.4 Scope and Limitations

This research is limited to roads, water mains and sewers (sanitary and storm) for a municipality due to availability of data for the case study presented later. Municipal infrastructures are spatially distributed among zones. The research uses a case study to demonstrate the applicability in practice. The data for the case study comes from the urban municipality of Kindersley in Saskatchewan. It was assumed that all interventions are given to external contractors.

1.5 Research Significance

This research makes the following contributions:

1. It proposes a method to connect all levels of planning through a decision-making support system.
2. It identifies a commercial decision making support tool that will help planners and engineers to conduct an optimal allocation of resources for maintenance and rehabilitation of municipal infrastructure.
3. It tests the applicability of such tool.

1.6 Organization of the Thesis

This thesis is presented in seven chapters as follows. Chapter 1 defines the problem and presents the objectives of the research and its scope and limitations. Chapter 2 contains a review of concepts related to the methods used by others and highlights the limitations and missing elements from current methods. Chapter 3 explains the methodology. Chapter 4 includes the testing and contains the strategic planning perspective. Chapter 5 continues with the testing and addresses the tactical planning portion. Chapter 6 finalizes the testing through the operational allocation of intervention works. Chapter 7 presents the conclusions and suggests future research work.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter introduces the foundations of modern infrastructure asset management as applicable to municipal assets. It reviews its historical evolution and three commonly accepted levels of planning from a manager's perspective: strategic, tactical and operational. This literature review is centered on pavements and underground pipes for water mains, sewers and storm drainage. The chapter concludes with a summary of findings that demonstrates how these three levels of planning are disconnected from a decision making support tool perspective and hence provides the main justification for the research conducted in this thesis.

2.2 Historical evolution of infrastructure management

Infrastructure asset management started in the late 1950s with an experiment conducted by the American Association of State Highway Officials (AASHO) to identify the correlation between pavement life subject to projected loads and its structural designs (FHWA, 2011). A design method that considered pavement performance across time was created. Pavements were fixed based on a worst first approach until the 1970's (Geiger 2005).

In 1974, New Zealand adopted the Local Government Act which demanded an annual plan to be produced by each council. This annual plan had to include performance measures, financial systems and policies connected and in harmony with yearly objectives (Howard, R. J., 2001). This was the first formal precursor of what would become infrastructure management. During the 1980's the World Bank developed the Highway Design Manual that also contained principles of road management related to the decision making process for the optimal selection of interventions from a long term perspective (Finn, 1998).

In 1993, in a context of aging infrastructures which were critical to the economy, asset management started to soar in Australia with the adoption of Accounting Standard 27. In September 1996, the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA) implemented the concept of asset management in the United States through a series of workshops (TAM 2002). Asset management became widely used around the world after the year 2000 with the publication of the International Manual of Asset Management (Stalebrink and Gifford, 2002). In 2005, the FHWA, AASHTO, and the National Cooperative Highway Research Program (NCHRP) sponsored an international study of transportation asset management experiences in Australia, Canada, England, and New Zealand. The study outlined asset management best practices outside the United States. It was found that all of these countries have a transportation asset management program that integrates at least one of the 10 classes of assets. (Geiger et al. 2005).

The following section provides details of the three common levels of planning (Figure 2.1) associated with infrastructure management. It is important to bear in mind that the vast majority of studies and decision support tools belong to the strategic analysis sphere. Just very recently research has been conducted on tactical coordination of interventions and there is an absence of tools that integrate all three levels of planning.

Figure 2-1. Schematic illustration of the levels of planning

2.2.1 Strategic planning

Strategic planning is a process that defines and estimates funding needs according to target levels of service for many periods of time (Figure 2-1). (Infra-guide, 2003). Strategic analysis has become a common interest of governments facing the daunting task of renewing their aging infrastructure. (Kleiner and Rajani, 1999; Sægrov, 2006;

Selvakumar and Tafuri, 2012; Vanier, 2001). Strategic analysis uses dynamic linear programming to identify the optimal allocation of interventions to infrastructures (Kuhn and Madanat, 2006, Arif and Bayraktar 2012). According to Cardoso et al., (2012) strategic asset management relies on knowledge about the expected condition of assets over time. The network-level infrastructure management problem involves selecting and scheduling maintenance, repair, and rehabilitation activities on networks of infrastructure facilities so as to maintain the level of service provided by the network in a cost-effective manner.

In New Zealand, and in England, local authorities are in charge of identifying mean levels of required funding for asset management at a local level which will then be used at larger scale by central and regional government for long term planning. (Geiger et al., 2005) (Arif and Bayraktar, 2012).

Many researchers had concentrated their attention in developing tools and case studies for the strategic analysis. Case studies had been developed for Portugal (Golabi and Pereira, 2003), Australia (Lawrence, 2002), Canada (Li, 2009), US (Zegras et al., 2004), Costa Rica (Amador and Mrawira, 2009), Japan (Kawanai, 2014).

Because of its very own nature, several limitations can be found for strategic planning: it is incapable of considering spatial location of asset and utility cut (AASHTO, 2011a). Utility cut consists of prematurely intervening an existing infrastructure in order to have access to another asset in need of rehabilitation; this explains one of the major downsides of this level of planning and shows the need to address the practical ineffectiveness of uncoordinated programs of works.

Strategic analysis doesn’t take into account the frontier effect and the time flexibility for advancing or deferring interventions (Ugarelli et al , 2010). In fact, the frontier effect is the ability for one to see the impact of his decision in the long term. This become critical when the time horizon is close to the decision making time.

Another limitation of the strategic is the time flexibility which is a capability of the decision maker to delay or advance an intervention already scheduled at the strategic level in order to coordinate interventions.

2.2.2 Tactical Planning: Coordination of Interventions

Tactical analysis is a process that organizes interventions to be undertaken on a medium term, typically 3 to 5 years (Figure 2-1). It was first proposed by Infra-guide in 2003 after realizing the need to organize interventions of municipal infrastructure to avoid utility cuts and reduce the impact of public works on users. Coordination of interventions is an important element for the improvement of infrastructure management systems (Faghih-Imani, 2013). It requires reallocating interventions originally planned at the strategic level. The coordination of interventions at the asset level for different infrastructures is the last step of a four-step asset management planning tool suggested by Hafskjold (2010).

Recent studies had concentrated their efforts on getting an analytical way to carry out the tactical analysis and obtain a coordinated program of interventions. (Amador and Magnusson 2011; Islam and Moselhi 2012). Halfawy (2008) pointed out the need to implement coordination in order to maximize economic and social benefits of infrastructure management. Nafi and Kleiner (2009) examined the coordination of actions in the planning of adjacent water and road systems. It was found that infrastructure adjacency and economies of scale had a great impact on budgeting and planning of pipe renewal and maintenance. On the other hand, Li et al. (2011) introduced a new grouping model useful for coordination of pipeline and road programs. Although these studies have mentioned coordination in their efforts, there is a paucity of literature providing a complete and practical framework for coordination of maintenance and rehabilitation actions.

The result of tactical analysis is used by managers to schedule work and prepare tenders by grouping proximal interventions together. This approach is neither applicable for the long term, nor for the short term planning because it lacks the capability to analyze the long term impact of decision and the short term usage of resources.

2.2.3 Operational Planning: Allocation of Interventions to Contractors

Operational planning is used to organize and schedule infrastructure projects within one planning period (Figure 2-1). It is used by municipal or government engineers to award tenders to contractors or to decide if the works should be done in-house. From the tactical plan, all interventions scheduled to be undertaken in the current year are selected and advertised through a tendering process to contractors. Allocation of interventions to contractors considers the quoted cost and the operational capabilities of the contractor, and the expected quality or maintenance and rehabilitation to be attained (Yvrande-billon 2006, Manelli and Vincent 1995, Bajari et al. 2003). Various researchers such as (Brook 1993); Holt et al. (1995a) have pointed out that apart from the acceptance of the lowest tender price, there should be a trade-off between cost, time and quality in the final selection of contractor. According to Latham (1994) the "choice of consultant or contractor should be made on a value for money basis, with proper weighting of criteria for skill, experience and previous performance, rather than automatically accepting the lowest cost in all cases". Contractor capacity, preparedness and historical record could also be considered. But unfortunately, in public projects, the tender price tends to dominate over other factors in tender assessment (Kumaraswamy 1996). One reason is that offering projects on the basis of the lowest tender can dispel suspicions of corruption (Fong and Choi 2000).

Some research has been conducted to develop optimal decision tools to aid in the selection of contractors and allocation of projects to contractors (Islam and Moselhi, 2012). However, to date there is not research on an approach that connects such decision making tools to tactical and strategic decision making tools.

2.3 Components of Infrastructure Management for Municipal Assets

Any infrastructure management system requires several components that are interconnected: first indicators for level of service are defined, then an assessment that estimates the current values of such indicators (being the most common condition) is done; then all the current and past information is stored in a database, including available interventions, the technical criteria for their applicability, cost and effectiveness. The information on the indicators allows us to build performance models to predict future values of the service indicators across time. A decision making process uses current levels of service and estimation of future values of service indicators to allocate interventions to achieve target levels of service. Table 3-1 shows the main components of infrastructure management.

Table 2-1. Component of infrastructure Management

Component of infrastructure Management	Definition	Main features	References
Service Indicators	Social and economic goals of the community: safety, customer satisfaction, quality, quantity, capacity, reliability, responsiveness, environmental acceptability, cost, and availability	Asset performance index	Infra-guide (2002)
		Survey to acquire users sensitivities about the condition of an existing asset	Ugarelli et al. (2010) Alegre et al. (2000); Matos et al. (2003); Sægrov (2006).
		Risk tolerance of a community	
		Financial considerations	
Assessment	Investigation of the physical state and the capacity or utilization of the performance indicators of an asset.	Pavement condition: assessment of pavement distress and the calculation and aggregation of data from surface and structural into average values per road segments.	Ugarelli et al. (2010)
		Sewers : Closed-Circuit Television (CCTV) inspections to classify pipes according to their condition	Al Barqawi and Zayed (2006)
		Water mains : artificial neural network and analytical hierarchy process	
		Linear Referencing System (LRS) as a way to store information on an integrated infrastructure management system	Ferreira and Duarte (2005)
Database	Data from current levels of service and history of applied interventions kept to support development of performance curves and estimation of interventions effectiveness	Integrated database using a centralized or distributed system	Elmasri and Navathe (1997).
		Maintenance of an information system that tracks assets and keeps a tab on costs and reliability under the management system.	U.S. EPA (2003)
		Coordinated and the integrated database	
Performance Modeling	used to link system operation to asset to attain specific corporate objectives	Key performance indicators for each asset class establish and measure performance link key performance indicators to a desired LOS	Shahata and Zayed (2010)
		using collected data inventories, condition assessment and performance evaluation	Infra-guide (2003)
Decision making process (Optimization and Prioritization)	Identifying decision variables and providing an optimal solution	Developing a sound renewal plan which includes economic analysis, coordination with growth needs regulations, and risk management	Vanier (2001); Halfawy et al.,(2006) Lee & Deighton, (1995); Quintero et al., (2003); Ferreira & Duarte (2005); Halfawy (2008)
		Benefit-cost analysis, lifecycle cost analysis, annual optimization and multi-period optimization (dynamic).	
		Usage of software tools focusing on infrastructure management processes	
	Consist of identifying a network investment strategies by maximizing total network benefits or minimize network costs and simultaneously evaluating entire network while considering constraints.	Multi-year optimization strives to minimize the present value of the total cost over the planning horizon.	Hwang and Masud (1979).
		Single-objective optimization problem, which can be solved to obtain the optimal result	

2.4 Typical Interventions for Municipal Infrastructures

This section summarizes some of the most frequently applied interventions for the preservation, maintenance or restoration of pavements and pipes used for water mains and sewers (sanitary and storm). There are seven types of interventions outlined in the following table: crack sealing, micro-surfacing, patching, resurfacing, reconstruction, pipe lining, and pipe replacement.

Table 2-2. Definition of typical intervention

Typical intervention	**Definition**	**References**
Crack-sealing	A placement of materials into developed cracks to prevent the intrusion of water and incompressible materials into cracks.	California Department of Transportation, (2003).
Microsurfacing	A surface-maintenance treatment where a polymer-modified emulsion mixture composed of graded aggregates, mineral fillers, water and additives is used to reduce water infiltration, provide skid resistance, improve aesthetics, and correct rutting, raveling, minor profile irregularities and damages caused by weathering.	California Department of Transportation (2003).
Patching	Realized in two different ways: dig-out or overlay. The first method consists of removing the defective pavement up until the bottom of the base layer and replacing it with by a new one. The second method is an overlay of the defective area with a suitable material to renew the surface; in such a case, the defective area is sealed and stabilized.	Washington State Department of Transportation (2013)
Resurfacing	A process of installing a new layer of asphalt (generally one and a half to two inches) over the existing pavement (also known as overlaying). Sometimes, resurfacing can be accompanied by milling, partially removing the damaged cracked portion of the existing layer before overlaying.	Washington State Department of Transportation (2013)
Reconstruction	The replacement of the entire existing pavement structure by the placement of an equivalent or an increased-strength pavement structure	FHWA, Office of Asset Management (2005)
Pipe lining	A treatment intended to protect the internal surface of pipes from deteriorating, to restore the structural integrity and/or hydraulic capacity or to prevent infiltration of groundwater and exfiltration of sewage	Sidney water (2013)
Pipe replacement	The installation of new pipes when the existing are defective and at the end of their life cycle.	Sidney water (2013)

2.5 Review of selected infrastructure management software

There are many different infrastructure management support tools available for infrastructure management. In this thesis, the focus was on those following a multiyear optimization process such as Deighton, Vemax, Riva modeling and *REMSOFT*.

Deighton dTIMS™ is a set of tools for implementing a custom database and custom analysis models. The software allows the user to create and maintain an inventory integrating any and all types of data (roads, bridges, signs, etc.) in one place and relate them together using location referencing. In addition, the software enables the user to perform life cycle cost analysis (LCCA) and determine the best maintenance or rehabilitation action subject to budget constraints. The analysis model is based on the incremental benefit cost analysis. The software also has the capacity to deal with projects that have already been scheduled throughout the analysis period.
(Smadi O. 2004)(Small et al. 2000)

VEMAX is an asset management for multiyear optimization done through the Performance Prediction Technology (PPT) models and fully integrated Maintenance Management System (MMS). The probabilistic model, called Strategic PPT, applies principles of semi-Markovian chain theory and is used at a network level. This model is used as a management support tool in optimizing and funneling down budgets targeted towards an overall strategic goal. The deterministic model called PPT Tactical is used for subnetwork analysis and focuses on the optimization of specific maintenance treatments including structural and non-structural rehabilitation, microsurfacing, full seals, etc. for a given network size. Both models are driven by the existing road condition data. (Lazic, Z. 2003).

RIVA (Real-time Asset Valuation Analysis) is a web based client-server application that provides capabilities for long-term asset management planning in a 10 to 200 year planning horizon. RIVA has a modelling capability that can be used for asset valuation, determination of deferred maintenance, condition assessment, estimating remaining service life, and prioritization of maintenance and rehabilitation (M&R) processes. Deterministic and probabilistic models can be created using the Formula Builder tool. (Halfawy et al., 2006)

REMSOFT is used to define the optimum level, type and schedule of expenditures over a long-term planning period in order to maximize financial return on investment for different forestry projects. (Walters et al., 1999). The goal is to identify the best combination of prescriptions and treatment regimes. The approach is to build a Woodstock model optimizing financial returns rather than harvest volume in order to evaluate different strategies and identify whether the short, mid and long-term net present value of the investment can be improved. This is done by gathering the most recent management plan, identifying and including costs and harvest revenues in the analysis. Then the software creates a treatment regimen considering a balance between timber quality and quantity for a greatest financial return. It builds optional treatments with a corresponding cost and change in volume and value; this is followed by setting operability criteria (ages and forest types) and finally applying the treatment, when and where it provides a financial gain.

The Woodstock model is a package of *REMSOFT* that elects what treatments to apply when and where to apply them based on treatment cost and associated impacts on current and future revenues. Moreover, using the stand-level factors, such as type and age class, the Woodstock model considered forest–level factors that influence harvest timing and therefore the economic viability of the investment (Remsoft Inc. 2006).

Then Stanley, *REMSOFT* 's block scheduling software, is used to produce treatment schedules and maps that demonstrates the location and timing of each treatment. It results with a confirmation of the capacity of Woodstock model analysis to demonstrate that significant gains in both harvest volumes and net revenues can be realized through incremental forest investment.

REMSOFT Allocation Optimizer performs a prioritization analysis. It determines the optimal preservation and rehabilitation strategies based on life cycle costs analysis. Projects are prioritized at the network level by giving prevalence to the cost/benefit ratio and cost effectiveness methods. The allocation problem is described in the AO Guide (2007) as "the amount of wood product X from forest origin Y allocated to destination Z in period W". (Remsoft Inc., 2006). The following Table 2-3 summarizes the software characteristics.

Table 2-3. Software characteristics

Softwares	Main field application	Capabilities	Country	References
Deighton dTIMS™ Software	Civil infrastructure management	Spatial database Performance models Hierarchical integration Multi-objective Re-optimization capability Operational Constraints Life cycle cost analysis Reporting capabilities Economic analysis	USA, Canada	Smadi O. (2004)
VEMAX	Asset management consulting	Performance models Hierarchical integration Multi-objective Operational Constraints	Australia	Lazic, Z. (2003)
RIVA MODELING	Asset management	Spatial database Performance models Hierarchical integration Multi-objective Re-optimization capability Operational Constraints Asset valuation, condition assessment, Estimation of remaining service life	Canada	Halfawy, R. et al.(2006)
REMSOFT	Forestry : optimization Planning Adapted to Civil infrastructure management in this thesis	Spatial database Performance models Hierarchical integration Multi-objective Re-optimization capability Operational Constraints	Canada	Remsoft Inc. (2006)

2.6 Literature main findings

There have been many studies for strategic analysis (Australian Procurement and Construction Council (APCC) (2001); R&V Anderson & Associates (2002); Ugarelli et al.(2007); Graham et al. (2007) etc. ; some for tactical (National Research Council (2003) ; Halfawy (2008); Hafskjold (2010); Li et al. (2011) and others operational planning (Yvrande-billon (2006); Manelli and Vincent (1995) ; Bajari et al. (2003). However, there is a lack of an approach capable of supporting an integrated planning process for infrastructure management. Alone, strategic, tactical and operational planning themselves have several drawbacks, as shown in Table 2-4.

The literature from current decision support systems found that the ideal system will have the capabilities of storing infrastructure information in a spatial fashion, and that two main systems drive the allocation of interventions, one is the capability to anticipate future states (condition or service) and the other is the ability to optimize resources in order to attain desired objectives. From this perspective it was found that *REMSOFT* had the potential to become a support tool capable of integrating all levels of planning. However, such tool was developed for forestry management and needs to be adapted to municipal asset management. A brief explanation of the most common interventions was provided as they would be extensively used during the adaptation of *REMSOFT* to municipal infrastructures.

Table 2-4. Level of planning and drawbacks

Level of planning	Summary of the approach	Results	Issues	Reference
Strategic planning	Primal and Dual using: Condition equation Cost equation Dynamic interdependent: Transfer function equation	Identification of: preferred scenario required funding achievable LOS	Frontier effect Spatial location Utility cut Advance/defer	Amador and Afghari (2011). Ugarelli et al (2010). Hudson et al. (1997), NCHRP (2002), Krugler et al. (2006)
Tactical analysis	Spatial Coordination Advance / defer interventions Treatment compatibility	Reallocation of intervention	No allocation of interventions to contractors Suboptimal distribution	Amador and Magnuson (2011) Li et al. (2011)
Operational Plans	Scheduling within a year Operational limits In house or external contractor Expected quality to be attained	Schedule of works Allocation to contractors	Municipal capacity Contractor's capacity Zonal contracts Other restrictions	Manelli and Vincent (1995) Bajari et al. (2003) Latham (1994)

As seen, each level takes care of different needs and together some of the issues could be solved. This thesis identifies and adapts a decision making tool capable of supporting hierarchical planning for municipal infrastructure.

CHAPTER 3 METHODOLOGY

3.1 Introduction

This chapter presents the proposed methodology. As seen in Figure 3-1, the methodology is subdivided into four main steps: Identification, formulation implementation and testing. The identification of the required approach comes from the findings of the literature review from which it is evident that although all 3-levels of planning are employed in some degree by municipalities, there is a lack of a system capable of not only supporting decision at each level but of transferring optimal results among them.

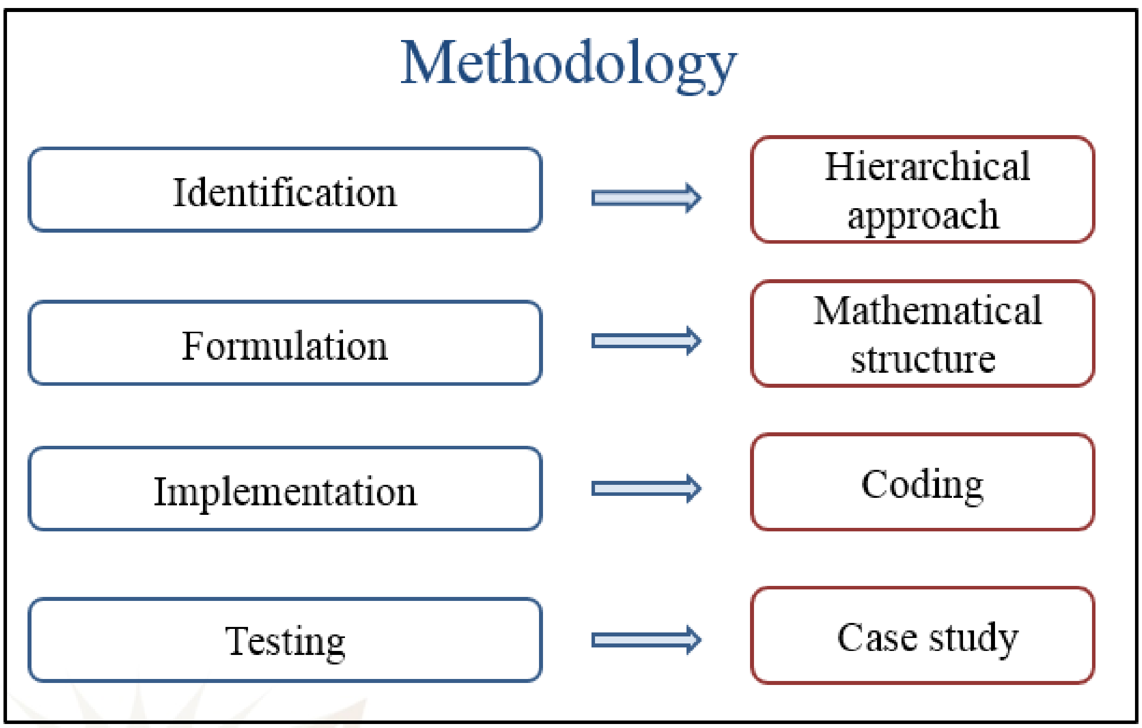


Figure 3-1. Methodological framework

The formulation provides the reader with a mathematical characterisation of the three decision support tools. The implementation explains the tasks required to adapt a forestry software to be able to model municipal infrastructures asset management process.

The testing was left to Chapters 4, 5 and 6 for the case study.

3.2 Identification

The long term needs from the strategic analysis consideration of spatial proximity of similar interventions scheduled on either the same period or a few periods away could be coordinated resulting in a reallocation of decisions from strategic analysis into tactical planning as illustrated in Figure 3-2

In a similar manner, coordinated interventions create packages of interventions that require to be allocated to contractors moving them into programs of works at the operational level.

For each stage of the hierarchical approach, a mathematical formulation is associated and a component of the package Remsoft is used to analyse that section. The following figure illustrates the relationship between each problem, the hierarchical level it belongs to, the mathematical formulation (except the tactical which was not possible to identify) and the correspondent component of the software being used for the analysis.

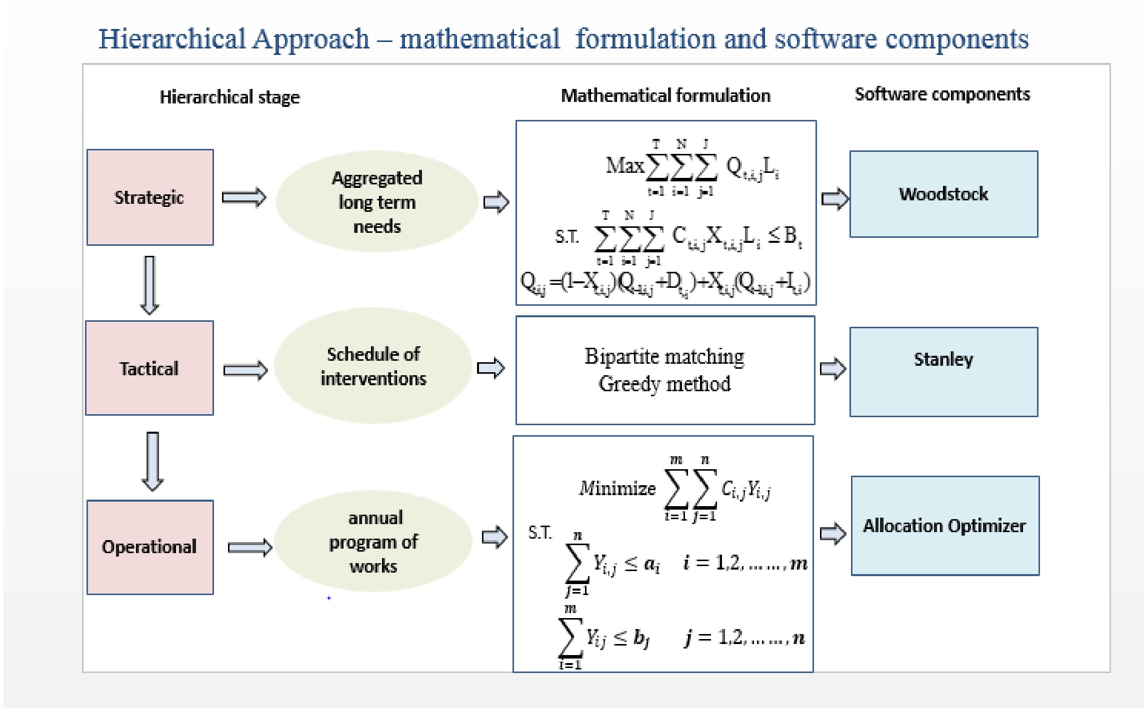


Figure 3-2. Hierarchical approach-mathematical formulation and software Components

3.3 Mathematical Formulation

This section documents the algorithms or mechanism behind the required capabilities to support the hierarchical decision making suggested in the previous section. These capabilities are used to select a suitable commercial software for municipal infrastructure management.

3.3.1 Formulation at strategic level

The goal of the strategic analysis is to identify aggregated measures of long term needs such as the required annual budget for maintenance and rehabilitation of municipal infrastructures or the progression of annual condition for a road and pipe network.

A binary decision variable $X_{t,i,j}$ is used to decide which segment of asset (road or pipe) (i) will be treated on a given period (t) with an intervention (j). This is the only output of the software. This variable characterizes the sets of assets at different periods of time (some of them receiving treatments others not) that give the most cost effective solution based on the objectives, in this case to maximize the level of service represented by a condition indicator.

A transfer function (equation 1) keeps track of the condition of individual segments across time updating their value according to their Improvement (I) or deterioration (D).

$Q_{t,i,j}$ represents the state of the asset; this condition is represented by a Visual Inspection Rating (VIR) that ranges from zero to ten and is related to the International Roughness Index (IRI). A pipe condition index (PCI) was developed over the basis of pipe age, and it ranges from zero to one hundred for pipes with age between 100 year and zero years (correspondingly). The values of both VIR and PCI were updated on an annual basis depending on whether an improvement ($I_{t,i}$) was applied or otherwise the asset deteriorated ($D_{t,i}$). These Variables are inputs in Woodstock.

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).

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

$$X_{t,i,j} \in (0,1) \quad (2)$$

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

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

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

Where:

$Q_{t,i,j}$ = Condition of asset i on time t when treatment (j) is applied

Lower boundary ≤ $Q_{t,i,j}$ ≤ Upper boundary

L_i = Length (size) of the asset (segment) i

$D_{t,i}$ = Deterioration on asset i condition on time t

$I_{t,i}$ = Improvement on asset i condition on time t

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

B_t = Budget for each planning period t.

3.3.2 Formulation at tactical level

In the medium term, results from the strategic analysis should be coordinated. The coordination of interventions looks at several candidate segments resulting from the mixed-integer-linear-programming model and advances or defers the application of possible interventions. In addition to timing, it considers their spatial proximity, intervention compatibility trying to prevent premature utility cuts. Figure 3-3 illustrates the algorithms for this level;

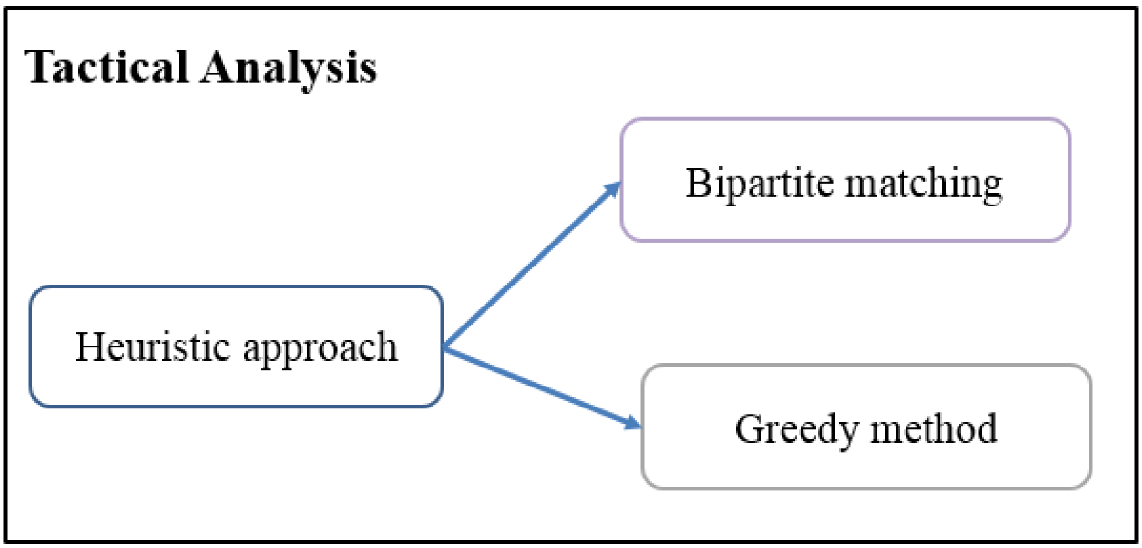


Figure 3-3. Algorithm for tactical analysis

As seen in Figure 3-3, it follows a heuristic approach (Feneukess et al. 2011), based on bipartite matching to create possible combinations of nearby assets (space and time of intervention) and Greedy method to identify the possible optimal schedule (Walters et al. 1999). A bipartite matching occurs when every element from a group of two sets of partitioned data are connected to each other. In that case, the maximal matching happens if no more edges can be added without increasing the degree of one node to higher than two (Buss and Yianilos, 1995). In the case of this research (figure 3-4), the matching is done between the nearby assets and the asset being scheduled on the appropriate timeframe. The following figure illustrates a flow chart for the bipartite matching.

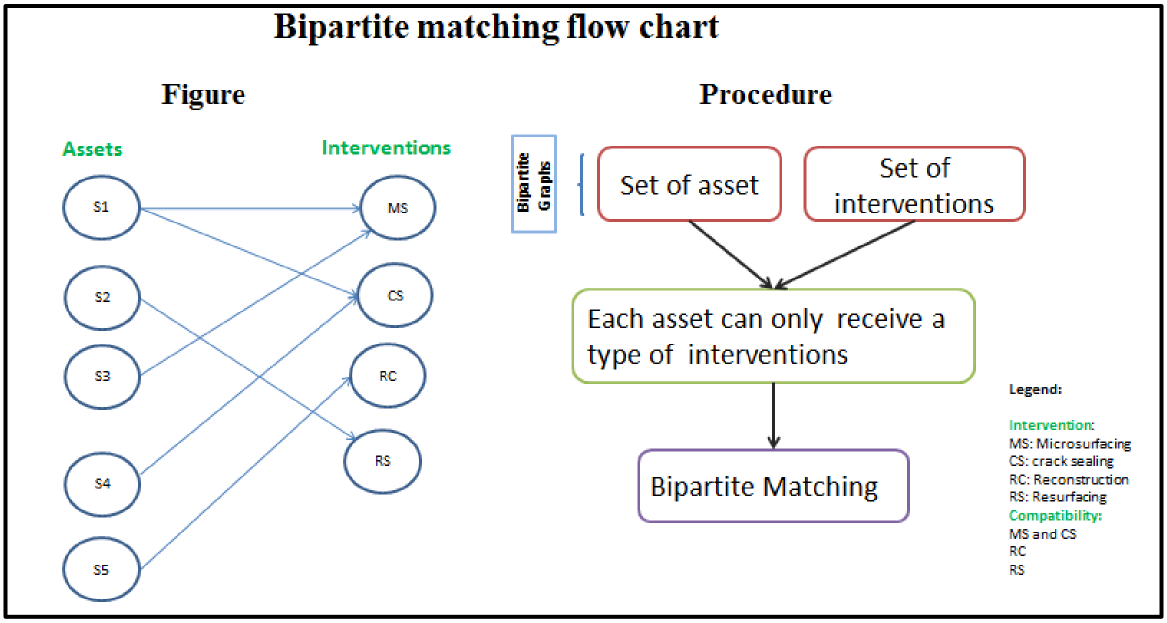


Figure 3-4. Bipartite Matching flow chart

A greedy algorithm is a simple iterative process looking for the best next solution to complex, multi-step problems. It selects and keeps the obvious solution until the result of the following iteration states a better one. (Uber et al., 2004) Greedy algorithms have five components:

1. A candidate set, from which a solution is created
2. A selection function, which chooses the best candidate to be added to the solution

3. A feasibility function, that is used to determine if a candidate can be used to contribute to a solution
4. An objective function, which assigns a value to a solution, or a partial solution,
5. A solution function, which will indicate when a complete solution is discovered

The following figure is a Greedy method flow chart.

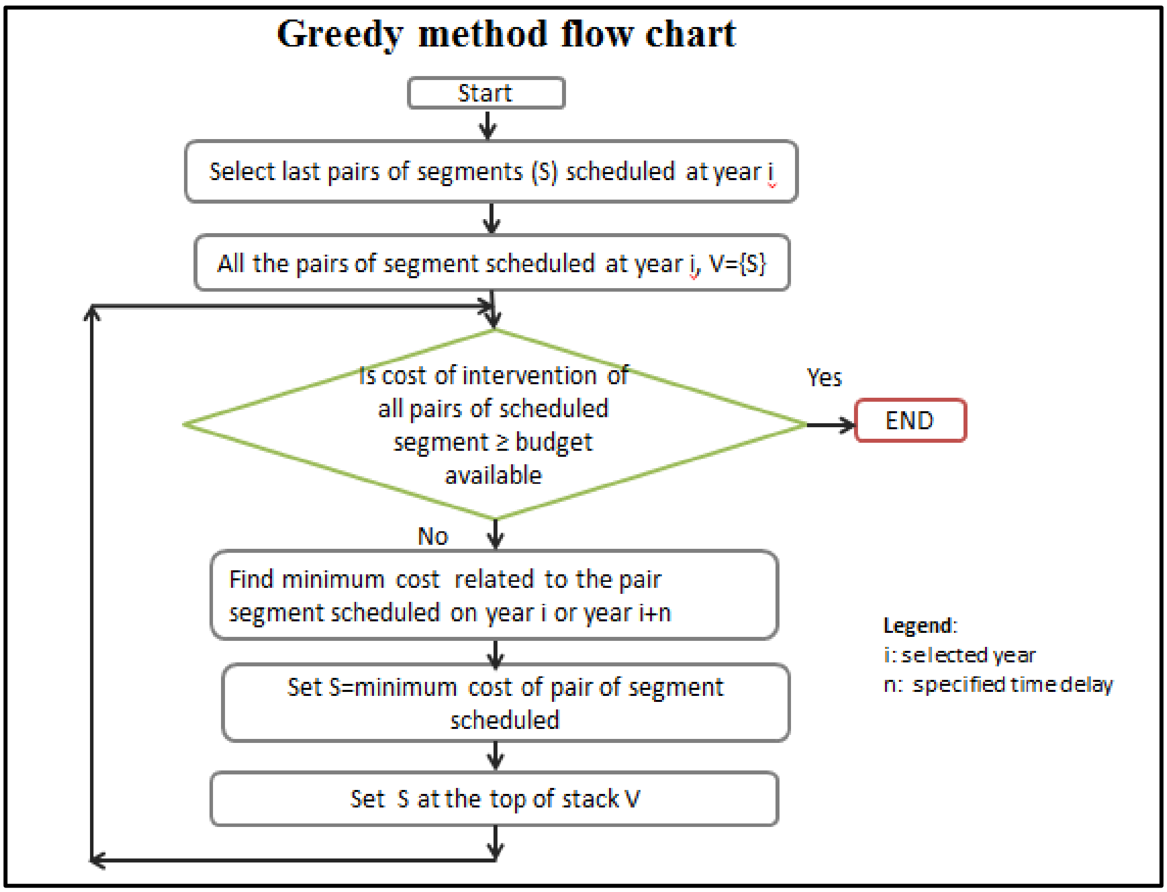


Figure 3-5. Greedy method flow chart

Figure 3-6 illustrates the logic behind these algorithms as applied to the coordination of interventions for 4 segments (S1, S2, S3, and S4) of roads originally scheduled during the strategic planning.

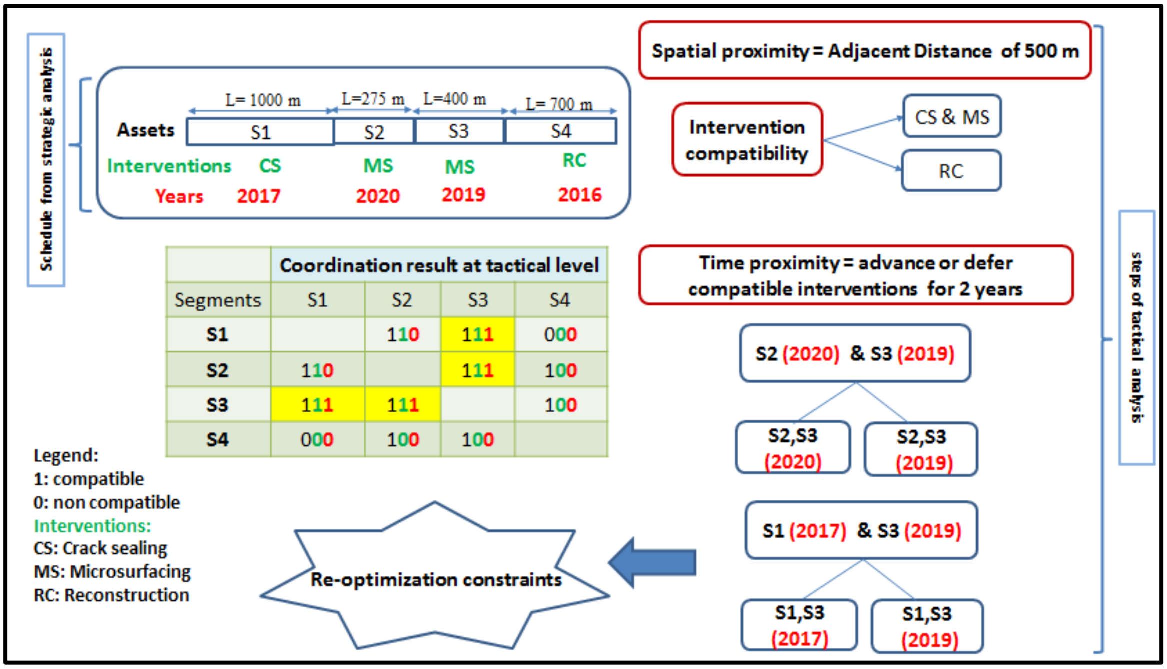


Figure 3-6. Application of tactical mathematical framework

An adjacent distance (AD) is used to create a table of adjacencies that contains the distance between any two segments on the spatial inventory. The bipartite matching proceeds by assembling a table that contains a binary variable for each of the relevant criteria to be fulfilled. A value of one is given to any pair of segments whose adjacent distance is smaller than the spatial proximity (500m). Similarly a table of time proximity based on the period of time intervention had been scheduled is built and in the bipartite matching table a value of one is given to those segments that fulfill the time-proximity criteria. Finally treatment compatibility is also considered; in a similar fashion as before a value of one is used in the bipartite matching to identify those pairs of segments with compatible interventions. In the example at hands one can see that segments one (S1) and segment three (S3), as well as S2 and S3, and finally segments S1 and S3, satisfy all three criteria and hence become candidates. Which pairs of segments to choose follows a greedy method in which the original objectives are used to guide the search. That is potential paired segments will be chosen based on those that return improvement in the sense of the optimization.

3.3.3 Formulation at the operational level

The support tool should take the coordinated interventions from the previous step and allocate them to construction contractors. The mathematical formulation follows the classical one used for a distribution problem: each source has a limited amount of goods available each year and each of a number of destinations has a required annual demand of such goods. An array of cost exists and these are the cost to ship one unit of a single type of good from each of the possibly many sources or origin to each of the potentially many or destinations. In the case of the infrastructures problem, the sources are the contractors with limited construction capability (amount of good) and the destinations are the urban zones or regions within a municipality in which annual construction works (for infrastructure) need to be done and awarded (allocated) to a contractor.

The objective is to distribute construction project for all areas to contractors at the least cost. The problem requires the following notation on an annual basis:

i,m: the indices for contractors (m in total)

j,n: the indices for regions (n in total)

a_i : the maximum construction capacity of contractor i

b_j : the total amount of works required at zone j

$C_{i,j}$: construction cost of one unit of intervention (i.e., square meter of rehabilitated road, linear meter of pipe replacement) with contractor i in zone j.

$Y_{i,j}$: Amount of works awarded to contractor i on region j.

The formulation for this problem is:

$$Minimize \sum_{\boldsymbol{i=1}}^{\boldsymbol{m}} \sum_{\boldsymbol{j=1}}^{\boldsymbol{n}} C_{i,j} Y_{i,j}$$

Subject to

$$\sum_{\boldsymbol{j=1}}^{\boldsymbol{n}} Y_{i,j} \leq \boldsymbol{a_i} \quad \boldsymbol{i = 1, 2, \ldots \ldots, m}$$

For each contractor i, the total amount of works given across region j ($\sum_{j=1}^{m} Y_{i,j}$) to such contractor cannot exceed contractor capacity a_i

$$\sum_{\boldsymbol{i=1}}^{\boldsymbol{m}} Y_{i,j} \leq \boldsymbol{b_j} \qquad \boldsymbol{j = 1, 2, \ldots \ldots, n}$$

The total amount of works allocated to contractors in region j cannot exceed the total amount of work b_j required in that zone.

For example:

$\mathbf{Y_{11} + Y_{21} + Y_{31} + \ldots\ldots\ldots \leq b_1}$

This equation correspond to the works allocated to contractors, 1,2,3, be equal or less to works demanded by region j

$$Y_{i,j} > 0 \qquad i = 1, 2, \ldots\ldots, n$$

$$j = 1, 2, \ldots\ldots, n$$

The distribution problem for this study can be summarized as following:
Zones in a town or city and regions within a province by classification, are commonly aimed for the awarding of maintenance contracts. There are different types of interventions or treatments available for infrastructure's maintenance and rehabilitation. A link between the two aforementioned elements is also possible and used to record the allocation of interventions per zone (products per origin). Interventions are awarded to contractors (destinations). Finally, cost (or productivity) must be added to allow the optimal decision making based on choices that truly minimize transportation cost (or maximizes profits if a price is to be charged for the goods) while achieving other desired goals (i.e., quality).

In this case, it represents the cost factor of each contractor. Depending on their location, some contractors will be cheaper than others. If the only factor that matters is transportation cost, then one expects that local contractors would have less expensive bids in general as compared to those contractors based at far locations (external), mostly as they have temporary relocation cost added into their overall cost structure. However, other elements such as technology (machine productivity) may make external contractors (even if not locals) more competitive above certain levels of scale. Based on each contractor area of expertise and quoted cost, interventions in different zones of the town are allocated to them. The following figure illustrates an example of an allocation of intervention diagram.

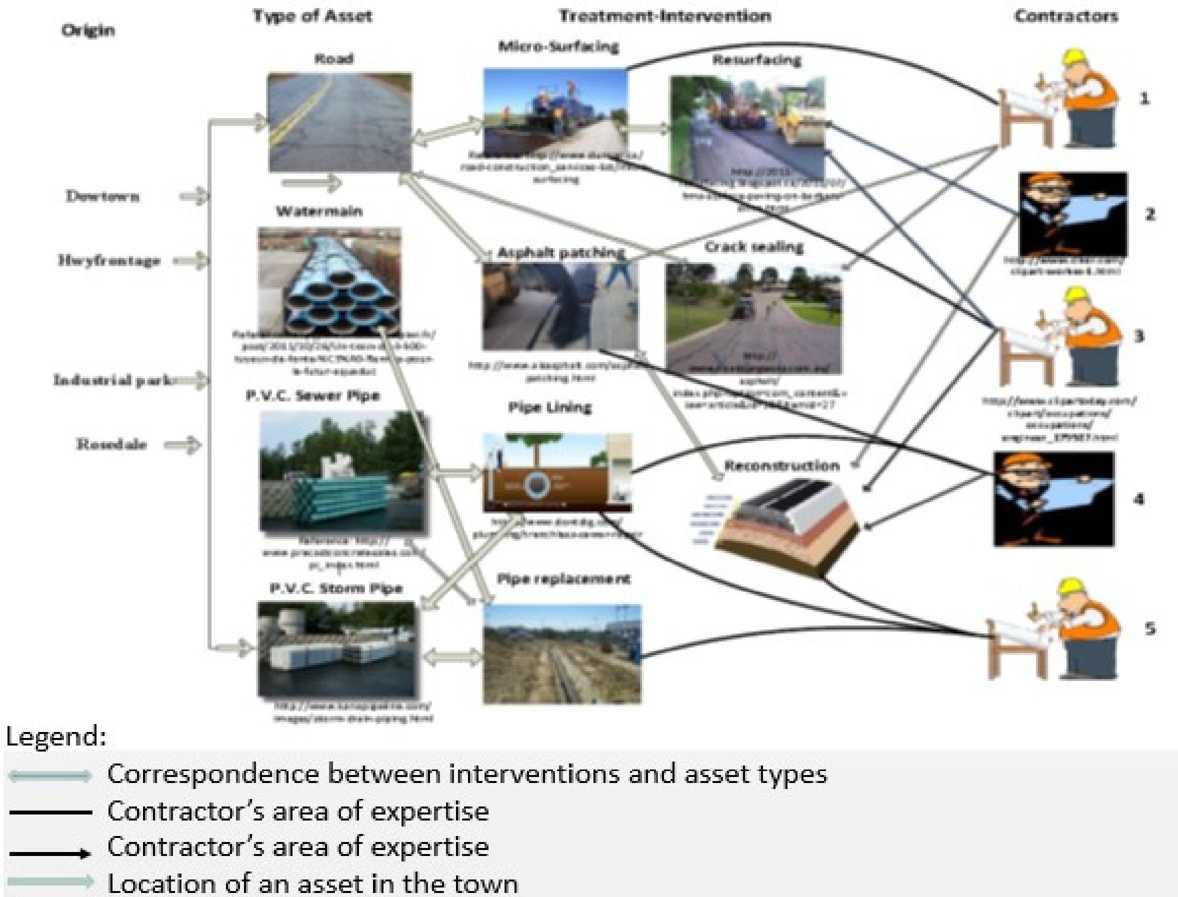


Figure 3-7. Urban infrastructures intervention allocation diagram

3.4 Implementation

The process previously described requires the identification of a software capable of conducting analysis at 3 levels of planning on an integrated hierarchical fashion. Figure 3-6 shows the implementation procedure.

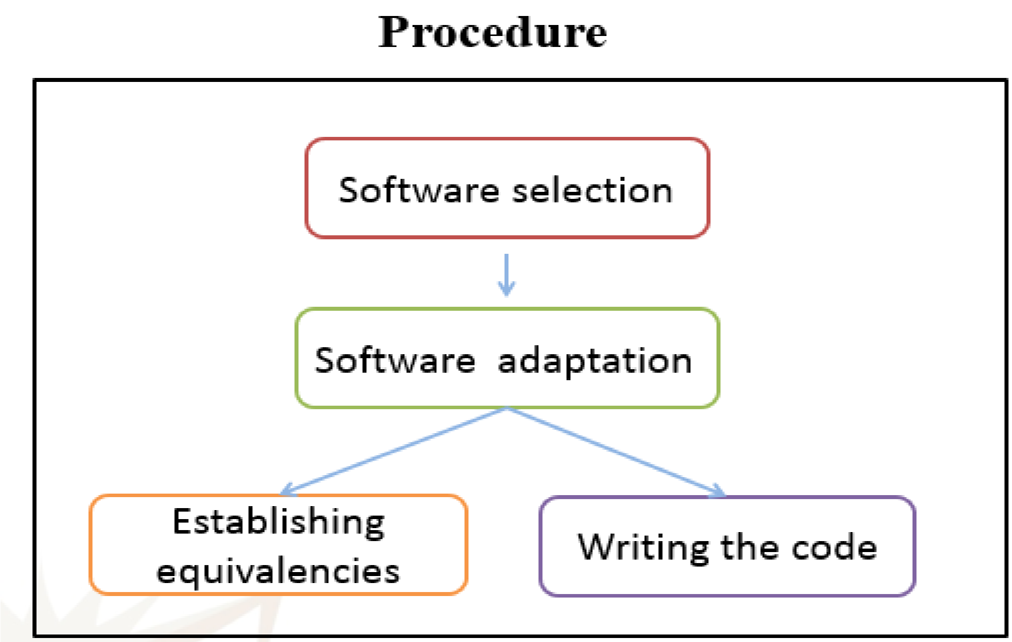


Figure 3-8. Implementation procedure diagram

The selected software needs to be adapted to the municipal infrastructures management system; it requires establishing equivalencies between both systems and writing codes.

3.4.1 Software selection

Having understood the mechanism behind an integrated approach provided us with valuable insights of those elements important to consider for the selection of the most adequate software in order to have an integrated hierarchical tool capable of supporting strategic, tactical and operational planning for municipal infrastructure. The elements found are the capability to have a spatial database, a performance model, a hierarchical integration, the ability to deal with multiple objectives, to re-optimize the results by adding additional considerations, and to be able to allocate projects to contractors in a maintenance management system. The following section presents a comparison of commercially available software from such perspective. These four softwares were selected among the well-known in the industry. Some main criteria in the hierarchical approach were selected and it was identified whether the criteria was applicable at either only one level of planning or at multiple levels simultaneously. Based on the occurrence of a criterion at the level of planning it is given a weighted importance which varies from one to three. When the criterion is completely fulfilled, it is worth a score of 1 and when it is partially fulfilled, the score is 0.5 and finally in the absence of the criteria capabilities in a software, the given score is 0. The analysis was based on information from the manuals and user guides. Table 3-1 illustrates the comparison of the different softwares.

Table 3-1. Comparison of infrastructures software

			A	B	A x B
Software	**Criteria**	**S=strategic, T=tactical, O=operational**	**Importance Weight**	**Score**	**Weight Scored**
DEIGHTON	Spatial database	T	1	1	1
dTIMS™	Performance models	S,T	2	0.5	1
	Hierarchical integration	S,T,O	3	0.5	1.5
	Multi-objective	S,T,O	3	1	3
	Re-optimization capability	T, O	2	0.5	1
	Operational Constraints	O	1	1	1
			Total		**8.5**
VEMAX	Spatial database	T	**1**	0	0
	Performance models	S,T	**2**	1	2
	Hierarchical integration	S,T,O	**3**	0.5	1.5
	Multi-objective	S,T,O	**3**	0.5	1.5
	Re-optimization capability	T, O	**2**	0	0
	Operational Constraints	O	**1**	1	1
			Total		**6**
RIVA	Spatial database	T	1	0	0
MODELING	Performance models	S,T	2	0.5	1
	Hierarchical integration	S,T,O	3	0.5	1.5
	Multi-objective	S,T,O	3	1	3
	Re-optimization capability	T, O	2	0	0
	Operational Constraints	O	1	0	0
			Total		**5.5**
REMSOFT	Spatial database	T	1	1	1
	Performance models	S,T	2	0.5	1
	Hierarchical integration	S,T,O	3	1	3
	Multi-objective	S,T,O	3	1	3
	Re-optimization capability	T, O	2	1	2
	Operational Constraints	O	1	1	1
			Total		**11**

3.4.2 Software adaptation

Since the commercial software selected (REMSOFT) was made for forestry, there is a need to establish equivalencies and write codes for three levels of planning (strategic, tactical and operational).

At the strategic level, the equivalencies established between forestry and civil infrastructure are illustrated in figure 3-7.

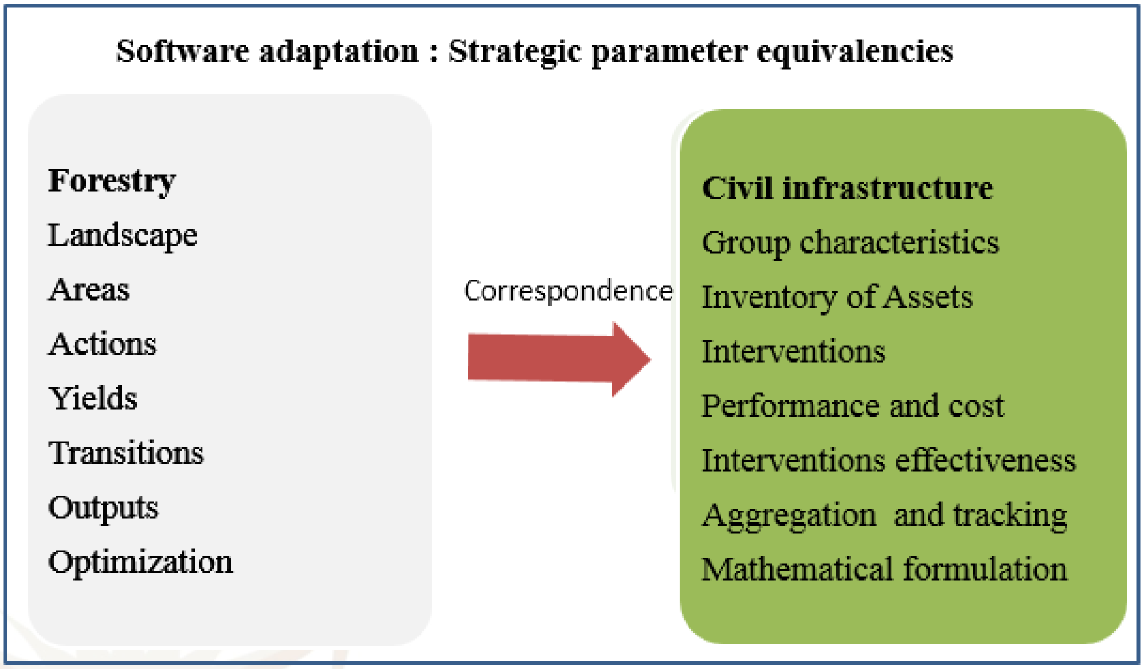


Figure 3-9. Strategic parameter equivalency

As seen on figure 3-7, at the strategic level, there are several modules used to define group characteristics, inventory of asset, interventions, performance and cost, intervention effectiveness, aggregation and tracking and finally mathematical formulation.

At the tactical level, additional constraints were added to represent space and time proximity for the purpose of creating group of assets. These additional elements are shown in the following table.

Table 3-2 Tactical parameter equivalency

Tactical parameter equivalencies

Forestry	Civil infrastructure
Period to block	Time range to consider
Max deviations	Flexibility to consider additional years if the other conditions are met
Auto-generate starting random number	Initial location of asset used to create blocks
Objectives	Goals for original objectives
Adjacent distance	Proximity between assets
Minimum block size	Minimum criteria to merge two assets together in a block
Target block size	Desired size of block of assets merge together
Proximal Distance	Distance between two separate assets that could be merge together
Greenup delay	Advancing or deferral of interventions
Maximum opening size	Proximal blocks being merged and programed in the same planning period.
Allow multi-period openings	Allows Stanley to do openings across time, adding flexibility

At the operational level, more elements were added to express the constraints related to allocation of intervention to contractors based on their capacity and quoted price and also the municipality capacity. The following table 3-3 is a summary of the parameter mentioned above.

Table 3-3 Operational parameter equivalency

Operational parameter equivalencies

Forestry	Civil Infrastructure
Origin	Type of asset
Product	Type of intervention
Destination	Contractor to which intervention will be given
Table	Variable for cost of transportation (cost factor of each contractor)
Volume	Contractor's capacity

After the parameter equivalencies completed, codes were written; at this stage, coding was required to allow the software to capture the input data for civil infrastructure parameters. The following table summarizes the built-in commands used in the model.

Table 3-4 Codes and their definition

Codes	Definition
Action	Definition of intervention
Invent	Type of intervention
Destination	Summation
Areas	Length/size
Yields	Performance curves
Source	Characteristics of origin
Landscape	Asset characteristics
Target	Characteristics of destination
Age	At a given age
Length	Last period of time
***@YLD**	At a given performance value
?	Any applicable characteristic
_TH1	Consider filter 1 to group
***Y**	Define time dependent variable
***YC**	Define time dependent composed variable that is multiplied by a specific characteristic
Times	Multiply
Operable	Applicable when
aggregate	Aggregate, union
Theme	Characteristic
Output	Aggregation

For the case study, different commands were used. The system commands are highlighted in green. User defined commands are in red and generally used to define objects of interest; anything that appears underlined represents a combination of specific attributes on an indexing system used by the software, in such context a question mark represents that the line of commands is applicable all possible attributes at that index.

For instance, the word (*Action) defines an intervention and (*Operable) means applicable to. For example road ? ? ? ? ? indicates that the command is applicable to roads only but the other characteristics are irrelevant. Figure 3-8 shows sample codes for the module Actions.

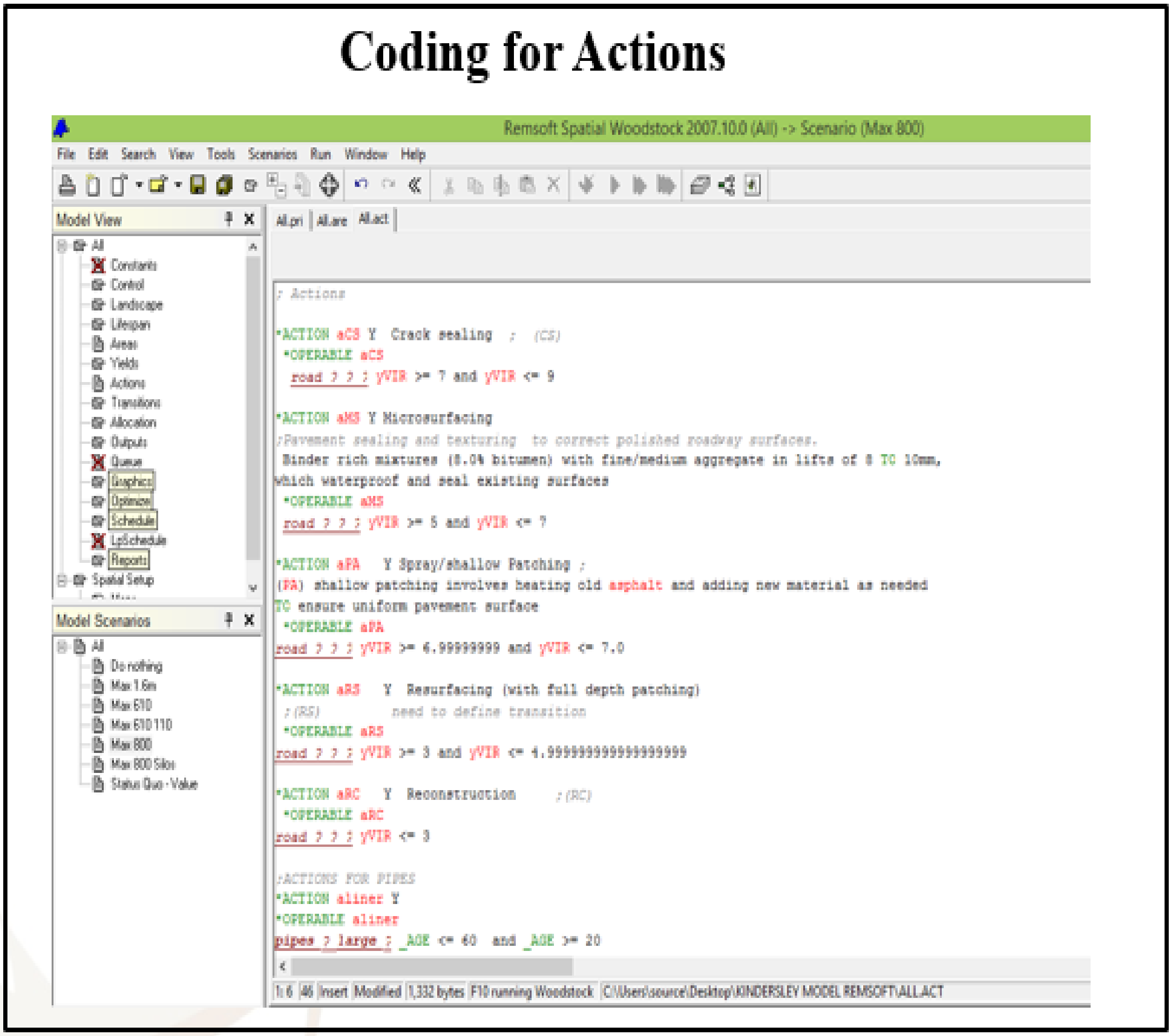


Figure 3-10. Coding for the module Actions

CHAPTER 4 STRATEGIC PLANNING: DETERMINING LONG TERM NEEDS

4.1 Introduction

The aim of this chapter is to test the applicability of the component *Woodstock* of the package *REMSOFT* for strategic planning. The chapter explains the role of different variables in the strategic planning of municipal interventions. It is divided in two sections: the first one presents the set up for the generalities of long term planning and the variables used in strategic analysis, the second one presents the results of a case study that will be used throughout this thesis and moves from strategic to tactical to operational planning.

4.2 Creating the strategic model

A strategic analysis requires an inventory of existing segments of infrastructure that is typically spatially stored in a shapefile and are categorized based on relevant characteristics (called themes). Strategic analysis also needs a performance curve which for *REMSOFT* is deterministic (stored in the yields section). In addition it necessitates the identification of possible interventions (called actions) their cost and range of applicability. Another module of the Woodstock management software takes care of identifying what happens after an action has begun (an intervention). Finally there are two more modules important for the problem at hand; one for the outputs which are those elements that require to be kept track. The second one is the definition of optimal decision process which is given in the methodology section.

An important mention is the fact that, this case study is based on a previous research done by Amador and Magnusson (2011). The results from their research were used as inputs for my case study. The long term optimal decision problem and the coordination of intervention were partially developed there. The inventory of assets, the performance curves came from that paper. I rerun the analysis to adjust the results for my case study. I used only the results of the scenario called SILO with a budget of $800,000, rather Amador and Magnuson (2011) dedicated their efforts to compare several scenarios and find the optimal planning strategy for the mixture of resources among asset networks. This research adapted the model to make it fit with the objective of my research, and further explored the mechanisms behind the hierarchical connectivity at those three levels of planning. The parameters values for the coordination analysis were changed for the purpose of this analysis.

For the sake of the software adaptation and the test of its applicability at the strategic level within my case study, the following table recap the different modules used in forestry and their correspondence civil engineering.

Table 4-1 Adapting a forestry management system for municipal infrastructure

Module name in forestry	Correspondence to Municipal Infrastructure
Landscape	Definition of characteristics to group infrastructure
Areas	Inventory of Assets (summarized on Table 4-2)
Actions	Definition of interventions
Yields	Definition of performance and cost
Transitions	Definition of interventions effectiveness
Outputs	Definition of amounts to aggregate and keep track of.
Optimization	Definition of mathematical formulation

The codes behind each component are shown in the appendix of this thesis, and they appear in the same order as shown in table 4-1.

4.2.1 Inventory of asset

In this case study, a model for the Town of Kindersley containing about 68273 m^2 of gravel roads, 426,216 m^2 of asphalt roads, 48,900 linear meters of water mains and a similar amount of waste water and storm water pipes was used. Approximately 153,090 m^2 of roads was categorized as strong and 311,978 m^2 as weak, 64,970 m^2 of roads experience high traffic intensity (above 80,000 repetitions of Equivalent Single Axle Loads -ESAL- per year), 72,694 m^2 of pavements carry medium loads (40,000 < ESAL < 80,000) and the rest 305,729 m^2 experience light traffic intensity (less than 40,000 ESAL per year). The water mains, the sewer and storm pipe age vary from 0 to over 50 years old while the pavement age range from 0 to 10 years old (Amador and Magnuson, 2011).

Many pipes are now reaching 60 years of operation and this implies the need to establish a replacement program. The budget available for pavements is $610,000 and a fixed budget of $190,000 is available for water systems. The overall budget is around $800,000 with an allowance of +/- 5 % of the total budget. Table 4-2 contains the summary of these assets.

Table 4-2. Assets summary

ASSET TYPE(i)	PIPE SIZE (inches)	MATERIAL	PIPE AGE (year) / ROAD VIR	PIPE LENGTH (m) / ROAD AREA (m^2)
Pavement	N/A	Asphalt	7.5 to 10	319,981
Pavement	N/A	Asphalt	5 to 7.5	93,332
Pavement	N/A	Asphalt	2.5 to 5	16,792
Pavement	N/A	Asphalt	0 to 2.5	4,735
Pipe	Six	PVC	0 to 20	2,335
Pipe	Eight	PVC	0 to 20	2,336
Pipe	Ten	PVC	0 to 20	121.08
Pipe	Sixteen	PVC	0 to 20	194.75
Pipe	Six	PVC	20 to 30	8,252
Pipe	Eight	PVC	20 to 30	4,001
Pipe	Ten	PVC	20 to 30	784.45
Pipe	Twelve	PVC	20 to 30	179.64
Pipe	Sixteen	PVC	20 to 30	1,848
Pipe	Unknown	PVC	20 to 30	87.63
Pipe	Six	PVC	30 to 40	314.61
Pipe	Eight	PVC	30 to 40	9
Pipe	Six	Cast Iron	40 to 50	1,341
Pipe	Six	Cast Iron	over 50	5,683
Pipe	Eight	Cast Iron	over 50	2,054
Pipe	Unknown	Cast Iron	over 50	2.14
Pipe	Six	Steel	over 50	56.68
Pipe	Eight	Steel	over 50	102.36
Pipe	Six	Asbestos Cement	30 to 40	4,256
Pipe	Eight	Asbestos Cement	30 to 40	1,226
Pipe	Six	Asbestos Cement	40 to 50	8,794
Pipe	Eight	Asbestos Cement	40 to 50	1,305

4.2.2 Definition of intervention

Interventions correspond to the treatment to be done in order to rehabilitate or maintain assets. There are major and minor interventions. Major interventions are reconstruction of pavement and replacement of pipes. Crack sealing, microsurfacing and resurfacing are minor intervention for roads as is lining for pipes. The following summarizes those interventions, the cost related, their operational windows and the treatment effectiveness. The information was provided by the town of Kindersley.

Table 4-3. Treatments Definition

Asset type (i)	Treatment type (j)	Cost (C_{tij})	Operational Window		Treatment Effectiveness (I_{ti})
			Lower Boundary	Upper Boundary	
Pavements	Crack Sealing	0.33 $/m^2	VIR > 7	VIR < 9	2-3 years
	Microsurfacing	6.74$/ m^2	VIR > 5	VIR < 7	8 years
	Resurfacing	25 $/ m^2	VIR > 3	VIR < 5	6 to 12 years[1]
	Reconstruction	42 $/ m^2	VIR > 0	VIR < 3	As new
Pipes	Pipe Lining	500$/m medium, 2500$/m large	Age > 20 years	Age < 60 years	As new
	Pipe Replacement	210 $/m small,	Age > 50 years		As new
		1200$/m medium,			
		4000 $/m large			
Note: For weak pavements 6 and 8 years respectively for medium and low traffic intensity, for strong pavements 7, 9, 12 years respectively for high, medium and low traffic intensities VIR: Visual Inspection Ratio					

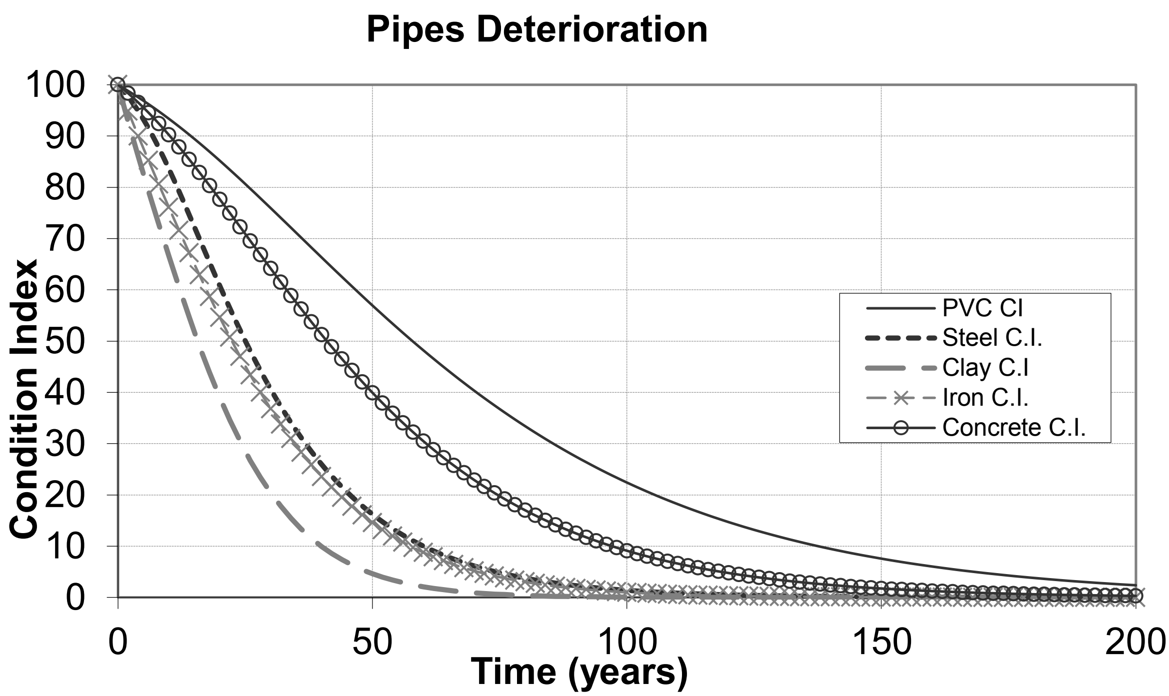
Source: Amador and Magnusson (2011)

4.2.3 Performance

Performance models were developed for roads and pipes. Performance curves provide a graphical representation of the expected service life of a pipeline or of pavement. Performance models are useful for planning as they allow the decision makers the ability to forecast future levels of condition for future planning periods. Performance curves were developed for international roughness and pipe condition.

Figure 4-1 shows the performance curves for pipe condition. A one-hundred index was used to model expected decay of the pipe condition, specific curves were developed for

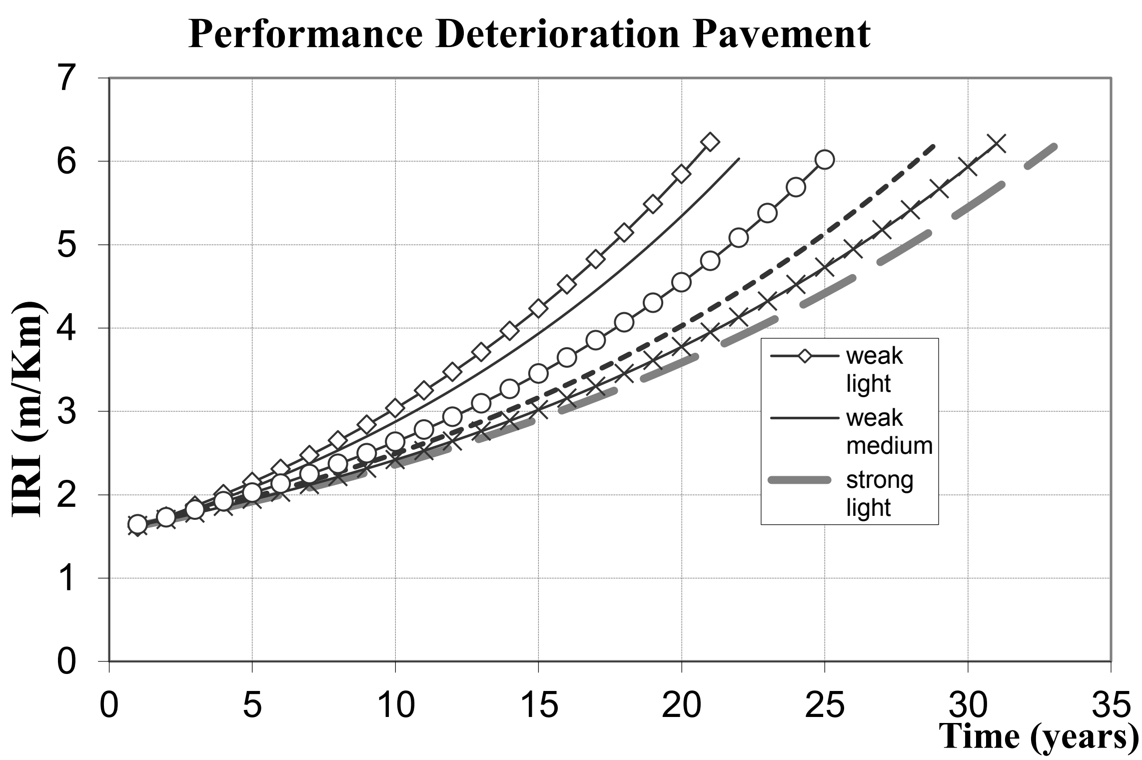
PVC, Steel, Clay, Iron and concrete pipes. The curves were based on expert criteria, and as such they should be revised in the future once information on actual (real) deterioration is collected.



Source: Amador and Willis (2012)

Figure 4-1. Pipe deterioration curves

A pavement performance is a measure of the in-service condition. Performance is often expressed in two ways: structural or functional performance. Structural performance could be expressed in terms of distress such as cracking and the functional performance is expressed in terms of serviceability, which in turn might be a function of distresses such as rutting and roughness. Pavement deterioration represents a negative change in condition of the pavement, i.e, an increase in distress. Curves for roughness were developed (figure 4-2). Roughness captured rutting and cracking together as a measure is longitudinal unevenness in the wheel path.



Source: Amador and Willis (2012)

Figure 4-2. Pavement deterioration curves

4.3 Results

Results can be outlined in two manners. The first way is using an aggregated indicator and the second way is by means of maps to illustrate the allocated intervention. A long term optimal decision analysis was used in this research, where pipes and roads shared a budget of $800,000 with the objectives to improve road condition and pipe age (correlated to condition through performance curves).

This section shows the aggregation of results based on the binary decision-making process implemented through a transfer function as explained before. As expected the software was able to handle the inputs and get the appropriate output in the form of allocation of interventions for several periods of time capable of improving the value of the objective while satisfying the constraint. Condition results followed expected time-trends of increasing VIR condition while decreasing IRI condition for roads, all this while not surpassing the budget restrictions of 800,000CAN$ (Figure 4-3)

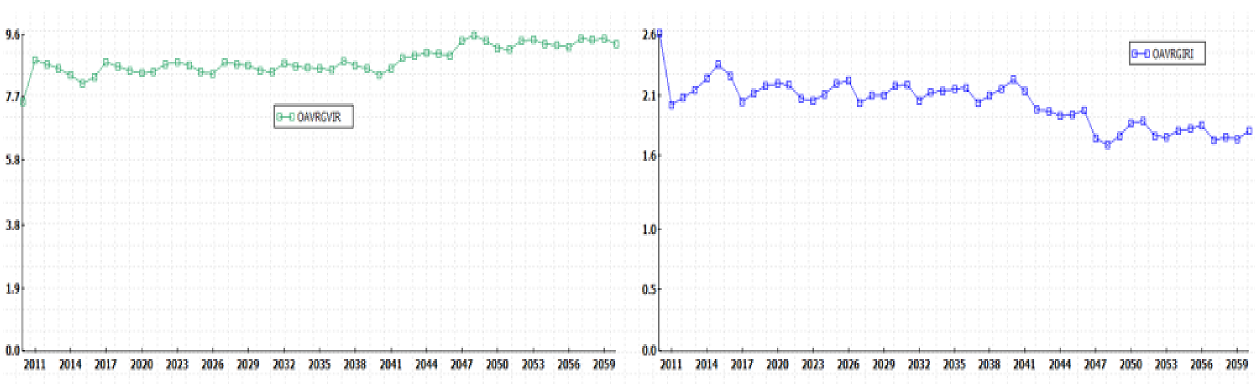


Figure 4-3. Pavement condition evolution across time (IRI and VIR)

For pipes, the bar diagram in Figure 4-4 illustrated the split of expenditure for pipes interventions per type of pipe (storm, sanitary, water main). Budget never surpasses the maximum allowed. As one can see, during some periods pipes received up to 799 434$ on replacements and lining and in other years they did not because the budget was used for road interventions as illustrated in figure 4-4

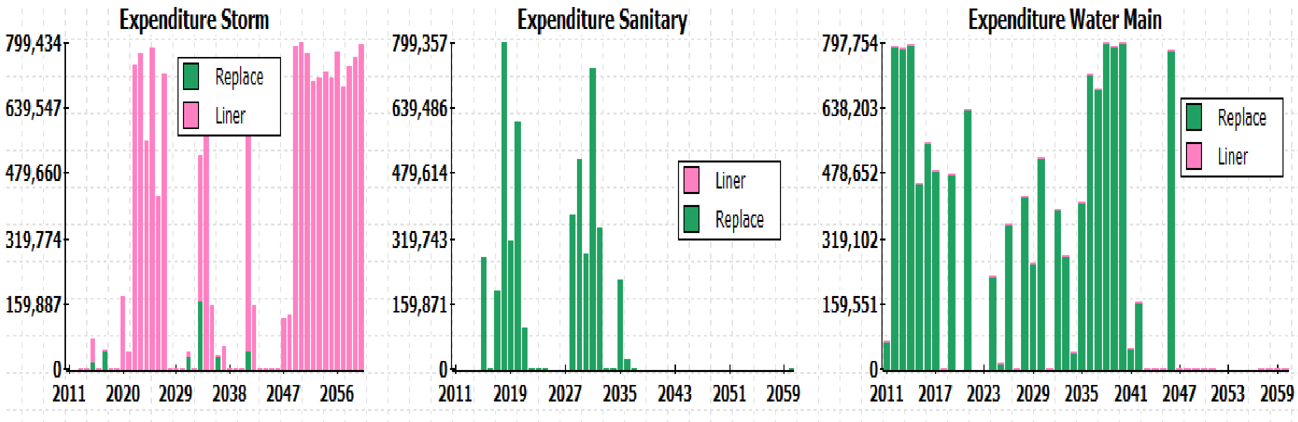


Figure 4-4. Bar diagrams summarizing expenditure for pipes across time

Figure 4-4 shows an intensive allocation of pipe replacement (on years 2018, 2020, 2031) as well as some lining for storm and sewer pipes on years. This responds to the poor levels of condition for all pipe networks. Similarly sanitary pipes will be massively replaced around the years 2018 and 2030. Some storm pipes will be lined (near the years 2015, 2031, 2033, 2041)

For pavements in figure 4.5, fewer interventions were observed because of their relative good condition, roads would experience an intensive campaign of rehabilitation in about 30 years in the future when their average level of condition has decayed and rejuvenation is required to preserve them.

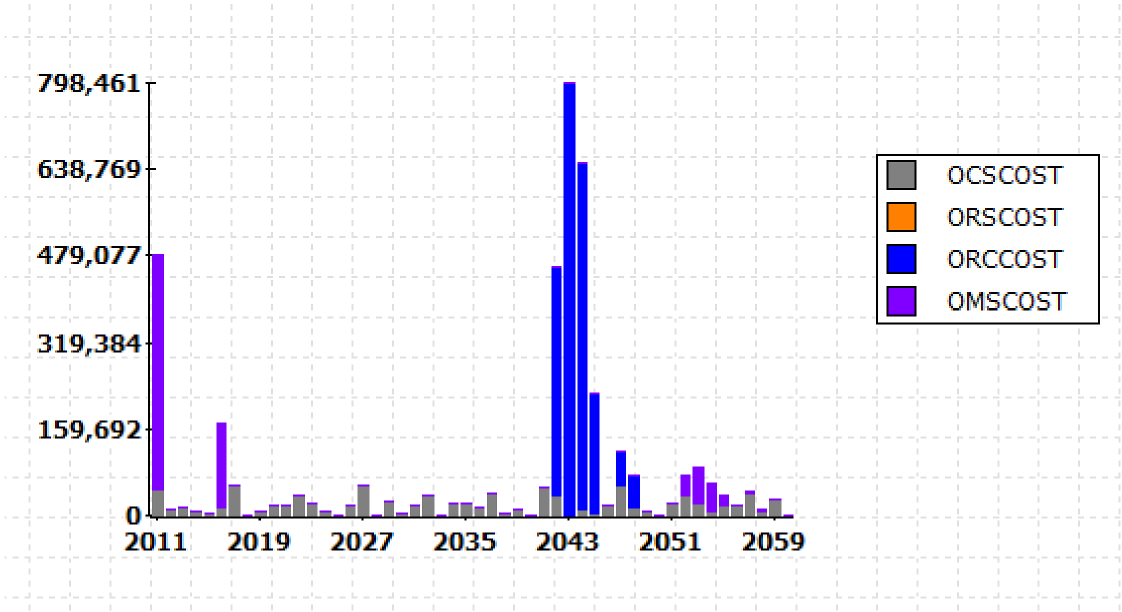


Figure 4-5. Bar diagrams summarizing expenditure on pavement intervention across time

The following figure presents the split of annual budget for all assets grouped into pipes and roads for the next 50 years. This demonstrates that the software uses the entire budget (binding constraint).

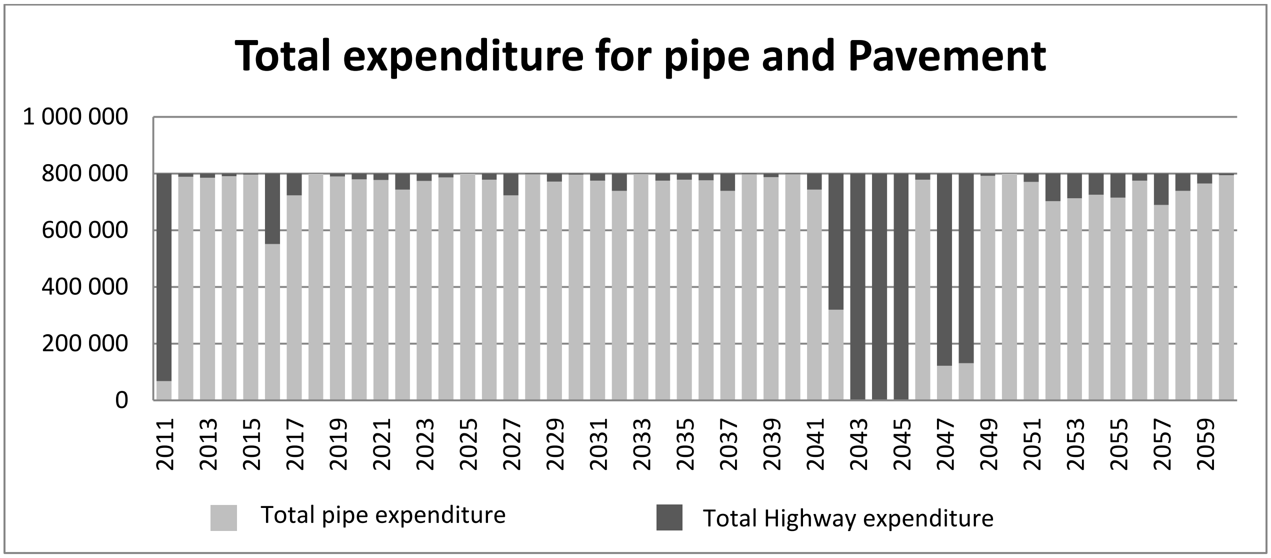


Figure 4-6. Total expenditure for pavement and pipe intervention across time

This can be seen by the splitting of budget between two competing assets (pipes and roads) and the trade-off of resources to achieve the goal of maximizing annual levels of condition of both networks. At some years (2015, 2019, 2025 etc.) pipes receive more resources, however, in general pipes utilize most of the resources available because of their much lower levels of condition (aged pipes urgently requiring improvements)

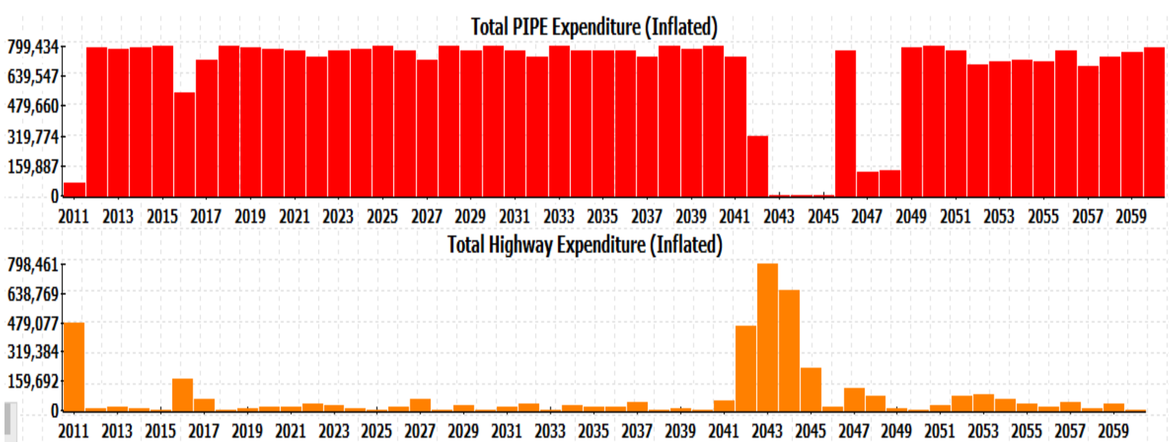


Figure 4-7. Total budget per year for all intervention

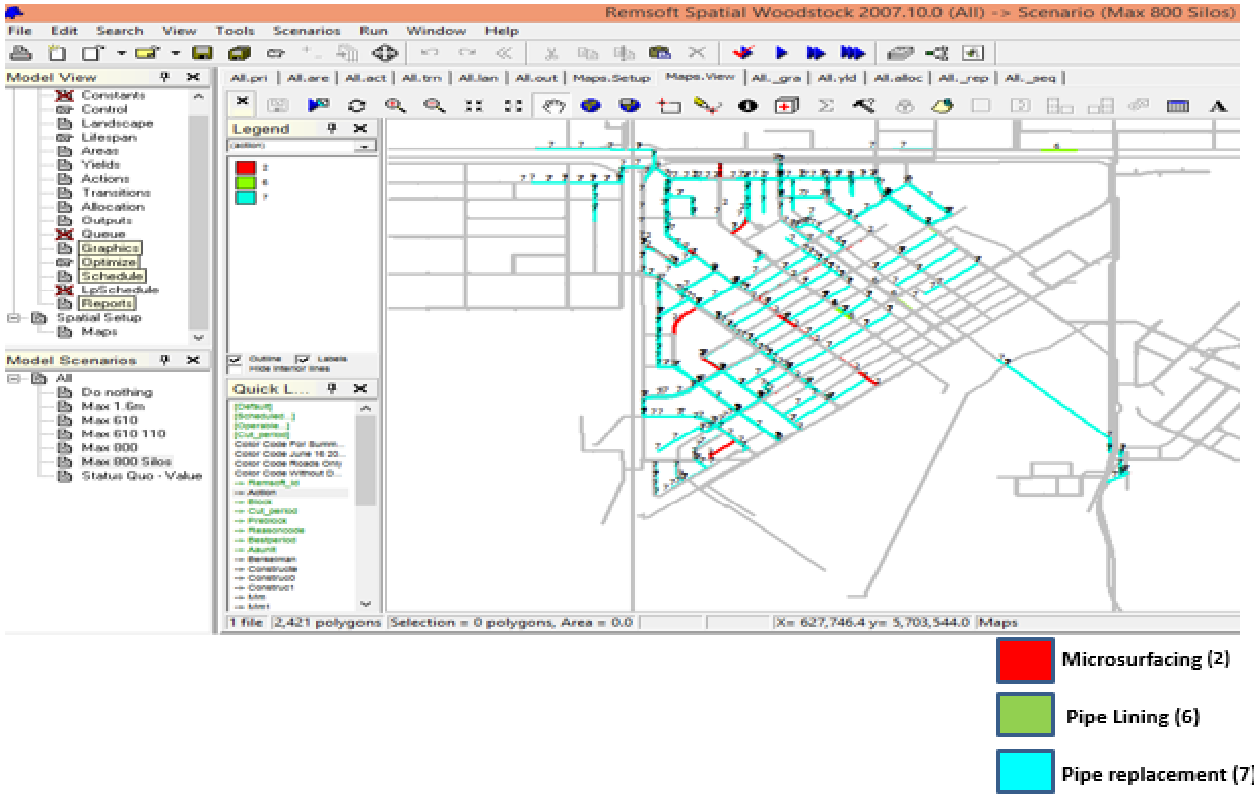


Figure 4-8. Map with allocation of intervention for 10 years

Figure 4.8 illustrates the allocation of interventions for the first 10 years, the model was run for 50 years but the figure only shows the first 10 years to avoid overcrowding of segments which will make it impossible to visualize interventions spatially. The year of planned interventions (microsurfacing, lining or replacement) is not shown. This figure serves as benchmark in order to have a baseline and must be compared to figure (other map)

CHAPTER 5 TACTICAL PLANNING: SCHEDULING INTERVENTIONS

5.1 Introduction

The aim of this chapter is to adapt the module Stanley of the package *REMSOFT* for tactical planning. The chapter explains the role of different variables in the coordination of municipal interventions. It is divided in two sections; the first section presents the additional constraints used in the analysis and explains their role in coordinating interventions, the second section presents the results and explains the sensitivity of the results to variations of the newly added constraints.

5.2 Additional elements to set up the tactical analysis

Results from coordination are expected to be arranged in corridor fashion with blocked interventions of compatible actions of neighbor assets (in time or space) allocated together. To achieve this one needs to add proximity requirements (in space) and opportunity considerations (time) for the same planning period. Table 5-1 shows the elements used for this coordination and Figure 5-1 illustrates the adjacent distance and the maximum opening size.

Table 5-1. Additional elements

Parameter in Forestry	Units	Municipal infrastructures
Period to block	Years (periods)	What time range to consider
Max deviations	Years (periods)	Flexibility to consider additional years if the other conditions are met
Adjacent distance	Units of the shapefile (meters in this case)	Proximity between assets (total length criteria)
Minimum block size	Units of assets	Minimum criteria to merge two assets together in a block
Target block size	Units of assets	Desired size of block of assets merge together
Proximal Distance	Units of the shapefile (meters in this case)	Distance between two assets that are not contiguous but could be merge together
Greenup delay	Years (periods)	Advancing or deferral of interventions
Maximum opening size	Units of the shapefile (meters in this case)	Combination of close blocks being merged and programed in the same planning period.
Allow multi-period openings	Not applicable	If checked, allow Stanley to go over one planning period to create opening. Add flexibility and increase score.

Note: The original parameters come from forestry spatial planning system *REMSOFT* /Woodstock, V8.2006)

Adjacent distance & Maximum opening size

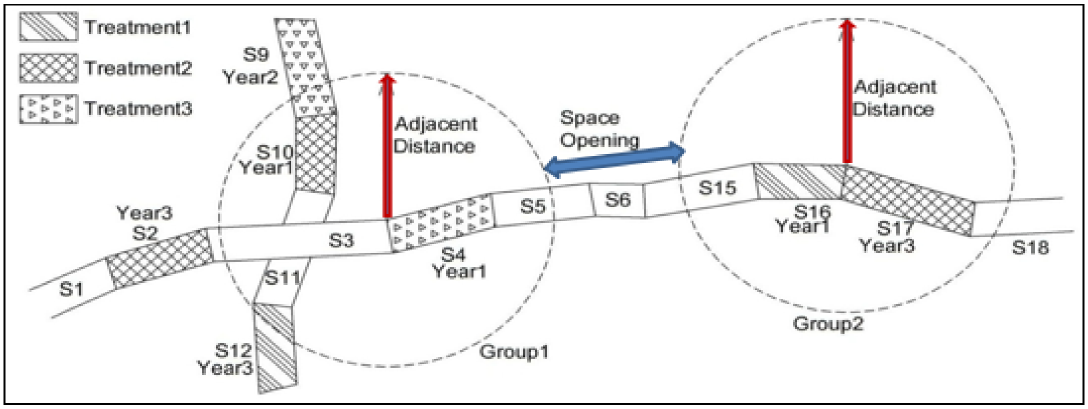


Figure 5-1. Main spatial elements of Stanley

As seen in figure 5-1, one would want to concentrate on a given period of time, of say 10 years (called period to block in Table 5-1) and have some flexibility (max deviation), then a table of adjacencies need to be built. The adjacent distance identifies nearby assets and their degree of proximity to each other. The next step consists of defining minimum and target block size which is nothing more than the planner's aspirations for total length of pipe/roads to be scheduled together. In some cases, assets that are not direct neighbors could still be scheduled together if they are within a maximum distance from each other (proximal distance). The application could be extended to blocks of assets (Maximum opening size). Finally, one could look at proximal period and advance or differ the scheduling of entire blocks (allow multiple-period opening).

Aggregation of assets within blocks is affected by the operational capabilities of the agency; in this sense minimum block size should seek the elimination of small segments of pipe or short areas of pavement such that they are scheduled to be repaired as part of a group. This is based on the agency aim to avoid small infrastructure work in order to pursue a larger infrastructure works. In the same vein, municipalities won't use a bid to repair a small pipe but will rather task public works personnel with these small repair jobs. Similarly governments won't mobilize machinery (which is costly) to resurface few meters of road. Ideally all these small jobs are merged where possible to create larger contracts which are more attractive to contractors. Target block size should reflect the desired size of interventions in terms of asset size (square meter (m^2) for roads or linear meter (m) for pipes to be treated.

A longer time span may be required to merge major interventions while a short time span may be used when merging preservation and minor rehabilitation activities. Rule sets should be defined for the compatible interventions. For instance road reconstruction and pipe replacement (which are normally schedule together) have the same rule set. This is illustrated in table 5-2.

Table 5-2. Parameter setting for base case model

Forestry Parameter name	Civil infrastructure	Rule set 1	Rule set 2
General			
Period to block	Time range to consider	10 years	10 years
Max deviations	Flexibility to consider additional years if the other conditions are met	2	2
Auto-generate starting random number	Initial location of asset used to create blocks	7699	7699
Objectives	Goals for original objectives	5	5
Blocks			
Adjacent distance	Proximity between assets	50	50
Minimum block size	Minimum criteria to merge two assets together in a block	5	5
Target block size	Desired size of block of assets merge together	1000	1000
Opening			
Proximal Distance	Distance between two separate assets that could be merge together	0	0
Greenup delay	Advancing or deferral of interventions	10	4
Interventions			
1- Crack-Sealing		No	Yes
2- Micro-Surfacing		No	Yes
3- Patching		No	Yes
4- Resurfacing		No	
5- Reconstruction		Yes	
6- Pipe Lining			Yes
7- Pipe replacement		Yes	

In some cases discrepancy of units may lead to the inability to obtain expected results. For instance, this may happen when dealing with pipes in linear meters and roads in square meters, which results in dissimilar orders of magnitude for their units of measurement.

5.3 Tactical analysis rule set

The model presented in chapter 4 was used as the base case and the value of elements previously defined were selected to look at the first 10 years with the possibility to extend an additional two (2) more years. The initial location of the asset used to create the blocks was fixed at 7,699 in order to have the same spatial reference point for the whole study. This also helped to reduce the dispersion of treatment selection throughout the asset network to prevent having results with different geographical starting points.

This case study focuses on five objectives corresponding to the optimal decision for four types of assets (water main, sanitary sewer, storm pipes and road network) and minimizing total expenditure. The same weight was chosen for these objectives as those used in the original strategic analysis. To group assets in blocks, the adjacent distance between candidate assets to be clustered together was set at fifty (50), minimum block size was set to five (5) drawing units (meters for pipes, square meters for pavements was used) in order to eliminate as many small segments as possible and have them grouped together. It is important to notice that the target block size sets the condition for the desirable size of final clusters, and it was set to 1000 drawing units. The proximal distance was set to zero (0); one for reconstruction/replacement) and 4 years for rehabilitation treatments. Compatibility was given to reconstruction and replacement of pipes for rule set one (1), and for surface treatments and lining to rule set two (2). The results from this case study are shown in Figure 5-2.

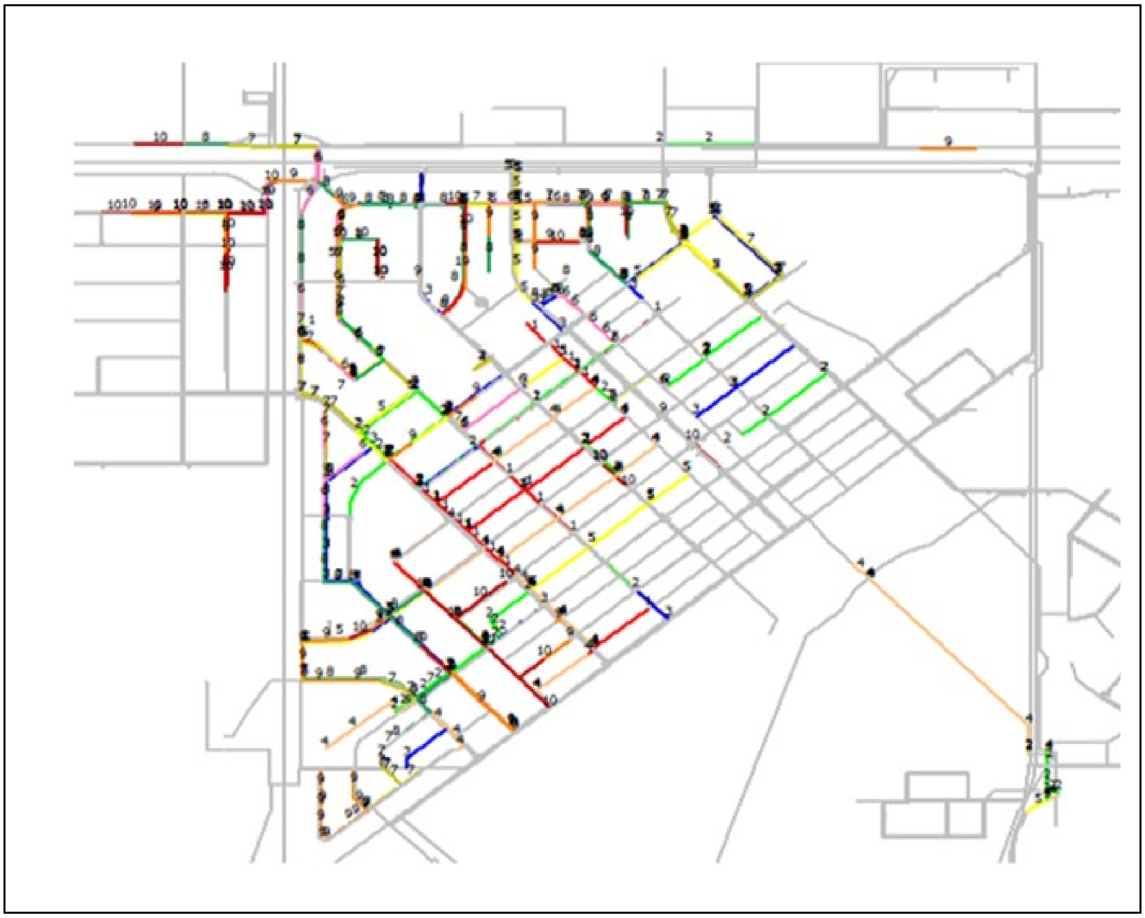


Figure 5-2. Allocation of intervention from coordination (numbers show the schedule year)

As seen, several clusters of assets at different period of time can be found at several spatial locations. If compared with figure 5-1, figure 5-2 shows a successful well-coordinated reallocation of interventions. For instance one can observe small corridors across town with interventions scheduled on the same year.

5.4 Model Sensitivity to Parameters

The sensitivity of the spatial results to changes in those new elements used to guide clustering of assets in blocks was explored. Thus, some elements were chosen and their value was changed in order to measure the impact on the model results, especially in the number of segments to be cluster together, as illustrated in figure 5-2. The previous model was called base case scenario and deviation from it was recorded by changing the value of one parameter at a time.

From the base case model described above, the value of parameter ‘’maximum opening size’’ was changed several times while keeping others values the same as it was in base case scenario. The maximum opening size value went from 0 to 5 in the case model 1. As a result, the value of the minimum block size and maximum opening size was the same; *REMSOFT* did not generate any blocked interventions. In the second case, the maximum opening size changed from 5 to 10, this resulted in 8 interventions grouped together over a 10 years period. No treatments were scheduled in the first 3 years. The algorithm allocated interventions mostly on year 3 and year 9. The majority of the interventions were scheduled on year 9.

The Maximum Opening Size was then set to 100 meters while keeping the other parameters value fixed. A total of 60 interventions were grouped together over a 10 year period. The scheduling of interventions started at year 3. From year 1 to year 2, there were no interventions being scheduled. Table 5-3 summarizes the result for the variation on Maximum opening size value.

Table 5-3. Result for variation on maximum opening size

Maximum opening Size value	# of blocked interventions /10 years	Action/Treatment	Polygon
		Microsurfacing (2)	22
0	151	Pipe Lining (6)	9
		Pipe replacement (7)	564
5	0	0	0
10	8	Pipe Lining (6)	1
		Pipe replacement (7)	14
100	60	Pipe Lining (6)	4
		Pipe replacement (7)	82

A value of 0 to the *maximum opening size* criteria (combination of proximal blocks to be merged and programed together in the same planning period) resulted in more treatments being applicable, more polygons to be selected and more corridors created. When the maximum opening size is equal to 0 there is no restriction on the blocks being merged together and scheduled for a planning horizon. The m*aximum opening size* can never be equal to the minimum opening size since otherwise the software doesn't respond and no answer is generated. Going further in the analysis, when the *maximum opening size* is assigned with other value, the coordinated actions and polygons become limited because of such spatial constraint. This result demonstrates that the *maximum opening size* is a very sensitive variable to be taken into account in order to optimize the coordination of interventions and to minimize expenditure. The sensitivity of each parameter is illustrated in table 5-4.

Table 5-4. Parameters vs their Sensitivity in a coordination of actions

Parameter name	Sensitivity
Period to block	Neutral
Max deviations	Medium
Auto-generate starting random number	High
Objectives	Neutral
Adjacent distance	Fixed
Minimum block size	Fixed
Target block size	fixed
Proximal Distance	medium
Greenup delay	Fixed
Maximum opening size	High
Allow multi-period openings	Medium

The model analysis showed that the maximum opening size and the Auto-Generate Starting Random Number have a high sensitivity. Changing those parameters value influenced the results generated by the model. It observed that the maximum opening size should not have the same value as the minimum block size. In this case, no result was found.

The Auto-Generate Starting Random Number should be fixed while running the model for different value of other parameters; otherwise the comparison base is not equal because of the spatial location characteristic provided by this parameter. In other word, it is not possible to compare different scenarios when the auto-generate starting random number is varied.

CHAPTER 6 OPERATIONAL PLANNING: AN ANNUAL PROGRAM OF WORKS

6.1 Introduction

This chapter illustrates the final step when moving a strategic and tactical-level analysis into a program of works. The aim is to adapt the module Allocation optimizer of the software *REMSOFT* for operational planning and to use the results from the coordinated set of interventions from the previous analysis. Two possible courses of action (or their combinations) are classically observed. In the following, we assume that the municipality will hire private contractors to take care of the interventions. Hence, the awarding process is not restricted to operational constraints and therefore inclusive inspections could be externally hired. However, selection of contractors follows a process that considers quoted cost, contractor's capacity, record of performance, among other elements.

This chapter illustrates how to allocate projects and interventions to contractors considering their qualifications and quoted cost. The case study presented is built upon the one developed in the previous chapters.

6.2 Operational planning setup: summary of blocked interventions

The results of the strategic analysis previously processed by a tactical analysis through a coordination approach was used as the departure point for the operational planning (table 6-1**).**

Blocked activities from the strategic model and non-blocked activities will be allocated to contractors. A list of projects from the blocked/non-blocked activities will be assigned to local and external contractors by taking into consideration contractors cost, capacity and ect. Typically a contractor is assessed for their experience, capacity, and other elements, through a point system during the bidding process. Another aspect sometimes over-rated is that of cost. An allocation of works -i.e., projects (blocks) and interventions (non-blocked activities) can be guided by both, maximizing total contractor value and minimizing total awarded works cost.

Table 6-1. Blocked interventions from coordination

Period	Pavements (m^2)			Pipes (m)
	Microsurfacing	Resurfacing	Reconstruction	Replacement
1	59,925	0.03	0	904.8
2	14,168	11,257	0.03	877.4
3	0	465	6,028	851.6
4	0.04	0.01	5,993	827.3
5	0.03	0.01	6,041	804.3
6	26,584	0.02	3,13	782.6
7	0.03	0.02	5,592	762
8	0.02	0.03	1,005	742.5
9	0.03	0.02	4,391	724
10	0.03	0.02	0.02	706.3

6.3 Operational planning setup: Allocation of Interventions to Contractors

The module allocation optimizer (AO) of the software *REMSOFT* is used to allocate interventions to contractors. The Allocation optimizer main use is for the movement and allocation of wood into processing industries and final sale markets. Correspondence between forestry terminology at the AO and urban infrastructure (used in this study) was required to set the context. The main parameters in Woodstock Allocation Optimizer are: origins, products and destinations. Other secondary elements used are: tables, residual products and transportation cost which are typically minimized in the context of a wider optimization (Table 6-2).

Table 6-2. Allocation Optimizer & correspondence in civil infrastructure

Forestry	**Civil Infrastructure**
Origin	Type of asset
Product	Type of intervention
Destination	Contractor to which intervention will be given
Table	Variable for cost of transportation (cost factor of each contractor)
Volume	Contractor's capacity

In general terms origins refer to zones in a town or city and regions within a province, commonly aimed for the awarding of maintenance contracts. Products correspond to the types of interventions or treatments available for infrastructure's maintenance, rehabilitation and upgrading. A link between the two aforementioned elements is also possible and used to record the allocation of interventions per zone (products per origin). Interventions are awarded to contractors (destinations). Finally, cost (or productivity) must be added to allow the optimizer to make choices that truly minimize transportation cost (or maximizes profits if a price is to be charged for the goods) while achieving other desired goals (i.e., quality). In this case, the variable table represents the cost factor of each Contractor. Depending on their location, some contractor will be cheaper than others. If the only factor that matters is transportation cost, then one expects that local contractors would have less expensive bids in general as compared to those contractors based at further locations (external). As they have temporary relocation cost into their overall cost structure. However, other elements such as technology (machine productivity) may make external contractors (even if not locals) more competitive above certain levels of scale.

In general terms, companies typically transform (process) their products and then sell them (deliver them). Such "delivered" goods, in this research, will be assumed to be equal to those processed, that is, no transformation is done, although from an economics perspective it would not make sense to have a for-profit company that does not transform and solely moved goods (unless transportation is its main role of activity).

One final element is that of capacity, this refers to the ability of a contractor to deliver up to a certain amount of works per unit of time (which could go from one (1) day to the entire period of the hiring). Capacities can be defined in the Allocation optimizer for each intervention (product) in the same units of the inventory of assets that is for this case study squared meters for roads and linear meters for pipes.

The town of Kindersley was divided into 4 different areas; Downtown, the Highway frontage, the industrial park and the Rosedale subdivision. For this case study, there are no restrictions in term of where contractors can have a contract for the allocation of interventions as long as the required expertise is available for that contractor. In other words, any contractor is eligible to work anywhere in the town. Five contractors are available and each of them have been given a specific definition of expertise for the type of treatment they are capable of doing (some of these definitions may not correspond to local available contractors). Three of the contractors are local and two contractors are external, from Regina and Saskatoon (about 200 km away). Table 6-3 shows the definition of capacities per type of intervention given to the contractor. For instance contractor 3 was tagged as a small company with a limited capability of doing reconstruction which was up to 55,000 m^2 of road reconstruction and resurfacing. Similarly, contractor 5 was a large company with almost unlimited capacity. Characterization of capacities in this thesis is academic and for real case application, one would need to refine these numbers since they have an important impact on allocation results.

Table 6-3 Interventions per contractor and maximum capacity allowed

Contractors	Interventions	Capacity (m^2 road /m pipes)	
		Min	**Max**
1	Crack-Sealing	0	3 000 000.00
	Micro-Surfacing	0	7 000 000.00
	Patching	0	110 000 000.00
	Total Volume		**220 000 000.00**
2	Reconstruction	0	500 000.00
	Resurfacing	0	250 000.00
	Total Volume		**330 000 000.00**
3	Micro-Surfacing	0	60 000.00
	Reconstruction	0	55 000.00
	Resurfacing	0	55 000.00
	Total		**440 000 000.00**
4	Pipe lining	0	50 000.00
	Patching	0	22 000 000.00
	Reconstruction	0	22 000 000.00
	Total		**550 000 000.00**
5	Pipe lining	0	25 000 000.00
	Pipe replacement	0	15 000 000.00
	Reconstruction	0	500 000 000.00
	Total Volume		**1 000 000 000.00**

6.4 Results from the Allocation Optimizer for Urban Infrastructures

An allocation optimizer was added to the strategic and tactical models defined in previous sections. This was done to aid in the selection of contractors based on a criteria of cost that took into consideration not only the actual construction cost, but also the contractor's expertise, capacity and their risk of default. Appendix 9.2 lists for each contractor the cost per type of intervention per zone per contractor. The overall contractor's intervention cost per period for a four year period is provided in the appendices at the end of this report. Results of this allocation are summarised in table 6-4 for contractors1 and 2. The term delivered/processed refers to square meters of road awarded to each contractor.

Table 6-4. Contractor 1 &2 interventions delivered per period

Destination/Contractors	Period	Products/ interventions	Delivered/Processed
Contractor_1	1	Crack sealing	216641.00
Contractor_1	1	Microsurfacing	57528.47
Contractor_1	2	Crack sealing	85195.00
Contractor_1	4	Crack sealing	22304.00
Contractor_1	5	Crack sealing	7441.00
Contractor_1	6	Crack sealing	140010.98
Contractor_1	6	Microsurfacing	18285.71
Contractor_1	7	Crack sealing	86692.00
Contractor_1	8	Crack sealing	89615.02
Contractor_1	9	Crack sealing	68049.00
Contractor_1	10	Crack sealing	6312.00
Contractor_1	11	Crack sealing	131340.97
Contractor_1	12	Crack sealing	32968.02
Contractor_1	13	Crack sealing	90851.98
Contractor_1	14	Crack sealing	27177.03
Contractor_1	15	Crack sealing	85300.00
Contractor_1	16	Crack sealing	172891.98
Contractor_1	17	Crack sealing	45063.02
Contractor_1	18	Crack sealing	2748.00
Contractor_1	19	Crack sealing	71690.98
Contractor_1	20	Crack sealing	39273.02
Contractor_1	21	Crack sealing	130386.98
Contractor_1	22	Crack sealing	119926.02
Contractor_1	23	Crack sealing	53183.00
Contractor_1	24	Crack sealing	22621.00
Contractor_1	25	Crack sealing	58641.98
Contractor_1	26	Crack sealing	127636.99
Contractor_1	27	Crack sealing	67926.02
Contractor_1	28	Crack sealing	6553.00
Contractor_1	29	Crack sealing	110708.00
Contractor_1	30	Crack sealing	47912.00
Contractor_2	28	Reconstruction	4744.53
Contractor_2	29	Reconstruction	7232.11
Contractor_2	30	Reconstruction	7445.99

Table 6-5 Shows the cost of intervention for contractors 3, 4 and 5 during year one. Similar table could be produced for all other period of time.

Table 6-5. Contractor 3-4 &5 interventions cost for period 1

Contractor	Period	Interventions	Polygon Length (m)	Area (m^2)	Origin-Destination COST
Contractor-3	1	Microsurfacing		113,192	6.7
Contractor-3	1	Microsurfacing		378,812	6.74
Contractor-3	1	Microsurfacing		87,601	9
Contractor-3	1	Reconstruction		79,701	41
Contractor-3	1	Reconstruction		87,601	55
Contractor-4	1	Pipe lining	488		1111
Contractor-4	1	Pipe lining	1.513		1350
Contractor-5	1	Pipe replacement	187		1111
Contractor-5	1	Pipe replacement	488		2222
Contractor-5	1	Pipe replacement	1.513		4000
Contractor-5	1	Pipe lining	488		1111
Contractor-5	1	Pipe lining	1.513		1500

As seen in table 6-3 and 6-4, not all contractors are allocated all types of interventions. As shown in the above tables, contractor 3 does some reconstruction during period one. Similarly, contractor 5 does some pipe replacement. In terms of lining and during the first period, both contractors 4 and 5 receive some allocation. In addition, it has to be noted contractors are selected based on cost. The cheapest contractor is allocated as much as his capacity allows, then the allocation moves to the next cheapest contractor up until one reaches its capacity and the allocation of intervention to contractors continue in that fashion.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The literature reveals the lack of a decision support analysis tool that integrally all levels of municipal infrastructure planning to supporting the decision making process for allocating maintenance and rehabilitation works.

It was found that it is possible to link the decision making by means of a hierarchical approach, addressing the problem through three stages. A hierarchical approach is herein suggested and the mathematical framework behind it outlined.

Commercial software was compared in light of its capabilities to conduct the proposed hierarchical approach. Forestry management software was adapted and a case study prepared. Specific conclusions follow.

For strategic planning, the case study reveals that $800 000 dollars are enough to achieve a network with pipes and roads in good average condition. Roads would experience an intensive campaign of rehabilitation in about 30 years. Similarly sanitary pipes will be massively replaced around the year 2018 and 2030. Some storm pipes will be lined (near the years 2015, 2031, 2033, 2041).

Although good results are achieved, it was found that interventions were allocated across time but no consideration of spatial or temporal proximity or interventions compatibility was given. This illustrated the need to have a coordination analysis.

For tactical planning a greedy algorithm was found to be the ideal method to reallocate interventions by considering the need to advance or defer the timing of groups of interventions in a way that identifies the optimal timing for groups instead of individual segments. Most of the microsurfacing was concentrated on year 1, 2,6,13, 14 and 15. Resurfacing was scheduled on year 2 while reconstruction was listed for year 3, 4,5,7,8,9,11 and12. Most of pipe replacements happened on from year 1 to 5

A sensitivity of the tactical model to variations on various parameters was tested. It was observed that the location at which the coordination started along with the distance used as criteria to join two blocks together could both have a large impact in the allocation of intervention. The proximal distance has a medium impact (spatial and temporal) as well as the maximum number of deviations.

At the operational level, the recommended approach follows the distribution problem and considers the optimal allocation of works by assigning tenders to bidders in order to hire external contractors to undertake maintenance, rehabilitation and upgrading for a yearly basis. The allocation of works to contractors was done through an optimization that considered not only the original goals and the compatibility of adjacent projects but also the qualifications and capabilities of the contractors. Two approaches were identified for doing so: one looks into each contractor's expertise and builds a qualification index; the other corrects contractor quoted prices by considering their qualifications. Both consider the capacity of the contractor per type of intervention. The second approach was used to obtained results that allocated interventions across zones for five contractors.

Not all type of interventions are allocated to all contractors. The allocation of interventions was based on both cost and technical qualifications of each contractor. This approach can help governments to have a decision making tool for the allocation of contracts, however, the final decision must be taken by looking into other criteria such as the record of historical contracts and previous performance among other factors.

This research presented an approach capable of connecting all levels of planning for municipal infrastructure; it will support policy makers at the strategic level, managers at the tactical level to schedule infrastructure work and engineers for the operational allocation of works.

7.2 Future Research

Future research could attempt to develop a solution from scratch; however, such task escaped the goal of this research.

Future research should look into the incorporation of operational constraints for the case when the agency undertakes works with its own resources (machinery, materials). Such case is expected to be an extension of the approach suggested herein.

Further research can explore the use of this approach having more than one region (origin) and multiple destinations (contractors) and compare both approaches suggested herein: the weighted factor method and the corrected quoted cost.

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APPENDICES: SOURCE CODES USED IN REMSOFT

This section illustrates all the Source codes used in *REMSOFT* and their definition for municipal infrastructures

1- Codes and their definition

Codes	Definition
Action	Definition of intervention
Invent	Type of intervention
Destination	Summation
Areas	Length/size
Yields	Performance curves
Source	Characteristics of origin
Landscape	Asset characteristics
Target	Characteristics of destination
Age	At a given age
Length	Last period of time
***@YLD**	At a given performance value
?	Any applicable characteristic
_TH1	Consider filter 1 to group
***Y**	Define time dependent variable
***YC**	Define time dependent composed variable that is multiplied by a specific characteristic
Times	Multiply
Operable	Applicable when
aggregate	Aggregate, union
Theme	Characteristic
Output	Aggregation

2- Codes

The following are the codes used in this thesis.

LANDSCAPE SECTION Assets Characteristics

; Landscape (assets characteristics)

*THEME 1
WM
ROAD
STORM
SANITARY
GRAVEL
HWY7
ROW
HWY21
*AGGREGATE pipes
 (storm sanitary water main)
*THEME 2
pvc
CI
UCI
AC
THEME 3
LIGHT
MEDIUM
HIGH
VHIGH
s4
s6
s7
s8
s9
s10
s12
s14
s15
s16
s18
s20
s21
s22
s24
s26
s30
s36
s48
Downtown
Rosedale

ACTIONS SECTION (interventions)
; Actions (interventions)

CONC
UNKNOWN
WEAK
STRONG
VCT
CLAY
CSP
HDPE
PLASTIC
RCP
SCHLAIR
SDR35
steel
VT
*AGGREGATE iron
CI UCI
*AGGREGATE pvc2
pvc hdpe plastic schlair sdr35
*AGGREGATE concrete
RCP conc AC CSP VCT clay vt unknown
*

unknown
*AGGREGATE small
s4 s6 s7 s8 s9 s10
*AGGREGATE moyen
s12 s14 s15 s16 s18

*AGGREGATE large
s20 s21 s22 s24 s26 s30 s36 s48 unknown
*AGGREGATE local
light medium
*THEME 4
NONE
Kindersley
Provincial
CS
MS
PA
RS
RC
liner
*THEME 5
hwyfrontage
Industrialpark

*ACTION aCS Y Crack sealing ; (CS)
 *OPERABLE aCS
  road ? ? ? ? yVIR >= 7 and yVIR <= 9
*ACTION aMS Y Microsurfacing ; Pavement sealing and texturing to correct

polished roadway surfaces. Binder rich mixtures (8.0% bitumen) with fine/medium aggregate in lifts of 8 to 10mm, which waterproof and seal existing surfaces
*OPERABLE aMS
road ? ? ? ? yVIR >= 5 and yVIR <= 7
*ACTION aPA Y Spray/shallow Patching ; (PA) shallow patching involves heating old asphalt and adding new material as needed to ensure uniform pavement surface
*OPERABLE aPA
road ? ? ? ? yVIR >= 6.99999999 and yVIR <= 7.0
*ACTION aRS Y Resurfacing (with full depth patching) ;(RS) need to define transition
*OPERABLE aRS
road ? ? ? ? yVIR >= 3 and yVIR <= 4.999999999999999999
*ACTION aRC Y Reconstruction ;(RC)
*OPERABLE aRC
road ? ? ? ? yVIR <= 3
;ACTIONS FOR PIPES
*ACTION aliner Y
*OPERABLE aliner
pipes ? large ? ? _AGE <= 60 and _AGE >= 20
pipes ? moyen ? ? _AGE <= 60 and _AGE >= 20
;pipes ? small ? _AGE <=60 and _AGE >=20
*ACTION areplace Y replace culvert with PVC C-900
*OPERABLE areplace
pipes iron ? ? ? _AGE >= 50
pipes plastic ? ? ? _AGE >= 75
pipes ? ? ? ? _AGE >= 50
*AGGREGATE aRepairPIPE
aliner areplace
*AGGREGATE aRepairROAD
aCS aMS aRS aRC ; ACTIONS

YIELDS SECTION

Yields (Performance)
*YT ? ? ? ? ?
ydiscount
_DISCOUNTFACTOR(2.5%,1,full)
yinflation
_INFLATIONFACTOR(2.46%,1,full)
;--------------Asset Valuation
*Y road ? ? ? ?
_AGE yDepre
1 1.0
5 0.95
10 0.80
20 0.5
25 0.0
*Y pipes ? ? ? ?
_AGE yDepre
1 1.0
10 0.95
25 0.75
50 0.5
100 0.0
*YC road ? ? ? ?
yValue ydepre * 42
*YC pipes ? small ? ?
yValue ydepre * 210
*YC pipes ? moyen ? ?
yValue ydepre * 1200
*YC pipes ? large ? ?
yValue ydepre * 4000
;--------------------Cost tables
*Y road ? ? ? ?
_AGE yCS$ yPA$ yRS$ yRC$ yMS$
1 0.33 4 25 42 6.74 ;this cost is per m2, i.e. 80000 for microsurf per km per 2 lanes
10 0.35 6 33 80.5 8.62
20 0.51 7 45 102.5 11.04
; Yields i.e. Performance Deterioration Curves
*Y road ? ? PA ?
_AGE YIRI YVIR
0 3 6.7
1 3.017596648 6.627563006
2 3.165412738 6.299082805
3 3.320781386 5.953819142
4 3.484104495 5.590878899
5 3.655806143 5.209319681
6 3.836333844 4.808147013
7 4.026159882 4.386311374
8 4.225782721 3.942705065
9 4.435728503 3.476158881
10 4.656552628 2.985438604
11 4.888841425 2.469241278
12 5.133213926 1.926191275
13 5.390323743 1.354836126
14 5.66086105 0.75364211
15 5.945554687 0.120989585

16 6 0
;AFTER CRACKSEALING BACK 1 YEAR EVERYBODY , cracksealing does not change deterioration rate but it does add 2-3 year to pavement lifespan
*Y hwy7 ? vhigh CS ?

_AGE	yIRI	yVIR
0	1.5	10
1	1.55	9.8
2	1.641825464	9.684832303
3	1.728882559	9.491372092
4	1.820937035	9.286806588
5	1.918296897	9.07045134
6	2.021290211	8.841577308
7	2.130266472	8.599407841
8	2.245598047	8.34311545
9	2.367681741	8.071818354
10	2.496940448	7.784576783
11	2.633824936	7.480389031
12	2.778815748	7.158187227
13	2.932425235	6.816832812
14	3.095199733	6.455111705
15	3.267721894	6.071729125
16	3.450613175	5.665304056
17	3.644536507	5.234363318
18	3.850199146	4.777335232
19	4.068355726	4.292542831
20	4.29981153	3.778196601
21	4.54542598	3.232386711
22	4.806116386	2.653074697
23	5.082861948	2.038084559
24	5.376708045	1.385093233
25	5.688770822	0.691620396
26	6	0

*Y road strong high CS ?

_AGE	yIRI	yVIR
0	1.5	10
1	1.55	9.8
2	1.634133316	9.701925964
3	1.712159486	9.528534475
4	1.794068564	9.346514303
5	1.880062065	9.155417633
6	1.970352386	8.954772477
7	2.065163403	8.744081326
8	2.164731124	8.522819724
9	2.269304361	8.290434753
10	2.37914545	8.046343445
11	2.494531011	7.789931087
12	2.615752752	7.520549439
13	2.74311832	7.237514844
14	2.876952196	6.940106232
15	3.017596648	6.627563006
16	3.165412738	6.299082805
17	3.320781386	5.953819142
18	3.484104495	5.590878899
19	3.655806143	5.209319681
20	3.836333844	4.808147013
21	4.026159882	4.386311374
22	4.225782721	3.942705065
23	4.435728503	3.476158881
24	4.656552628	2.985438604
25	4.888841425	2.469241278
26	5.133213926	1.926191275
27	5.390323743	1.354836126
28	5.66086105	0.75364211
29	5.945554687	0.120989585
30	6	0

*Y road strong medium CS ?

_AGE	yIRI	yVIR
0	1.5	10
1	1.55	9.8
2	1.629374903	9.712500215
3	1.702054186	9.550990698
4	1.77808062	9.382043066
5	1.85761429	9.205301579
6	1.940823257	9.020392762
7	2.027883981	8.826924486
8	2.118981753	8.624484993
9	2.214311157	8.412641873
10	2.314076557	8.190940984
11	2.41849261	7.958905312
12	2.527784802	7.716033774
13	2.642190023	7.461799948
14	2.761957167	7.195650739
15	2.887347762	6.917004972
16	3.018636643	6.625251905
17	3.156112652	6.319749662
18	3.300079389	5.999823579
19	3.450855991	5.664764464
20	3.608777962	5.31382675
21	3.774198048	4.946226559
22	3.947487159	4.561139648
23	4.129035339	4.157699246
24	4.319252801	3.734993776
25	4.518571004	3.292064436
26	4.727443802	2.827902663
27	4.946348652	2.34144744
28	5.175787891	1.831582464
29	5.416290082	1.29713315
30	5.66841144	0.736863467

31 5.932737332 0.149472596
32 6 0
*Y road strong light CS ?
_AGE yIRI yVIR
0 1.5 10
1 1.55 9.8
2 1.626044014 9.719902191
3 1.694930207 9.566821763
4 1.766757081 9.407206487
5 1.841651275 9.240774944
6 1.919744936 9.067233476
7 2.001175958 8.886275649
8 2.08608824 8.697581688
9 2.174631948 8.500817893
10 2.26696379 8.295636022
11 2.363247305 8.081672656
12 2.463653165 7.858548523
13 2.568359487 7.625867806
14 2.677552166 7.383217409
15 2.791425214 7.130166192
16 2.910181119 6.86626418
17 3.034031223 6.591041728
18 3.163196109 6.304008647
19 3.297906014 6.004653302
20 3.438401252 5.692441661
21 3.584932665 5.3668163
22 3.737762084 5.027195368
23 3.897162822 4.672971508
24 4.063420176 4.30351072
25 4.236831967 3.918151183
26 4.417709092 3.516202019
27 4.606376101 3.096941999
28 4.803171811 2.659618198
29 5.008449936 2.203444586
30 5.222579753 1.72760055
31 5.445946788 1.231229359
32 5.67895355 0.713436555
33 5.922020278 0.173288271
34 6 0
*Y road weak light CS ?
_AGE yIRI yVIR
0 1.5 10
1 1.55 9.8
2 1.603418482 9.77018115
3 1.713662748 9.525193894
4 1.830701158 9.265108538
5 1.954928533 8.989047703
6 2.08676183 8.696084822
7 2.226641347 8.385241452
8 2.375032006 8.05548443
9 2.532424699 7.705722892
10 2.699337699 7.334805113
11 2.876318163 6.941515193
12 3.063943701 6.524569554
13 3.262824035 6.082613255
14 3.473602752 5.614216107
15 3.696959138 5.117868583
16 3.933610125 4.5919775
17 4.184312334 4.034861481
18 4.449864225 3.444746167
19 4.731108371 2.819759175
20 5.028933848 2.157924782
21 5.344278749 1.457158335
22 5.678132842 0.715260351
23 6 0
*Y road weak medium CS ?
_AGE yIRI yVIR
0 1.5 10
1 1.613969063 9.746735416
2 1.735845784 9.475898257
3 1.865565128 9.187633049
4 2.00359409 8.880902022
5 2.150426253 8.554608327
6 2.306583252 8.207592773
7 2.472616328 7.838630381
8 2.649107962 7.446426752
9 2.836673593 7.029614237
10 3.035963442 6.586747906
11 3.247664419 6.116301291
12 3.472502143 5.616661904
13 3.711243071 5.086126509
14 3.964696735 4.522896145
15 4.233718106 3.925070875
16 4.519210087 3.290644251
17 4.822126131 2.617497486
18 5.14347301 1.903393311
19 5.484313727 1.145969495
20 5.845770588 0.342732026
21 6 0
;***
; MICROSURFACED ROADS
;***
*Y hwy7 ? vhigh MS ?
_AGE yIRI yVIR
0 1.5 10
1 1.641825464 9.684832303
2 1.728882559 9.491372092
3 1.820937035 9.286806588

4 1.918296897 9.07045134
5 2.021290211 8.841577308
6 2.130266472 8.599407841
7 2.245598047 8.34311545
8 2.367681741 8.071818354
9 2.496940448 7.784576783
10 2.633824936 7.480389031
11 2.778815748 7.158187227
12 2.932425235 6.816832812
13 3.095199733 6.455111705
14 3.267721894 6.071729125
15 3.450613175 5.665304056
16 3.644536507 5.234363318
17 3.850199146 4.777335232
18 4.068355726 4.292542831
19 4.29981153 3.778196601
20 4.54542598 3.232386711
21 4.806116386 2.653074697
22 5.082861948 2.038084559
23 5.376708045 1.385093233
24 5.688770822 0.691620396

*Y road strong high MS ?

_AGE yIRI yVIR
0 1.5 10
1 1.634133316 9.701925964
2 1.712159486 9.528534475
3 1.794068564 9.346514303
4 1.880062065 9.155417633
5 1.970352386 8.954772477
6 2.065163403 8.744081326
7 2.164731124 8.522819724
8 2.269304361 8.290434753
9 2.37914545 8.046343445
10 2.494531011 7.789931087
11 2.615752752 7.520549439
12 2.74311832 7.237514844
13 2.876952196 6.940106232
14 3.017596648 6.627563006
15 3.165412738 6.299082805
16 3.320781386 5.953819142
17 3.484104495 5.590878899
18 3.655806143 5.209319681
19 3.836333844 4.808147013
20 4.026159882 4.386311374
21 4.225782721 3.942705065
22 4.435728503 3.476158881
23 4.656552628 2.985438604
24 4.888841425 2.469241278
25 5.133213926 1.926191275
26 5.390323743 1.354836126
27 5.66086105 0.75364211
28 5.945554687 0.120989585

*Y road strong medium MS ?

_AGE yIRI yVIR
0 1.5 10
1 1.629374903 9.712500215
2 1.702054186 9.550990698
3 1.77808062 9.382043066
4 1.85761429 9.205301579
5 1.940823257 9.020392762
6 2.027883981 8.826924486
7 2.118981753 8.624484993
8 2.214311157 8.412641873
9 2.314076557 8.190940984
10 2.41849261 7.958905312
11 2.527784802 7.716033774
12 2.642190023 7.461799948
13 2.761957167 7.195650739
14 2.887347762 6.917004972
15 3.018636643 6.625251905
16 3.156112652 6.319749662
17 3.300079389 5.999823579
18 3.450855991 5.664764464
19 3.608777962 5.31382675
20 3.774198048 4.946226559
21 3.947487159 4.561139648
22 4.129035339 4.157699246
23 4.319252801 3.734993776
24 4.518571004 3.292064436
25 4.727443802 2.827902663
26 4.946348652 2.34144744
27 5.175787891 1.831582464
28 5.416290082 1.29713315
29 5.66841144 0.736863467
30 5.932737332 0.149472596

*Y road strong light MS ?

_AGE yIRI yVIR
0 1.5 10
1 1.626044014 9.719902191
2 1.694930207 9.566821763
3 1.766757081 9.407206487
4 1.841651275 9.240774944
5 1.919744936 9.067233476
6 2.001175958 8.886275649
7 2.08608824 8.697581688
8 2.174631948 8.500817893
9 2.26696379 8.295636022
10 2.363247305 8.081672656
11 2.463653165 7.858548523
12 2.568359487 7.625867806

13 2.677552166 7.383217409
14 2.791425214 7.130166192
15 2.910181119 6.86626418
16 3.034031223 6.591041728
17 3.163196109 6.304008647
18 3.297906014 6.004653302
19 3.438401252 5.692441661
20 3.584932665 5.3668163
21 3.737762084 5.027195368
22 3.897162822 4.672971508
23 4.063420176 4.30351072
24 4.236831967 3.918151183
25 4.417709092 3.516202019
26 4.606376101 3.096941999
27 4.803171811 2.659618198
28 5.008449936 2.203444586
29 5.222579753 1.72760055
30 5.445946788 1.231229359
31 5.67895355 0.713436555
32 5.922020278 0.173288271
*Y road weak medium MS ?
_AGE yIRI yVIR
0 1.5 10
1 1.603418482 9.77018115
2 1.713662748 9.525193894
3 1.830701158 9.265108538
4 1.954928533 8.989047703
5 2.08676183 8.696084822
6 2.226641347 8.385241452
7 2.375032006 8.05548443
8 2.532424699 7.705722892
9 2.699337699 7.334805113
10 2.876318163 6.941515193
11 3.063943701 6.524569554
12 3.262824035 6.082613255
13 3.473602752 5.614216107
14 3.696959138 5.117868583
15 3.933610125 4.5919775
16 4.184312334 4.034861481
17 4.449864225 3.444746167
18 4.731108371 2.819759175
19 5.028933848 2.157924782
20 5.344278749 1.457158335
21 5.678132842 0.715260351
*Y road weak light MS ?
_AGE yIRI yVIR
0 1.5 10
1 1.613969063 9.746735416
2 1.735845784 9.475898257
3 1.865565128 9.187633049
4 2.00359409 8.880902022
5 2.150426253 8.554608327
6 2.306583252 8.207592773
7 2.472616328 7.838630381
8 2.649107962 7.446426752
9 2.836673593 7.029614237
10 3.035963442 6.586747906
11 3.247664419 6.116301291
12 3.472502143 5.616661904
13 3.711243071 5.086126509
14 3.964696735 4.522896145
15 4.233718106 3.925070875
16 4.519210087 3.290644251
17 4.822126131 2.617497486
18 5.14347301 1.903393311
19 5.484313727 1.145969495
20 5.845770588 0.342732026
;***
; RESURFACING EFFECTIVENESS = JUMP OF 7 YEARS based on untreated performance curves
;***
*Y road strong high RS ?
; jump = 7 years
_AGE yIRI yVIR
0 0.8 10.36
1 0.9 10.35
2 1 10.33
3 1.1 10.3
4 1.2 10.2
5 1.3 10.1
6 1.4 10
7 1.5 9.9
8 1.63 9.7
9 1.71 9.53
10 1.79 9.35
11 1.88 9.16
12 1.97 8.95
13 2.07 8.74
14 2.16 8.52
15 2.27 8.29
16 2.38 8.05
17 2.49 7.79
18 2.62 7.52
19 2.74 7.24
20 2.88 6.94
21 3.02 6.63
22 3.17 6.3

23 3.32 5.95
24 3.48 5.59
25 3.66 5.21
26 3.84 4.81
27 4.03 4.39
28 4.23 3.94
29 4.44 3.48
30 4.66 2.99
31 4.89 2.47
32 5.13 1.93
33 5.39 1.35
34 5.66 0.75
35 5.95 0.12
36 6 0
*Y road strong medium RS ? ; jump = 9 years
_AGE yIRI yVIR
0 0.95 10.57
1 1 10.55
2 1.1 10.5
3 1.18 10.4
4 1.28 10.3
5 1.3 10.2
6 1.4 10.1
7 1.5 10
8 1.58 9.9
9 1.629374903 9.712500215
10 1.702054186 9.550990698
11 1.77808062 9.382043066
12 1.85761429 9.205301579
13 1.940823257 9.020392762
14 2.027883981 8.826924486
15 2.118981753 8.624484993
16 2.214311157 8.412641873
17 2.314076557 8.190940984
18 2.41849261 7.958905312
19 2.527784802 7.716033774
20 2.642190023 7.461799948
21 2.761957167 7.195650739
22 2.887347762 6.917004972
23 3.018636643 6.625251905
24 3.156112652 6.319749662
25 3.300079389 5.999823579
26 3.450855991 5.664764464
27 3.608777962 5.31382675
28 3.774198048 4.946226559
29 3.947487159 4.561139648
30 4.129035339 4.157699246
31 4.319252801 3.734993776
32 4.518571004 3.292064436
33 4.727443802 2.827902663
34 4.946348652 2.34144744
35 5.175787891 1.831582464
36 5.416290082 1.29713315
37 5.66841144 0.736863467
38 5.932737332 0.149472596
39 6 0
*Y road strong light RS ? ;jump = 12 years
_AGE yIRI yVIR
0 1.02 10.38
1 1.03 10.37
2 1.05 10.36
3 1.08 10.35
4 1.13 10.34
5 1.17 10.32
6 1.21 10.3
7 1.28 10.25
8 1.35 10.22
9 1.4 10.16
10 1.5 10.1
11 1.55 10
12 1.6 9.9
13 1.626044014 9.719902191
14 1.694930207 9.566821763
15 1.766757081 9.407206487
16 1.841651275 9.240774944
17 1.919744936 9.067233476
18 2.001175958 8.886275649
19 2.08608824 8.697581688
20 2.174631948 8.500817893
21 2.26696379 8.295636022
22 2.363247305 8.081672656
23 2.463653165 7.858548523
24 2.568359487 7.625867806
25 2.677552166 7.383217409
26 2.791425214 7.130166192
27 2.910181119 6.86626418
28 3.034031223 6.591041728
29 3.163196109 6.304008647
30 3.297906014 6.004653302
31 3.438401252 5.692441661
32 3.584932665 5.3668163
33 3.737762084 5.027195368
34 3.897162822 4.672971508
35 4.063420176 4.30351072
36 4.236831967 3.918151183
37 4.417709092 3.516202019
38 4.606376101 3.096941999
39 4.803171811 2.659618198

40 5.008449936 2.203444586
41 5.222579753 1.72760055
42 5.445946788 1.231229359
43 5.67895355 0.713436555
44 5.922020278 0.173288271
45 6 0
*Y road weak medium RS ? ;jump=6years
_AGE yIRI yVIR
0 1.03 10.55
1 1.08 10.5
2 1.15 10.45
3 1.2 10.4
4 1.3 10.3
5 1.4 10.15
6 1.5 10
7 1.603418482 9.77018115
8 1.713662748 9.525193894
9 1.830701158 9.265108538
10 1.954928533 8.989047703
11 2.08676183 8.696084822
12 2.226641347 8.385241452
13 2.375032006 8.05548443
14 2.532424699 7.705722892
15 2.699337699 7.334805113
16 2.876318163 6.941515193
17 3.063943701 6.524569554
18 3.262824035 6.082613255
19 3.473602752 5.614216107
20 3.696959138 5.117868583
21 3.933610125 4.5919775
22 4.184312334 4.034861481
23 4.449864225 3.444746167
24 4.731108371 2.819759175
25 5.028933848 2.157924782
26 5.344278749 1.457158335
27 5.678132842 0.715260351
28 6 0
*Y road weak light RS ? ; (jump =8yrs)
_AGE yIRI yVIR
0 1 10.48
1 1.05 10.47
2 1.1 10.44
3 1.15 10.4
4 1.2 10.35
5 1.3 10.27
6 1.35 10.2
7 1.4 10.1
8 1.5 9.9
9 1.613969063 9.746735416
10 1.735845784 9.475898257
11 1.865565128 9.187633049
12 2.00359409 8.880902022
13 2.150426253 8.554608327
14 2.306583252 8.207592773
15 2.472616328 7.838630381
16 2.649107962 7.446426752
17 2.836673593 7.029614237
18 3.035963442 6.586747906
19 3.247664419 6.116301291
20 3.472502143 5.616661904
21 3.711243071 5.086126509
22 3.964696735 4.522896145
23 4.233718106 3.925070875
24 4.519210087 3.290644251
25 4.822126131 2.617497486
26 5.14347301 1.903393311
27 5.484313727 1.145969495
28 5.845770588 0.342732026
29 6 0
;**
; UNTREATED ROADS
;**
*Y hwy7 ? vhigh ? ?
_AGE yIRI yVIR
0 1.5 10
1 1.641825464 9.684832303
2 1.728882559 9.491372092
3 1.820937035 9.286806588
4 1.918296897 9.07045134
5 2.021290211 8.841577308
6 2.130266472 8.599407841
7 2.245598047 8.34311545
8 2.367681741 8.071818354
9 2.496940448 7.784576783
10 2.633824936 7.480389031
11 2.778815748 7.158187227
12 2.932425235 6.816832812
13 3.095199733 6.455111705
14 3.267721894 6.071729125
15 3.450613175 5.665304056
16 3.644536507 5.234363318
17 3.850199146 4.777335232
18 4.068355726 4.292542831
19 4.29981153 3.778196601
20 4.54542598 3.232386711
21 4.806116386 2.653074697

22 5.082861948 2.038084559
23 5.376708045 1.385093233
24 5.688770822 0.691620396
25 6 0

*Y road strong high ? ?
_AGE yIRI yVIR
0 1.5 10
1 1.634133316 9.701925964
2 1.712159486 9.528534475
3 1.794068564 9.346514303
4 1.880062065 9.155417633
5 1.970352386 8.954772477
6 2.065163403 8.744081326
7 2.164731124 8.522819724
8 2.269304361 8.290434753
9 2.37914545 8.046343445
10 2.494531011 7.789931087
11 2.615752752 7.520549439
12 2.74311832 7.237514844
13 2.876952196 6.940106232
14 3.017596648 6.627563006
15 3.165412738 6.299082805
16 3.320781386 5.953819142
17 3.484104495 5.590878899
18 3.655806143 5.209319681
19 3.836333844 4.808147013
20 4.026159882 4.386311374
21 4.225782721 3.942705065
22 4.435728503 3.476158881
23 4.656552628 2.985438604
24 4.888841425 2.469241278
25 5.133213926 1.926191275
26 5.390323743 1.354836126
27 5.66086105 0.75364211
28 5.945554687 0.120989585
29 6 0
*Y road strong medium ? ?
_AGE yIRI yVIR
0 1.5 10
1 1.629374903 9.712500215
2 1.702054186 9.550990698
3 1.77808062 9.382043066
4 1.85761429 9.205301579
5 1.940823257 9.020392762
6 2.027883981 8.826924486
7 2.118981753 8.624484993
8 2.214311157 8.412641873
9 2.314076557 8.190940984
10 2.41849261 7.958905312
11 2.527784802 7.716033774
12 2.642190023 7.461799948
13 2.761957167 7.195650739
14 2.887347762 6.917004972
15 3.018636643 6.625251905
16 3.156112652 6.319749662
17 3.300079389 5.999823579
18 3.450855991 5.664764464
19 3.608777962 5.31382675
20 3.774198048 4.946226559
21 3.947487159 4.561139648
22 4.129035339 4.157699246
23 4.319252801 3.734993776
24 4.518571004 3.292064436
25 4.727443802 2.827902663
26 4.946348652 2.34144744
27 5.175787891 1.831582464
28 5.416290082 1.29713315
29 5.66841144 0.736863467
30 5.932737332 0.149472596
31 6 0
*Y road strong light ? ?
_AGE yIRI yVIR
0 1.5 10
1 1.626044014 9.719902191
2 1. 694930207 9.566821763
3 1.766757081 9.407206487
4 1.841651275 9.240774944
5 1.919744936 9.067233476
6 2.001175958 8.886275649
7 2.08608824 8.697581688
8 2.174631948 8.500817893
9 2.26696379 8.295636022
10 2.363247305 8.081672656
11 2.463653165 7.858548523
12 2.568359487 7.625867806
13 2.677552166 7.383217409
14 2.791425214 7.130166192
15 2.910181119 6.86626418
16 3.034031223 6.591041728
17 3.163196109 6.304008647
18 3.297906014 6.004653302
19 3.438401252 5.692441661
20 3.584932665 5.3668163
21 3.737762084 5.027195368
22 3.897162822 4.672971508
23 4.063420176 4.30351072
24 4.236831967 3.918151183
25 4.417709092 3.516202019
26 4.606376101 3.096941999

27 4.803171811 2.659618198
28 5.008449936 2.203444586
29 5.222579753 1.72760055
30 5.445946788 1.231229359
31 5.67895355 0.713436555
32 5.922020278 0.173288271
33 6 0
*Y road weak medium ? ?

_AGE yIRI yVIR
0 1.5 10
1 1.603418482 9.77018115
2 1.713662748 9.525193894
3 1.830701158 9.265108538
4 1.954928533 8.989047703
5 2.08676183 8.696084822
6 2.226641347 8.385241452
7 2.375032006 8.05548443
8 2.532424699 7.705722892
9 2.699337699 7.334805113
10 2.876318163 6.941515193
11 3.063943701 6.524569554
12 3.262824035 6.082613255
13 3.473602752 5.614216107
14 3.696959138 5.117868583
15 3.933610125 4.5919775
16 4.184312334 4.034861481
17 4.449864225 3.444746167
18 4.731108371 2.819759175
19 5.028933848 2.157924782
20 5.344278749 1.457158335
21 5.678132842 0.715260351
22 6 0
*Y road weak light ? ?
_AGE yIRI yVIR
0 1.5 10
1 1.613969063 9.746735416
2 1.735845784 9.475898257
3 1.865565128 9.187633049
4 2.00359409 8.880902022
5 2.150426253 8.554608327
6 2.306583252 8.207592773
7 2.472616328 7.838630381
8 2.649107962 7.446426752
9 2.836673593 7.029614237
10 3.035963442 6.586747906
11 3.247664419 6.116301291
12 3.472502143 5.616661904
13 3.711243071 5.086126509
14 3.964696735 4.522896145
15 4.233718106 3.925070875
16 4.519210087 3.290644251
17 4.822126131 2.617497486
18 5.14347301 1.903393311
19 5.484313727 1.145969495
20 5.845770588 0.342732026
21 6 0
;------------------------------ PIPES YIELDS--
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*Y pipes concrete ? ? ?

_AGE ybci
0 100.00
1 98.33
2 96.51
3 94.55
4 92.45
5 90.22
6 87.87
7 85.43
8 82.90
9 80.31
10 77.66
11 74.97
12 72.27
13 69.55
14 66.84
15 64.15
16 61.49
17 58.86
18 56.28
19 53.75
20 51.27
21 48.87
22 46.53
23 44.26
24 42.06
25 39.94
26 37.90
27 35.93
28 34.04
29 32.23
30 30.49
31 28.83
32 27.24
33 25.73
34 24.29
35 22.91
36 21.61

37 20.37
38 19.19
39 18.07
40 17.01
41 16.00
42 15.05
43 14.15
44 13.30
45 12.50
46 11.74
47 11.03
48 10.35
49 9.72
50 9.12
51 8.55
52 8.02
53 7.52
54 7.05
55 6.61
56 6.19
57 5.80
58 5.43
59 5.09
60 4.77
61 4.46
62 4.18
63 3.91
64 3.66
65 3.42
66 3.20
67 3.00
68 2.80
69 2.62
70 2.45
71 2.29
72 2.14
73 2.00
74 1.87
75 1.75
76 1.64
77 1.53
78 1.43
79 1.34
80 1.25
81 1.17
82 1.09
83 1.02
84 0.95
85 0.89
86 0.83
87 0.78
88 0.72
89 0.68
90 0.63
91 0.59
92 0.55
93 0.51
94 0.48
95 0.45
96 0.42
97 0.39
98 0.37
99 0.34
100 0.32
*Y ? iron ? ? ?
_AGE ybci
0 100.00
1 94.84
2 89.96
3 85.24
4 80.62
5 76.08
6 71.60
7 67.20
8 62.90
9 58.71
10 54.65
11 50.74
12 46.99
13 43.41
14 40.02
15 36.82
16 33.80
17 30.97
18 28.34
19 25.88
20 23.60
21 21.49
22 19.54
23 17.75
24 16.10
25 14.59
26 13.21
27 11.94
28 10.79
29 9.74
30 8.79
31 7.92
32 7.14
33 6.42

34 5.78
35 5.20
36 4.67
37 4.19
38 3.77
39 3.38
40 3.03
41 2.72
42 2.44
43 2.18
44 1.95
45 1.75
46 1.57
47 1.40
48 1.25
49 1.12
50 1.00
51 0.90
52 0.80
53 0.72
54 0.64
55 0.57
56 0.51
57 0.46
58 0.41
59 0.36
60 0.32
61 0.29
62 0.26
63 0.23
64 0.21
65 0.18
66 0.16
67 0.15
68 0.13
69 0.12
70 0.10
71 0.09
72 0.08
73 0.07
74 0.07
75 0.06
76 0.05
77 0.05
78 0.04
79 0.04
80 0.03
81 0.03
82 0.03
83 0.02
84 0.02
85 0.02
86 0.02
87 0.01
88 0.01
89 0.01
90 0.01
91 0.01
92 0.01
93 0.01
94 0.01
95 0.01
96 0.01
97 0.00
98 0.00
99 0.00
100 0.00
*Y ? clay ? ? ?
_AGE ybci
0 100.00
1 92.68
2 85.87
3 79.30
4 72.87
5 66.58
6 60.48
7 54.62
8 49.06
9 43.84
10 38.98
11 34.51
12 30.43
13 26.73
14 23.40
15 20.43
16 17.78
17 15.43
18 13.36
19 11.55
20 9.96
21 8.58
22 7.37
23 6.32
24 5.42
25 4.64
26 3.97
27 3.39
28 2.89
29 2.46
30 2.10

31 1.78
32 1.52
33 1.29
34 1.09
35 0.93
36 0.79
37 0.67
38 0.56
39 0.48
40 0.40
41 0.34
42 0.29
43 0.24
44 0.21
45 0.17
46 0.15
47 0.12
48 0.11
49 0.09
50 0.07
51 0.06
52 0.05
53 0.04
54 0.04
55 0.03
56 0.03
57 0.02
58 0.02
59 0.02
60 0.01
61 0.01
62 0.01
63 0.01
64 0.01
65 0.01
66 0.00
67 0.00
68 0.00
69 0.00
70 0.00
71 0.00
72 0.00
73 0.00
74 0.00
75 0.00
76 0.00
77 0.00
78 0.00
79 0.00
80 0.00
81 0.00
82 0.00
83 0.00
84 0.00
85 0.00
86 0.00
87 0.00
88 0.00
89 0.00
90 0.00
91 0.00
92 0.00
93 0.00
94 0.00
95 0.00
96 0.00
97 0.00
98 0.00
99 0.00
100 0.00
*Y ? steel ? ? ?
_AGE ybci
0 100.00
1 97.64
2 94.83
3 91.51
4 87.73
5 83.59
6 79.18
7 74.60
8 69.96
9 65.33
10 60.78
11 56.36
12 52.12
13 48.07
14 44.23
15 40.62
16 37.25
17 34.10
18 31.17
19 28.47
20 25.97
21 23.67
22 21.56
23 19.62
24 17.85
25 16.23
26 14.74
27 13.39

28	12.16
29	11.04
30	10.02
31	9.09
32	8.24
33	7.48
34	6.78
35	6.15
36	5.57
37	5.05
38	4.58
39	4.15
40	3.76
41	3.41
42	3.09
43	2.80
44	2.53
45	2.30
46	2.08
47	1.88
48	1.71
49	1.55
50	1.40
51	1.27
52	1.15
53	1.04
54	0.94
55	0.85
56	0.77
57	0.70
58	0.63
59	0.57
60	0.52
61	0.47
62	0.43
63	0.39
64	0.35
65	0.32
66	0.29
67	0.26
68	0.24
69	0.21
70	0.19
71	0.18
72	0.16
73	0.14
74	0.13
75	0.12
76	0.11
77	0.10
78	0.09
79	0.08
80	0.07
81	0.07
82	0.06
83	0.05
84	0.05
85	0.04
86	0.04
87	0.04
88	0.03
89	0.03
90	0.03
91	0.02
92	0.02
93	0.02
94	0.02
95	0.02
96	0.01
97	0.01
98	0.01
99	0.01
100	0.01

*Y pipes PVC2 ? ? ?

_AGE	ybci
0	100
2	98.79
4	97.53
6	96.21
8	94.82
10	93.36
12	91.84
14	90.26
16	88.62
18	86.93
20	85.19
22	83.4
24	81.58
26	79.72
28	77.84
30	75.94
32	74.03
34	72.11
36	70.18
38	68.25
40	66.33
42	64.42
44	62.53
46	60.65
48	58.79

50 56.95
52 55.14
54 53.36
56 51.61
58 49.89
60 48.21
62 46.56
64 44.95
66 43.37
68 41.83
70 40.33
72 38.87
74 37.45
76 36.07
78 34.72
80 33.42
82 32.15
84 30.92
86 29.73
88 28.58
90 27.46
92 26.39
94 25.34
96 24.33
98 23.36
100 22.42
102 21.51
104 20.64
106 19.79
108 18.98
110 18.2
112 17.44
114 16.72
116 16.02
118 15.35
120 14.7
122 14.08
124 13.48
126 12.91
128 12.36
130 11.83
132 11.32
134 10.83
136 10.36
138 9.91
140 9.48
142 9.07
144 8.67
146 8.29
148 7.93
150 7.58
152 7.24
154 6.92
156 6.61
158 6.32
160 6.04
162 5.77
164 5.51
166 5.26
168 5.03
170 4.8
172 4.59
174 4.38
176 4.18
178 3.99
180 3.81
182 3.64
184 3.47
186 3.31
188 3.16
190 3.02
192 2.88
194 2.75
196 2.62
198 2.5
200 2.39
;*Y CV con liner ? marine small ydeterioration liner in concrete pipes in marine enviro
;_AGE ybci
;1 100
;12 60
;22 15
;30 1
;*Y CV con liner ? mar50 small ydeterioration liner in concrete pipes in 50% marine enviro
;_AGE ybci
;1 100
;20 60
;37 15
;50 0

;*Y CV con liner ? nonmar small ydeterioration liner in concrete pipes in non marine enviro
;_AGE ybci
;1 100
;30 65
;55 30

```
;75         0
*YT       pipes ? moyen ? ?
_AGE       y$liner          ;$/m
1          500
10         640                         ; actual quoted cost for 543m of 240,000 plus trench excavation and reconstruction of pavement
20         820
30         1050
40         1350
50         1720
*YT   pipes ? large ? ?
_AGE      y$liner
1         2500
10        3200
20        4096
30        5244
40        6713
50        8593

 {}
*YT      pipes ? small ? ?
_AGE     y$replace          ;$/m
 ; actual quoted cost for pipes
under 10 inches
1        210
10       269
20       344
30       440
40       564
50       721
*YT pipes ? moyen ? ?
_AGE   y$replace
1        1200
10       1536
20       1966
30       2517
40       3222
50       4124
*YT pipes ? large ? ?
_AGE    y$replace
1        4000
10       5120
20       6554
30       8390
40       10740
50       13748
;*YT        CV ? ? ? ? ? ? ? ? ?
;_AGE       y$piperehab          ;$/m
;1          5000
;
;*YC        CV ? ? under3 ? ? ? ? ? ?
;
;y$repcon        _TIMES(inflation,14000)
;y$repalmzed     _TIMES(inflation,10000)
;y$replace       _TIMES(inflation,200)
;
;*YC        ? ? ? ?
;
;y$repcon        _TIMES(inflation,15250)
;y$repalmzed     _TIMES(inflation,11250)
;y$repalum       _TIMES(inflation,14500)
;
;*YC         ? ? ? ?
;
;y$repcon        _TIMES(inflation,17500)
;y$repalmzed     _TIMES(inflation,12500)
;y$repalum       _TIMES(inflation,16875)
;
            ;---------Risk
*Y          pipes ac ? ? ? Risk curve
_AGE        yrisk
0          0
30         15
55         40
70         60
80         75
90         100
*Y           pipes iron ? ? ? Risk curve
_AGE        yrisk
1          1
30         15
60         50
74         75
80         100
;*Y                pipes steel ? ?   Risk curve ;concrete
;_AGE       yrisk
;1          1
;5          2
;10         5
;15         7
;20         10
;25         20
;30         35
;35         40
;40         55
;45         70
;50         80
;100        100
```

;*Y pipes ? ? ? Risk curve
;cast iron
;_AGE yrisk
;1 1
;5 2
;10 5
;15 10
;20 25
;25 45
;30 60
;35 70
;40 75
;45 85
;50 95
;100 100
;*Y CV con
Normal ? ? ? ? ? ? ? Risk curve
;_AGE yrisk
;1 1
;5 2
;10 5
;15 7
;20 10
;25 20
;30 35
;35 40
;40 50
;45 60
;50 75
;100 100
;
;*Y CV con
liner ? ? ? ? ? ? ? Risk curve
;_AGE yrisk
;1 1
;5 2
;10 5
;15 7
;20 10
;25 20
;30 35
;35 40
;40 50
;45 60
;50 75
;100 100
;
;*Y CV almum liner ? ? ? ? ? ? ? Risk curve
;_AGE yrisk
;1 1
;5 2
;10 5
;15 7
;20 10
;25 20
;30 35
;35 40
;40 50
;45 60
;50 75
;100 100

TRANSITIONS SECTION

; Outputs (Aggregation)
*OUTPUT ototaltreatmentsroads
*SOURCE road ? ? ? ? _INVENT _AREA (summation over area in m2)
*OUTPUT ototaltreatmentspipes
*SOURCE pipes ? ? ? ? _INVENT _AREA (summation over lenght
*OUTPUT oTotallenght ; RETURN THE TOTAL LENGHT OF PAVEMENTS
*SOURCE road ? ? ? ? _INVENT _AREA
*OUTPUT oTotalVIR ; RETURN DE SUM OF ALL THE PCI VALUES each year
*SOURCE road ? ? ? ? _INVENT yVIR
*OUTPUT OavrgVIR ; COMPUTE THE AVERAGE VALUE OF PCI
*SOURCE oTotalVIR / oTotallenght
*OUTPUT oTotIRI(_TH2)
*SOURCE road ? ? ? ? _INVENT yIRI
*OUTPUT oAvrgIRI(_TH2)
*SOURCE ototIRI / ototallenght
*OUTPUT oAvrgVIR_scaled
*SOURCE oAvrgVIR * 10
;--------------ASSET VALUE
*OUTPUT oTotValueROAD Value of Roads
*SOURCE road ? ? ? ? _INVENT yValue ; go to the area table and get the yValue
*OUTPUT oTotValuePIPE Value of Pipes
*SOURCE pipes ? ? ? ? _INVENT yValue ; go to the area table and get the yValue
*OUTPUT oVALUEROAD Value of roads

*SOURCE oTotValueROAD * yinflation
*OUTPUT oVALUEPipe Value of pipes
*SOURCE oTotValuePIPE * yinflation
*OUTPUT odiscVALUEROAD Present value of roads
*SOURCE oValueROAD * ydiscount
*OUTPUT odiscVALUEPipe Present value of pipes
*SOURCE oValuePIPE * ydiscount
*OUTPUT VALUEALL Value of all assets
*SOURCE ototVALUEPipe + ototVALUEROAD
;--------------------LENGTH classes etc-------------------------------
*OUTPUT om2CS(_TH5)
*SOURCE road ? ? ? ? aCS _AREA ; total area of Crack Sealing TREATMENT
*OUTPUT om2PA(_TH5)
*SOURCE road ? ? ? ? aPA _AREA ; total area (m2) Patching TREATMENT
*OUTPUT om2MS(_TH5)
*SOURCE road ? ? ? ? aMS _AREA ; total area (m2) Patching TREATMENT
*OUTPUT om2RS(_TH5)
*SOURCE road ? ? ? ? aRS _AREA ;total are of resurfacing TREATMENT
*OUTPUT om2RC(_TH5)
*SOURCE road ? ? ? ? aRC _AREA ;total area reconstruction TREATMENT
*OUTPUT oWEAK
*SOURCE road weak ? ? ? aRC _AREA ;total area reconstruction TREATMENT
*OUTPUT oSTRONG
*SOURCE road strong ? ? ? aRC _AREA ;total area reconstruction TREATMENT
*OUTPUT oHIGHintensity
*SOURCE road ? high ? ? aRC _AREA ;total area reconstruction TREATMENT
*OUTPUT oMEDIUMintensity
*SOURCE road ? medium ? ? aRC _AREA ;total area reconstruction TREATMENT
*OUTPUT oLOWintensity
*SOURCE road ? light ? ? aRC _AREA ;total area reconstruction TREATMENT
*OUTPUT olining(_TH5)
*SOURCE ? ? ? ? ? aliner _AREA ;total area reconstruction TREATMENT
*OUTPUT oreplacement(_TH5)
*SOURCE ? ? ? ? ? areplace _AREA ;total area reconstruction TREATMENT
*OUTPUT om2aRepairROAD
*SOURCE ? ? ? ? ? aRepairROAD _AREA
*OUTPUT om2aRepairPIPE
*SOURCE ? ? ? ? ? aRepairPIPE _AREA
*OUTPUT oCScost
*SOURCE road ? ? ? ? aCS yCS$;total expenditure of A TREATMENT
*OUTPUT oPAcost
*SOURCE road ? ? ? ? aPA yPA$;total expenditure of B TREATMENT
*OUTPUT oMScost
*SOURCE road ? ? ? ? aMS yMS$;total expenditure of B TREATMENT
*OUTPUT oRScost
*SOURCE road ? ? ? ? aRS yRS$;total expenditure of C TREATMENT
*OUTPUT oRCcost
*SOURCE road ? ? ? ? aRC yRC$; total expenditure oF D TREATMENT
*OUTPUT oTot$Spend
*SOURCE oCScost + oPAcost + oRScost + oRCcost + oMScost
;====== Asset condition =====
*OUTPUT Good_Roads Roads in Good Condition
*SOURCE road ? ? ? ? @YLD(yVIR,7.5..10) _INVENT _AREA
*OUTPUT Fair_Roads Roads in Fair Condition
*SOURCE road ? ? ? ? @YLD(yVIR,5..7.49999999999) _INVENT _AREA
*OUTPUT Poor_Roads Roads in Poor Condition
*SOURCE road ? ? ? ? @YLD(yVIR,2.5..4.99999999999) _INVENT _AREA
*OUTPUT VeryPoor_Roads Roads in Very poor Condition
*SOURCE road ? ? ? ? @YLD(yVIR,0..2.49999999999) _INVENT _AREA
*OUTPUT Killroads
*SOURCE road ? ? ? ? @YLD(yVIR,0..5) _INVENT _AREA
;--------------------OUPUTS PIPES
;--------------------------------OUPUTS--------------------------------
*OUTPUT oTotPIPECI(_TH1) Total Pipes CI

*SOURCE pipes ? ? ? ? _INVENT ybci
*OUTPUT ototpipelength(_TH1) Total length of pipes
*SOURCE pipes ? ? ? ? _INVENT _AREA
*OUTPUT ototroadlength(_TH1) Total length of roads
*SOURCE road ? ? ? ? _INVENT _AREA

*OUTPUT ototalpvc2(_TH1) Total pvc
*SOURCE pipes pvc2 ? ? ? _INVENT _AREA
*OUTPUT ototaliron(_TH1) Total iron
*SOURCE pipes iron ? ? ? _INVENT _AREA
*OUTPUT ototalsteel(_TH1) Total steel
*SOURCE pipes steel ? ? ? _INVENT _AREA
*OUTPUT ototalAC(_TH1) Total concrete
*SOURCE ? concrete ? ? ? _INVENT _AREA
*OUTPUT ototSTORMlength
*SOURCE storm ? ? ? ? _INVENT _AREA
*OUTPUT ototSANITARYlength
*SOURCE sanitary ? ? ? ? _INVENT _AREA
*OUTPUT ototWATERMAINlength
*SOURCE wm ? ? ? ? _INVENT _AREA
*OUTPUT ototstormCI
*SOURCE storm ? ? ? ? _INVENT ybci
*OUTPUT ototsanitaryCI
*SOURCE sanitary ? ? ? ? _INVENT ybci
*OUTPUT ototwatermainCI
*SOURCE wm ? ? ? ? _INVENT ybci
*OUTPUT oavestormci
*SOURCE ototstormci / ototstormlength
*OUTPUT oavesanitaryci
*SOURCE ototsanitaryci / ototsanitarylength
*OUTPUT oavewatermainci
*SOURCE ototwatermainci / ototwatermainlength
;average
*OUTPUT oavepipeci ; Average Culvert BCI
*SOURCE ototpipeci / ototpipelength
;------------------average cond pvc
*OUTPUT oTotCIpvc Total PVC and plastic Condition Index
*SOURCE pipes pvc2 ? ? ? _INVENT ybci
*OUTPUT ototlengthpvc(_TH1) Total length of PVC all pipe
*SOURCE pipes pvc2 ? ? ? _INVENT _AREA
;average
*OUTPUT oavecipvc ; Average Culvert BCI
*SOURCE ototcipvc / ototlengthpvc
;--
;------------------average cond CI and UCI
*OUTPUT oTotwmCIiron Total iron Condition index
*SOURCE pipes iron ? ? ? _INVENT ybci
*OUTPUT ototwmlengthiron(_TH1) Total length of iron all pipe
*SOURCE pipes iron ? ? ? _INVENT _AREA
;average
*OUTPUT oavewmciiron ; Average Culvert BCI
*SOURCE ototwmciiron / ototwmlengthiron
;--
;------------------average cond Asbestos cement
*OUTPUT oTotwmCIac Total concrete Condition Index
*SOURCE pipes concrete ? ? ? _INVENT ybci
*OUTPUT ototwmlengthac(_TH1) Total length of concrete all pipe
*SOURCE pipes concrete ? ? ? _INVENT _AREA
;average
*OUTPUT oavewmciac ; Average Culvert BCI
*SOURCE ototwmciac / ototwmlengthac
;--
;------- replacement / rehabilitation costs-----
----
*OUTPUT qtyreplace(_TH1) qty of replaced pipe
*SOURCE pipes ? ? ? ? areplace _AREA
*OUTPUT qtyliner
*SOURCE pipes ? ? ? ? aliner _AREA
;*OUTPUT qtyrehab(_TH1) qty of rehab pipe
;*SOURCE CV ? ? ? ? ? ? ? ? ? arehab _AREA

```
;*OUTPUT qtyliner(_TH1) qty of liner installed
;*SOURCE cv ? ? ? ? ? ? ? ? ? aliner _AREA
;-----------
;*OUTPUT oTot$rehab Cost of rehab pipes
;*SOURCE CV ? ? ? ? ? ? ? ? ? arehab y$piperehab
;*OUTPUT otot$liner Cost of liner installed
;*SOURCE cv ? ? ? ? ? ? ? ? ? aliner yliner
;*************** COST PIPES *********************
*OUTPUT otot$replacestorm
*SOURCE storm ? ? ? ? areplace y$replace
*OUTPUT otot$replacesanitary
*SOURCE sanitary ? ? ? ? areplace y$replace
*OUTPUT otot$replacewatermain
*SOURCE wm ? ? ? ? areplace y$replace
*OUTPUT otot$linerstorm
*SOURCE storm ? ? ? ? aliner y$liner
*OUTPUT otot$linersanitary
*SOURCE sanitary ? ? ? ? aliner y$liner
*OUTPUT otot$linerwatermain
*SOURCE wm ? ? ? ? aliner y$liner
*OUTPUT oTot$replace Cost of replaced pipes
*SOURCE otot$replacestorm + otot$replacesanitary + otot$replacewatermain
*OUTPUT oTot$liner Cost of lining pipes
*SOURCE otot$linerstorm + otot$linersanitary + otot$linerwatermain
*OUTPUT ototPIPE$spent Total spent on Pipes
*SOURCE otot$replace + oTot$liner
*OUTPUT otot$expenditure
*SOURCE ototPIPE$spent + oTot$Spend
;*OUTPUT ototwm$spent_disc Total spent discounted
; *SOURCE ototwm$spent * ydiscount
; ****************condition states*************************
*OUTPUT Vpoor_pvc(_TH1)
*SOURCE pipes pvc2 ? ? ? @YLD(ybci,0..17.99999999999) _INVENT _AREA
*OUTPUT Vpoor_iron(_TH1)
*SOURCE pipes iron ? ? ? @YLD(ybci,0..17.99999999999) _INVENT _AREA
*OUTPUT Vpoor_ac(_TH1)
*SOURCE pipes concrete ? ? ? @YLD(ybci,0..17.99999999999) _INVENT _AREA
*OUTPUT Vpoor_steel(_TH1)
*SOURCE pipes steel ? ? ? @YLD(ybci,0..17.99999999999) _INVENT _AREA
*OUTPUT Vpoor_pipes Length of very poor Pipes
*SOURCE Vpoor_pvc + Vpoor_iron + Vpoor_ac + Vpoor_steel
*OUTPUT poor_pvc(_TH1)
*SOURCE pipes pvc2 ? ? ? @YLD(ybci,18..29.99999999999) _INVENT _AREA
*OUTPUT poor_iron(_TH1)
*SOURCE pipes iron ? ? ? @YLD(ybci,18..29.99999999999) _INVENT _AREA
*OUTPUT poor_ac(_TH1)
*SOURCE pipes concrete ? ? ? @YLD(ybci,18..29.99999999999) _INVENT _AREA
*OUTPUT poor_steel(_TH1)
*SOURCE pipes steel ? ? ? @YLD(ybci,18..29.99999999999) _INVENT _AREA
*OUTPUT poor_pipes(_TH2) Length of poor Pipes
*SOURCE poor_pvc + poor_ac + poor_steel + poor_iron
*OUTPUT fair_pvc(_TH1)
*SOURCE pipes pvc2 ? ? ? @YLD(ybci,30..49.9999999999) _INVENT _AREA
*OUTPUT fair_iron(_TH1)
*SOURCE pipes iron ? ? ? @YLD(ybci,30..49.9999999999) _INVENT _AREA
*OUTPUT fair_ac(_TH1)
*SOURCE pipes concrete ? ? ? @YLD(ybci,30..49.9999999999) _INVENT _AREA
*OUTPUT fair_steel(_TH1)
```

*SOURCE pipes steel ? ? ? @YLD(ybci,30..49.99999999999) _INVENT _AREA
*OUTPUT fair_pipes(_TH2) Length of fair culverts
*SOURCE fair_pvc + fair_iron + fair_ac + fair_steel
*OUTPUT good_pvc(_TH1)
*SOURCE pipes pvc2 ? ? ? @YLD(ybci,50..74.99999999999) _INVENT _AREA
*OUTPUT good_iron(_TH1)
*SOURCE pipes iron ? ? ? @YLD(ybci,50..74.99999999999) _INVENT _AREA
*OUTPUT good_ac(_TH1)
*SOURCE ? concrete ? ? ? @YLD(ybci,50..74.99999999999) _INVENT _AREA
*OUTPUT good_steel(_TH1)
*SOURCE ? steel ? ? ? @YLD(ybci,50..74.99999999999) _INVENT _AREA
*OUTPUT good_pipes(_TH2) length of good Pipes
*SOURCE good_pvc + good_iron + good_steel
*OUTPUT vgood_pvc(_TH1)
*SOURCE ? pvc2 ? ? ? @YLD(ybci,75..100) _INVENT _AREA
*OUTPUT Vgood_iron(_TH1)
*SOURCE ? iron ? ? ? @YLD(ybci,75..100) _INVENT _AREA
*OUTPUT Vgood_ac(_TH1)
*SOURCE ? concrete ? ? ? @YLD(ybci,75..100) _INVENT _AREA
*OUTPUT Vgood_steel(_TH1)
*SOURCE ? steel ? ? ? @YLD(ybci,75..100) _INVENT _AREA
*OUTPUT VGood_pipes(_TH2) Length of Very Good Pipes
*SOURCE vgood_pvc + vgood_iron + vgood_ac + vgood_steel

Contractor's intervention cost per period for period 1-2-3-4 & 5

Period 1

Destination/Contractors	Product/Treatment	Theme 5/Area	Origin-Destination COST
Contractor_1	Crack sealing	Downtown	0.3
Contractor_1	Crack sealing	Hwy frontage	0.26
Contractor_1	Crack sealing	Industrial park	1
Contractor_1	Crack sealing	Rosedale	0.3
Contractor_1	Patching	Downtown	4.2
Contractor_1	Patching	Hwy frontage	3.7
Contractor_1	Patching	Industrial park	6
Contractor_1	Patching	Rosedale	4
Contractor_1	Microsurfacing	Downtown	6.66
Contractor_1	Microsurfacing	Hwy frontage	6
Contractor_1	Microsurfacing	Industrial park	9
Contractor_1	Microsurfacing	Rosedale	6.7
Contractor_2	Resurfacing	Downtown	24.5
Contractor_2	Resurfacing	Hwy frontage	24
Contractor_2	Resurfacing	Industrial park	44
Contractor_2	Resurfacing	Rosedale	25
Contractor_2	Reconstruction	Downtown	44.5
Contractor_2	Reconstruction	Hwy frontage	41
Contractor_2	Reconstruction	Industrial park	55

Destination/Contractors	Product/Treatment	Theme 5/Area	Origin-Destination COST
Contractor_2	Reconstruction	Rosedale	44
Contractor_3	Microsurfacing	Downtown	6.74
Contractor_3	Microsurfacing	Hwy frontage	6.1
Contractor_3	Microsurfacing	Industrial park	9
Contractor_3	Microsurfacing	Rosedale	6.7
Contractor_3	Resurfacing	Downtown	25.3
Contractor_3	Resurfacing	Hwy frontage	23
Contractor_3	Resurfacing	Industrial park	44
Contractor_3	Resurfacing	Rosedale	25
Contractor_3	Reconstruction	Downtown	46
Contractor_3	Reconstruction	Hwy frontage	41
Contractor_3	Reconstruction	Industrial park	55
Contractor_3	Reconstruction	Rosedale	44
Contractor_4	Patching	Downtown	4
Contractor_4	Patching	Hwy frontage	3.6
Contractor_4	Patching	Industrial park	6
Contractor_4	Patching	Rosedale	4
Contractor_4	Reconstruction	Downtown	46.5
Contractor_4	Reconstruction	Hwy frontage	41
Contractor_4	Reconstruction	Industrial park	55
Contractor_4	Reconstruction	Rosedale	44
Contractor_4	Pipe lining	Downtown	1350
Contractor_4	Pipe lining	Hwy frontage	666

Destination/Contractors	Product/Treatment	Theme 5/Area	Origin-Destination COST
Contractor_4	Pipe lining	Industrial park	1111
Contractor_4	Pipe lining	Rosedale	1111
Contractor_5	Reconstruction	Downtown	44.88
Contractor_5	Reconstruction	Hwy frontage	41
Contractor_5	Reconstruction	Industrial park	55
Contractor_5	Reconstruction	Rosedale	44
Contractor_5	Pipe lining	Downtown	1500
Contractor_5	Pipe lining	Hwy frontage	777
Contractor_5	Pipe lining	Industrial park	1111
Contractor_5	Pipe lining	Rosedale	1111
Contractor_5	Pipe replacement	Downtown	4000
Contractor_5	Pipe replacement	Hwy frontage	1111
Contractor_5	Pipe replacement	Industrial park	2222
Contractor_5	Pipe replacement	Rosedale	2222

Period 2

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_1	Crack-Sealing	Downtown	2	0.30
Contractor_1	Crack-Sealing	Hwy frontage	2	0.26
Contractor_1	Crack-Sealing	Industrial park	2	1.00
Contractor_1	Crack-Sealing	Rosedale	2	0.30
Contractor_1	Patching	Downtown	2	4.20

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_1	Patching	Hwy frontage	2	3.70
Contractor_1	Patching	Industrial park	2	6.00
Contractor_1	Patching	Rosedale	2	4.00
Contractor_1	Micro-Surfacing	Downtown	2	6.66
Contractor_1	Micro-Surfacing	Hwy frontage	2	6.00
Contractor_1	Micro-Surfacing	Industrial park	2	9.00
Contractor_1	Micro-Surfacing	Rosedale	2	6.70
Contractor_2	Resurfacing	Downtown	2	24.50
Contractor_2	Resurfacing	Hwy frontage	2	24.00
Contractor_2	Resurfacing	Industrial park	2	44.00
Contractor_2	Resurfacing	Rosedale	2	25.00
Contractor_2	Reconstruction	Downtown	2	44.50
Contractor_2	Reconstruction	Hwy frontage	2	41.00
Contractor_2	Reconstruction	Industrial park	2	55.00
Contractor_2	Reconstruction	Rosedale	2	44.00
Contractor_3	Micro-Surfacing	Downtown	2	6.74
Contractor_3	Micro-Surfacing	Hwy frontage	2	6.10
Contractor_3	Micro-Surfacing	Industrial park	2	9.00
Contractor_3	Micro-Surfacing	Rosedale	2	6.70
Contractor_3	Resurfacing	Downtown	2	25.30
Contractor_3	Resurfacing	Hwy frontage	2	23.00

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_3	Resurfacing	Industrial park	2	44.00
Contractor_3	Resurfacing	Rosedale	2	25.00
Contractor_3	Reconstruction	Downtown	2	46.00
Contractor_3	Reconstruction	Hwy frontage	2	41.00
Contractor_3	Reconstruction	Industrial park	2	55.00
Contractor_3	Reconstruction	Rosedale	2	44.00
Contractor_4	Patching	Downtown	2	4.00
Contractor_4	Patching	Hwy frontage	2	3.60
Contractor_4	Patching	Industrial park	2	6.00
Contractor_4	Patching	Rosedale	2	4.00
Contractor_4	Reconstruction	Downtown	2	46.50
Contractor_4	Reconstruction	Hwy frontage	2	41.00
Contractor_4	Reconstruction	Industrial park	2	55.00
Contractor_4	Reconstruction	Rosedale	2	44.00
Contractor_4	Pipe Lining	Downtown	2	1350.00
Contractor_4	Pipe Lining	Hwy frontage	2	666.00
Contractor_4	Pipe Lining	Industrial park	2	1111.00
Contractor_4	Pipe Lining	Rosedale	2	1111.00
Contractor_5	Reconstruction	Downtown	2	44.88
Contractor_5	Reconstruction	Hwy frontage	2	41.00
Contractor_5	Reconstruction	Industrial park	2	55.00

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_5	Reconstruction	Rosedale	2	44.00
Contractor_5	Pipe Lining	Downtown	2	1500.00
Contractor_5	Pipe Lining	Hwy frontage	2	777.00
Contractor_5	Pipe Lining	Industrial park	2	1111.00
Contractor_5	Pipe Lining	Rosedale	2	1111.00
Contractor_5	Pipe replacement	Downtown	2	4000.00
Contractor_5	Pipe replacement	Hwy frontage	2	1111.00
Contractor_5	Pipe replacement	Industrial park	2	2222.00
Contractor_5	Pipe replacement	Rosedale	2	2222.00

Period 3

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_1	Crack-Sealing	Downtown	3	0.30
Contractor_1	Crack-Sealing	Hwy frontage	3	0.26
Contractor_1	Crack-Sealing	Industrial park	3	1.00
Contractor_1	Crack-Sealing	Rosedale	3	0.30
Contractor_1	Patching	Downtown	3	4.20
Contractor_1	Patching	Hwy frontage	3	3.70
Contractor_1	Patching	Industrial park	3	6.00
Contractor_1	Patching	Rosedale	3	4.00
Contractor_1	Micro-Surfacing	Downtown	3	6.66

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_1	Micro-Surfacing	Hwy frontage	3	6.00
Contractor_1	Micro-Surfacing	Industrial park	3	9.00
Contractor_1	Micro-Surfacing	Rosedale	3	6.70
Contractor_2	Resurfacing	Downtown	3	24.50
Contractor_2	Resurfacing	Hwy frontage	3	24.00
Contractor_2	Resurfacing	Industrial park	3	44.00
Contractor_2	Resurfacing	Rosedale	3	25.00
Contractor_2	Reconstruction	Downtown	3	44.50
Contractor_2	Reconstruction	Hwy frontage	3	41.00
Contractor_2	Reconstruction	Industrial park	3	55.00
Contractor_2	Reconstruction	Rosedale	3	44.00
Contractor_3	Micro-Surfacing	Downtown	3	6.74
Contractor_3	Micro-Surfacing	Hwy frontage	3	6.10
Contractor_3	Micro-Surfacing	Industrial park	3	9.00
Contractor_3	Micro-Surfacing	Rosedale	3	6.70
Contractor_3	Resurfacing	Downtown	3	25.30
Contractor_3	Resurfacing	Hwy frontage	3	23.00
Contractor_3	Resurfacing	Industrial park	3	44.00
Contractor_3	Resurfacing	Rosedale	3	25.00
Contractor_3	Reconstruction	Downtown	3	46.00
Contractor_3	Reconstruction	Hwy frontage	3	41.00

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_3	Reconstruction	Industrial park	3	55.00
Contractor_3	Reconstruction	Rosedale	3	44.00
Contractor_4	Patching	Downtown	3	4.00
Contractor_4	Patching	Hwy frontage	3	3.60
Contractor_4	Patching	Industrial park	3	6.00
Contractor_4	Patching	Rosedale	3	4.00
Contractor_4	Reconstruction	Downtown	3	46.50
Contractor_4	Reconstruction	Hwy frontage	3	41.00
Contractor_4	Reconstruction	Industrial park	3	55.00
Contractor_4	Reconstruction	Rosedale	3	44.00
Contractor_4	Pipe Lining	Downtown	3	1350.00
Contractor_4	Pipe Lining	Hwy frontage	3	666.00
Contractor_4	Pipe Lining	Industrial park	3	1111.00
Contractor_4	Pipe Lining	Rosedale	3	1111.00
Contractor_5	Reconstruction	Downtown	3	44.88
Contractor_5	Reconstruction	Hwy frontage	3	41.00
Contractor_5	Reconstruction	Industrial park	3	55.00
Contractor_5	Reconstruction	Rosedale	3	44.00
Contractor_5	Pipe Lining	Downtown	3	1500.00
Contractor_5	Pipe Lining	Hwy frontage	3	777.00
Contractor_5	Pipe Lining	Industrial park	3	1111.00

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_5	Pipe Lining	Rosedale	3	1111.00
Contractor_5	Pipe replacement	Downtown	3	4000.00
Contractor_5	Pipe replacement	Hwy frontage	3	1111.00
Contractor_5	Pipe replacement	Industrial park	3	2222.00
Contractor_5	Pipe replacement	Rosedale	3	2222.00

Period 4

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_1	Crack-Sealing	Downtown	4	0.30
Contractor_1	Crack-Sealing	Hwy frontage	4	0.26
Contractor_1	Crack-Sealing	Industrial park	4	1.00
Contractor_1	Crack-Sealing	Rosedale	4	0.30
Contractor_1	Patching	Downtown	4	4.20
Contractor_1	Patching	Hwy frontage	4	3.70
Contractor_1	Patching	Industrial park	4	6.00
Contractor_1	Patching	Rosedale	4	4.00
Contractor_1	Micro-Surfacing	Downtown	4	6.66
Contractor_1	Micro-Surfacing	Hwy frontage	4	6.00
Contractor_1	Micro-Surfacing	Industrial park	4	9.00
Contractor_1	Micro-Surfacing	Rosedale	4	6.70
Contractor_2	Resurfacing	Downtown	4	24.50

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_2	Resurfacing	Hwy frontage	4	24.00
Contractor_2	Resurfacing	Industrial park	4	44.00
Contractor_2	Resurfacing	Rosedale	4	25.00
Contractor_2	Reconstruction	Downtown	4	44.50
Contractor_2	Reconstruction	Hwy frontage	4	41.00
Contractor_2	Reconstruction	Industrial park	4	55.00
Contractor_2	Reconstruction	Rosedale	4	44.00
Contractor_3	Micro-Surfacing	Downtown	4	6.74
Contractor_3	Micro-Surfacing	Hwy frontage	4	6.10
Contractor_3	Micro-Surfacing	Industrial park	4	9.00
Contractor_3	Micro-Surfacing	Rosedale	4	6.70
Contractor_3	Resurfacing	Downtown	4	25.30
Contractor_3	Resurfacing	Hwy frontage	4	23.00
Contractor_3	Resurfacing	Industrial park	4	44.00
Contractor_3	Resurfacing	Rosedale	4	25.00
Contractor_3	Reconstruction	Downtown	4	46.00
Contractor_3	Reconstruction	Hwy frontage	4	41.00
Contractor_3	Reconstruction	Industrial park	4	55.00
Contractor_3	Reconstruction	Rosedale	4	44.00
Contractor_4	Patching	Downtown	4	4.00
Contractor_4	Patching	Hwy frontage	4	3.60

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_4	Patching	Industrial park	4	6.00
Contractor_4	Patching	Rosedale	4	4.00
Contractor_4	Reconstruction	Downtown	4	46.50
Contractor_4	Reconstruction	Hwy frontage	4	41.00
Contractor_4	Reconstruction	Industrial park	4	55.00
Contractor_4	Reconstruction	Rosedale	4	44.00
Contractor_4	Pipe Lining	Downtown	4	1350.00
Contractor_4	Pipe Lining	Hwy frontage	4	666.00
Contractor_4	Pipe Lining	Industrial park	4	1111.00
Contractor_4	Pipe Lining	Rosedale	4	1111.00
Contractor_5	Reconstruction	Downtown	4	44.88
Contractor_5	Reconstruction	Hwy frontage	4	41.00
Contractor_5	Reconstruction	Industrial park	4	55.00
Contractor_5	Reconstruction	Rosedale	4	44.00
Contractor_5	Pipe Lining	Downtown	4	1500.00
Contractor_5	Pipe Lining	Hwy frontage	4	777.00
Contractor_5	Pipe Lining	Industrial park	4	1111.00
Contractor_5	Pipe Lining	Rosedale	4	1111.00
Contractor_5	Pipe replacement	Downtown	4	4000.00
Contractor_5	Pipe replacement	Hwy frontage	4	1111.00
Contractor_5	Pipe replacement	Industrial park	4	2222.00

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_5	Pipe replacement	Rosedale	4	2222.00

Period 5

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_1	Crack-Sealing	Downtown	5	0.30
Contractor_1	Crack-Sealing	Hwy frontage	5	0.26
Contractor_1	Crack-Sealing	Industrial park	5	1.00
Contractor_1	Crack-Sealing	Rosedale	5	0.30
Contractor_1	Patching	Downtown	5	4.20
Contractor_1	Patching	Hwy frontage	5	3.70
Contractor_1	Patching	Industrial park	5	6.00
Contractor_1	Patching	Rosedale	5	4.00
Contractor_1	Micro-Surfacing	Downtown	5	6.66
Contractor_1	Micro-Surfacing	Hwy frontage	5	6.00
Contractor_1	Micro-Surfacing	Industrial park	5	9.00
Contractor_1	Micro-Surfacing	Rosedale	5	6.70
Contractor_2	Resurfacing	Downtown	5	24.50
Contractor_2	Resurfacing	Hwy frontage	5	24.00
Contractor_2	Resurfacing	Industrial park	5	44.00
Contractor_2	Resurfacing	Rosedale	5	25.00
Contractor_2	Reconstruction	Downtown	5	44.50

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_2	Reconstruction	Hwy frontage	5	41.00
Contractor_2	Reconstruction	Industrial park	5	55.00
Contractor_2	Reconstruction	Rosedale	5	44.00
Contractor_3	Micro-Surfacing	Downtown	5	6.74
Contractor_3	Micro-Surfacing	Hwy frontage	5	6.10
Contractor_3	Micro-Surfacing	Industrial park	5	9.00
Contractor_3	Micro-Surfacing	Rosedale	5	6.70
Contractor_3	Resurfacing	Downtown	5	25.30
Contractor_3	Resurfacing	Hwy frontage	5	23.00
Contractor_3	Resurfacing	Industrial park	5	44.00
Contractor_3	Resurfacing	Rosedale	5	25.00
Contractor_3	Reconstruction	Downtown	5	46.00
Contractor_3	Reconstruction	Hwy frontage	5	41.00
Contractor_3	Reconstruction	Industrial park	5	55.00
Contractor_3	Reconstruction	Rosedale	5	44.00
Contractor_4	Patching	Downtown	5	4.00
Contractor_4	Patching	Hwy frontage	5	3.60
Contractor_4	Patching	Industrial park	5	6.00
Contractor_4	Patching	Rosedale	5	4.00
Contractor_4	Reconstruction	Downtown	5	46.50
Contractor_4	Reconstruction	Hwy frontage	5	41.00

Destination/Contractors	Product/Treatment	Themes/Area	Period	Origin-Destination COST
Contractor_4	Reconstruction	Industrial park	5	55.00
Contractor_4	Reconstruction	Rosedale	5	44.00
Contractor_4	Pipe Lining	Downtown	5	1350.00
Contractor_4	Pipe Lining	Hwy frontage	5	666.00
Contractor_4	Pipe Lining	Industrial park	5	1111.00
Contractor_4	Pipe Lining	Rosedale	5	1111.00
Contractor_5	Reconstruction	Downtown	5	44.88
Contractor_5	Reconstruction	Hwy frontage	5	41.00
Contractor_5	Reconstruction	Industrial park	5	55.00
Contractor_5	Reconstruction	Rosedale	5	44.00
Contractor_5	Pipe Lining	Downtown	5	1500.00
Contractor_5	Pipe Lining	Hwy frontage	5	777.00
Contractor_5	Pipe Lining	Industrial park	5	1111.00
Contractor_5	Pipe Lining	Rosedale	5	1111.00
Contractor_5	Pipe replacement	Downtown	5	4000.00
Contractor_5	Pipe replacement	Hwy frontage	5	1111.00
Contractor_5	Pipe replacement	Industrial park	5	2222.00
Contractor_5	Pipe replacement	Rosedale	5	2222.00

Interventions processed and delivered by contractors 3, 4 and 5 for 30 years period

Contractor 3

Destination/contractor	Period	Product/ interventions	Delivered/Processed
Contractor_3	1	Microsurfacing	8331.53
Contractor_3	1	Reconstruction	0.00
Contractor_3	1	Resurfacing	0.00
Contractor_3	2	Microsurfacing	0.00
Contractor_3	2	Reconstruction	0.00
Contractor_3	2	Resurfacing	0.00
Contractor_3	3	Microsurfacing	0.00
Contractor_3	3	Reconstruction	0.00
Contractor_3	3	Resurfacing	0.00
Contractor_3	4	Microsurfacing	0.00
Contractor_3	4	Reconstruction	0.00
Contractor_3	4	Resurfacing	0.00
Contractor_3	5	Microsurfacing	0.00
Contractor_3	5	Reconstruction	0.00
Contractor_3	5	Resurfacing	0.00
Contractor_3	6	Microsurfacing	52.28
Contractor_3	6	Reconstruction	0.00
Contractor_3	6	Resurfacing	0.00
Contractor_3	7	Microsurfacing	0.00
Contractor_3	7	Reconstruction	0.00
Contractor_3	7	Resurfacing	0.00
Contractor_3	8	Microsurfacing	0.00
Contractor_3	8	Reconstruction	0.00
Contractor_3	8	Resurfacing	0.00
Contractor_3	9	Microsurfacing	0.00
Contractor_3	9	Reconstruction	0.00
Contractor_3	9	Resurfacing	0.00
Contractor_3	10	Microsurfacing	0.00

Destination/contractor	Period	Product/ interventions	Delivered/Processed
Contractor_3	10	Reconstruction	0.00
Contractor_3	10	Resurfacing	0.00
Contractor_3	11	Microsurfacing	0.00
Contractor_3	11	Reconstruction	0.00
Contractor_3	11	Resurfacing	0.00
Contractor_3	12	Microsurfacing	0.00
Contractor_3	12	Reconstruction	0.00
Contractor_3	12	Resurfacing	0.00
Contractor_3	13	Microsurfacing	0.00
Contractor_3	13	Reconstruction	0.00
Contractor_3	13	Resurfacing	0.00
Contractor_3	14	Microsurfacing	0.00
Contractor_3	14	Reconstruction	0.00
Contractor_3	14	Resurfacing	0.00
Contractor_3	15	Microsurfacing	0.00
Contractor_3	15	Reconstruction	0.00
Contractor_3	15	Resurfacing	0.00
Contractor_3	16	Microsurfacing	0.00
Contractor_3	16	Reconstruction	0.00
Contractor_3	16	Resurfacing	0.00
Contractor_3	17	Microsurfacing	0.00
Contractor_3	17	Reconstruction	0.00
Contractor_3	17	Resurfacing	0.00
Contractor_3	18	Microsurfacing	0.00
Contractor_3	18	Reconstruction	0.00
Contractor_3	18	Resurfacing	0.00
Contractor_3	19	Microsurfacing	0.00
Contractor_3	19	Reconstruction	0.00
Contractor_3	19	Resurfacing	0.00

Destination/contractor	Period	Product/ interventions	Delivered/Processed
Contractor_3	20	Microsurfacing	0.00
Contractor_3	20	Reconstruction	0.00
Contractor_3	20	Resurfacing	0.00
Contractor_3	21	Microsurfacing	0.00
Contractor_3	21	Reconstruction	0.00
Contractor_3	21	Resurfacing	0.00
Contractor_3	22	Microsurfacing	0.00
Contractor_3	22	Reconstruction	0.00
Contractor_3	22	Resurfacing	0.00
Contractor_3	23	Microsurfacing	0.00
Contractor_3	23	Reconstruction	0.00
Contractor_3	23	Resurfacing	0.00
Contractor_3	24	Microsurfacing	0.00
Contractor_3	24	Reconstruction	0.00
Contractor_3	24	Resurfacing	0.00
Contractor_3	25	Microsurfacing	0.00
Contractor_3	25	Reconstruction	0.00
Contractor_3	25	Resurfacing	0.00
Contractor_3	26	Microsurfacing	0.00
Contractor_3	26	Reconstruction	0.00
Contractor_3	26	Resurfacing	0.00
Contractor_3	27	Microsurfacing	0.00
Contractor_3	27	Reconstruction	0.00
Contractor_3	27	Resurfacing	0.00
Contractor_3	28	Microsurfacing	0.00
Contractor_3	28	Reconstruction	505.62
Contractor_3	28	Resurfacing	0.00
Contractor_3	29	Microsurfacing	0.00
Contractor_3	29	Reconstruction	69.05

Destination/contractor	Period	Product/ interventions	Delivered/Processed
Contractor_3	29	Resurfacing	0.00
Contractor_3	30	Microsurfacing	0.00
Contractor_3	30	Reconstruction	64.01
Contractor_3	30	Resurfacing	0.00

Contractor 4

Destination/contractor	Period	Product/ interventions	Delivered/Processed
Contractor_4	1	Pipe lining	0.00
Contractor_4	1	Patching	0.00
Contractor_4	1	Reconstruction	0.00
Contractor_4	2	Pipe lining	0.00
Contractor_4	2	Patching	0.00
Contractor_4	2	Reconstruction	0.00
Contractor_4	3	Pipe lining	0.00
Contractor_4	3	Patching	0.00
Contractor_4	3	Reconstruction	0.00
Contractor_4	4	Pipe lining	0.00
Contractor_4	4	Patching	0.00
Contractor_4	4	Reconstruction	0.00
Contractor_4	5	Pipe lining	97.00
Contractor_4	5	Patching	0.00
Contractor_4	5	Reconstruction	0.00
Contractor_4	6	Pipe lining	0.00
Contractor_4	6	Patching	0.00
Contractor_4	6	Reconstruction	0.00
Contractor_4	7	Pipe lining	0.00
Contractor_4	7	Patching	0.00
Contractor_4	7	Reconstruction	0.00

Destination/contractor	Period	Product/ interventions	Delivered/Processed
Contractor_4	8	Pipe lining	0.00
Contractor_4	8	Patching	0.00
Contractor_4	8	Reconstruction	0.00
Contractor_4	9	Pipe lining	404.80
Contractor_4	9	Patching	0.00
Contractor_4	9	Reconstruction	0.00
Contractor_4	10	Pipe lining	1246.11
Contractor_4	10	Patching	0.00
Contractor_4	10	Reconstruction	0.00
Contractor_4	11	Pipe lining	184.03
Contractor_4	11	Patching	0.00
Contractor_4	11	Reconstruction	0.00
Contractor_4	12	Pipe lining	1166.90
Contractor_4	12	Patching	0.00
Contractor_4	12	Reconstruction	0.00
Contractor_4	13	Pipe lining	1107.98
Contractor_4	13	Patching	0.00
Contractor_4	13	Reconstruction	0.00
Contractor_4	14	Pipe lining	791.81
Contractor_4	14	Patching	0.00
Contractor_4	14	Reconstruction	0.00
Contractor_4	15	Pipe lining	1027.66
Contractor_4	15	Patching	0.00
Contractor_4	15	Reconstruction	0.00
Contractor_4	16	Pipe lining	365.24
Contractor_4	16	Patching	0.00
Contractor_4	16	Reconstruction	0.00
Contractor_4	17	Pipe lining	368.10
Contractor_4	17	Patching	0.00

Destination/contractor	Period	Product/ interventions	Delivered/Processed
Contractor_4	17	Reconstruction	0.00
Contractor_4	18	Pipe lining	180.23
Contractor_4	18	Patching	0.00
Contractor_4	18	Reconstruction	0.00
Contractor_4	19	Pipe lining	0.00
Contractor_4	19	Patching	0.00
Contractor_4	19	Reconstruction	0.00
Contractor_4	20	Pipe lining	0.00
Contractor_4	20	Patching	0.00
Contractor_4	20	Reconstruction	0.00
Contractor_4	21	Pipe lining	0.00
Contractor_4	21	Patching	0.00
Contractor_4	21	Reconstruction	0.00
Contractor_4	22	Pipe lining	0.00
Contractor_4	22	Patching	0.00
Contractor_4	22	Reconstruction	0.00
Contractor_4	23	Pipe lining	0.00
Contractor_4	23	Patching	0.00
Contractor_4	23	Reconstruction	0.00
Contractor_4	24	Pipe lining	0.00
Contractor_4	24	Patching	0.00
Contractor_4	24	Reconstruction	0.00
Contractor_4	25	Pipe lining	0.00
Contractor_4	25	Patching	0.00
Contractor_4	25	Reconstruction	0.00
Contractor_4	26	Pipe lining	0.00
Contractor_4	26	Patching	0.00
Contractor_4	26	Reconstruction	0.00
Contractor_4	27	Pipe lining	0.00

Destination/contractor	Period	Product/ interventions	Delivered/Processed
Contractor_4	27	Patching	0.00
Contractor_4	27	Reconstruction	0.00
Contractor_4	28	Pipe lining	97.00
Contractor_4	28	Patching	0.00
Contractor_4	28	Reconstruction	524.31
Contractor_4	29	Pipe lining	0.00
Contractor_4	29	Patching	0.00
Contractor_4	29	Reconstruction	68.22
Contractor_4	30	Pipe lining	0.00
Contractor_4	30	Patching	0.00
Contractor_4	30	Reconstruction	69.70

Contractor 5

Destination/contractor	Period	Product/ interventions	Delivered/Processed
Contractor_5	1	Pipe lining	0.00
Contractor_5	1	Reconstruction	0.00
Contractor_5	1	Pipe replacement	538.75
Contractor_5	2	Pipe lining	0.00
Contractor_5	2	Reconstruction	0.00
Contractor_5	2	Pipe replacement	3560.68
Contractor_5	3	Pipe lining	0.00
Contractor_5	3	Reconstruction	0.00
Contractor_5	3	Pipe replacement	3585.66
Contractor_5	4	Pipe lining	0.00

Destination/contractor	Period	Product/ interventions	Delivered/Processed
Contractor_5	4	Reconstruction	0.00
Contractor_5	4	Pipe replacement	3450.55
Contractor_5	5	Pipe lining	0.00
Contractor_5	5	Reconstruction	0.00
Contractor_5	5	Pipe replacement	3145.12
Contractor_5	6	Pipe lining	0.00
Contractor_5	6	Reconstruction	0.00
Contractor_5	6	Pipe replacement	2443.49
Contractor_5	7	Pipe lining	0.00
Contractor_5	7	Reconstruction	0.00
Contractor_5	7	Pipe replacement	3090.25
Contractor_5	8	Pipe lining	0.00
Contractor_5	8	Reconstruction	0.00
Contractor_5	8	Pipe replacement	3006.16
Contractor_5	9	Pipe lining	0.00
Contractor_5	9	Reconstruction	0.00
Contractor_5	9	Pipe replacement	1996.43
Contractor_5	10	Pipe lining	0.00
Contractor_5	10	Reconstruction	0.00
Contractor_5	10	Pipe replacement	0.00
Contractor_5	11	Pipe lining	0.00
Contractor_5	11	Reconstruction	0.00
Contractor_5	11	Pipe replacement	2294.00
Contractor_5	12	Pipe lining	0.00
Contractor_5	12	Reconstruction	0.00
Contractor_5	12	Pipe replacement	0.00
Contractor_5	13	Pipe lining	0.00
Contractor_5	13	Reconstruction	0.00
Contractor_5	13	Pipe replacement	0.00

Destination/contractor	Period	Product/ interventions	Delivered/Processed
Contractor_5	14	Pipe lining	0.00
Contractor_5	14	Reconstruction	0.00
Contractor_5	14	Pipe replacement	758.00
Contractor_5	15	Pipe lining	6.70
Contractor_5	15	Reconstruction	0.00
Contractor_5	15	Pipe replacement	51.00
Contractor_5	16	Pipe lining	152.56
Contractor_5	16	Reconstruction	0.00
Contractor_5	16	Pipe replacement	1127.00
Contractor_5	17	Pipe lining	120.34
Contractor_5	17	Reconstruction	0.00
Contractor_5	17	Pipe replacement	1277.00
Contractor_5	18	Pipe lining	180.52
Contractor_5	18	Reconstruction	0.00
Contractor_5	18	Pipe replacement	1569.06
Contractor_5	19	Pipe lining	0.00
Contractor_5	19	Reconstruction	0.00
Contractor_5	19	Pipe replacement	2304.86
Contractor_5	20	Pipe lining	0.00
Contractor_5	20	Reconstruction	0.00
Contractor_5	20	Pipe replacement	2286.41
Contractor_5	21	Pipe lining	0.00
Contractor_5	21	Reconstruction	0.00
Contractor_5	21	Pipe replacement	2137.43
Contractor_5	22	Pipe lining	0.00
Contractor_5	22	Reconstruction	0.00
Contractor_5	22	Pipe replacement	2089.69
Contractor_5	23	Pipe lining	0.00
Contractor_5	23	Reconstruction	0.00

Destination/contractor	Period	Product/ interventions	Delivered/Processed
Contractor_5	23	Pipe replacement	2096.97
Contractor_5	24	Pipe lining	0.00
Contractor_5	24	Reconstruction	0.00
Contractor_5	24	Pipe replacement	2071.95
Contractor_5	25	Pipe lining	0.00
Contractor_5	25	Reconstruction	0.00
Contractor_5	25	Pipe replacement	1989.80
Contractor_5	26	Pipe lining	0.00
Contractor_5	26	Reconstruction	0.00
Contractor_5	26	Pipe replacement	1884.30
Contractor_5	27	Pipe lining	0.00
Contractor_5	27	Reconstruction	0.00
Contractor_5	27	Pipe replacement	1889.17
Contractor_5	28	Pipe lining	0.00
Contractor_5	28	Reconstruction	673.07
Contractor_5	28	Pipe replacement	93.85
Contractor_5	29	Pipe lining	0.00
Contractor_5	29	Reconstruction	65.70
Contractor_5	29	Pipe replacement	0.00
Contractor_5	30	Pipe lining	0.00
Contractor_5	30	Reconstruction	64.67
Contractor_5	30	Pipe replacement	0.00