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A Multi-Objective Approach to Incorporate Indirect Costs into Optimisation Models of Waterborne Sewer Systems

By
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DECLARATION

I, the undersigned, declare that the work contained in this dissertation is my own original work and has not previously been submitted at any University for a degree.

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SYNOPSIS

Waterborne sewage system design and expansion objectives are often focused on minimising initial investment while increasing system capacity and meeting hydraulic requirements. Although these objectives make good sense in the short term, the solutions obtained might not represent the optimal cost-effective solution to the complete useful life of the system. Maintenance and operation of any system can have a significant impact on the life-cycle cost. The costing process needs to be better understood, which include maintenance and operation criteria in the design of a sewer system. Together with increasing public awareness regarding global warming and environmental degradation, environmental impact, or carbon cost, is also an important factor in decision-making for municipal authorities. This results in a multiplicity of different objectives, which can complicate the decisions faced by waterborne sewage utilities.

Human settlement and migration is seen as the starting point of expansion problems. An investigation was conducted into the current growth prediction models for municipal areas in order to determine their impact on future planning and to assess similarities between the models available. This information was used as a platform to develop a new method incorporating indirect costs into models for planning waterborne sewage systems.

The need to balance competing objectives such as minimum cost, optimal reliability, and minimum environmental impact was identified. Different models were developed to define the necessary criteria, thus minimising initial investment, operating cost and environmental impact, while meeting hydraulic constraints. A non-dominated sorting genetic algorithm (NSGA-II) was applied to certain waterborne sewage system (WSS) scenarios that simulated the evolutionary processes of genetic selection, crossover, and mutation to find a number of suitable solutions that balance all of the given objectives. Stakeholders could in future apply optimisation results derived in this thesis in the decision making process to find a solution that best fits their concerns and priorities. Different models for each of the above-mentioned objectives were installed into a multi-objective NSGA and applied to a hypothetical baseline sewer system problem. The results show that the triple-objective optimisation approach supplies the best solution to the problem. This approach is currently not applied in practice due to its inherent complexities. However, in the future this approach may become the norm.

SAMEVATTING

Spoelafvoering rioolstelsel ontwerp en uitbreiding doelwitte is dikwels gefokus op die vermindering van aanvanklike belegging, terwyl dit die verhoging van stelsel kapasiteit insluit en ook voldoen aan hidrouliese vereistes. Alhoewel hierdie doelwitte goeie sin maak in die kort termyn, sal die oplossings verkry dikwels nie die optimale koste-effektiewe oplossing van die volledige nuttige lewensduur van die stelsel verteenwoordig nie. Bedryf en instandhouding van 'n stelsel kan 'n beduidende impak op die lewensiklus-koste hê, en die kostebepalings proses moet beter verstaan word en die nodige kriteria ingesluit word in die ontwerp van 'n rioolstelsel. Saam met 'n toenemende openbare bewustheid oor aardverwarming en die agteruitgang van die omgewing, is omgewingsimpak, of koolstof koste, 'n belangrike faktor in besluitneming vir munisipale owerhede. As gevolg hiervan, kan die diversiteit van die verskillende doelwitte die besluite wat munisipale besluitnemers in die gesig staar verder bemoeilik.

Menslike vestiging en migrasie is gesien as die beginpunt van die uitbreiding probleem. 'n Ondersoek na die huidige groeivoorspelling modelle vir munisipale gebiede is van stapel gestuur om hul impak op die toekomstige beplanning te bepaal, en ook om die ooreenkomstes tussen die modelle wat beskikbaar is te asesseer. Hierdie inligting is gebruik as 'n platform om ‘n nuwe metode te ontwikkel wat indirekte kostes inkorporeer in die modelle vir die beplanning van spoelafvoer rioolstelsels.

Die behoefte is geïdentifiseer om meedingende doelwitte soos minimale aanvanklike koste, optimale betroubaarheid en minimum invloed op die omgewing te balanseer. Verskillende modelle is ontwikkel om die bogenoemde kriteria te definiëer, in die strewe na die minimaliseering van aanvanklike belegging, bedryfskoste en omgewingsimpak, terwyl onderhewig aan hidrouliese beperkinge. ‘n Nie-gedomineerde sorteering genetiese algoritme (NSGA-II), istoegepas op sekere spoelafvoering rioolstelsel moontlikhede wat gesimuleerde evolusionêre prosesse van genetiese seleksie, oorplasing, en mutasie gebruik om 'n aantal gepaste oplossings te balanseer met inagname van al die gegewe doelwitte. Belanghebbendes kan in die toekoms gebruik maak van die resultate afgelei in hierdie tesis in besluitnemings prosesse om die bes-passende oplossing vir hul bekommernisse en prioriteite te vind. Verskillende modelle vir elk van die bogenoemde doelwitte is geïnstalleer in die nie-gedomineerde sorteering genetiese algoritme en toegepas op 'n hipotetiese basislyn rioolstelsel probleem. Die resultate toon dat die drie-objektief optimalisering benadering die beste oplossing vir die probleem lewer. Hierdie benadering word tans nie in die praktyk toegepas nie, as gevolg van sy inherente kompleksiteite. Desnieteenstaande, kan hierdie benadering in die toekoms die norm word.

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ACRONYMS

CCI	Construction Cost Index
CPI	Consumer Price Index
EF	Ecological Footprint
EI	Environmental Impact
EIO	Economic Input-Output
EIO-LCA	Economic Input-Output Life Cycle Assessment
EMO	Evolutionary Multi-Objective Optimisation
GHG	Green House Gas
GIS	Geographical Information System
GWP	Global Warming Potential
IDP	Integrated Development Plan
LCA	Life Cycle Assessment
MIG	Municipal Infrastructure Grant
MOEA	Multi-Objective Evolutionary Algorithm
MOGA	Multi-Objective Genetic Algorithms
NERSA	National Energy Regulator Of South Africa
NIMS	National Infrastructure Maintenance Strategy
NPGA	Niched Pareto Genetic Algorithm
NSGA	Non-Dominated Sorting Genetic Algorithm
NSGA-II	Non-Dominated Sorting Genetic Algorithm II
PAES	Pareto Archived Evolution Strategy

PESA	Pareto Envelope-Based Selection Algorithm
POS	Public Open Space
PPI	Producer Price Index
PVC	Polyvinyl Chloride
SDF	Spatial Development Framework
SOGA	Single-Objective Genetic Algorithms
SPEA	Strength Pareto Evolutionary Algorithm
SPEA2	Strength Pareto Evolutionary Algorithm Number 2
SSO	Sanitary Sewer Overflow
uPVC	Un-Plasticised Polyvinyl Chloride
WDS	Water Distribution Systems
WISA	Water Institute Of South Africa
WRC	Water Research Commission
WSS	Waterborne Sewage System
WWTP	Waste Water Treatment Plant
WWTW	Waste Water Treatment Works

TERMINOLOGY

The following terms and definitions are to be interpreted as follows throughout the thesis:

Cost	Costs in this thesis can refer to either capital cost (cost of construction of new infrastructure), operation cost (electricity and human resources), maintenance and rehabilitation cost (expenditures on repair and refurbishment), or carbon cost (environmental impact).
Asset Register	A record of items considered worthy of identification as discrete assets, including information such as construction and technical details (Stephenson et al., 2001).
Discount rate	A rate to relate present and future money values.
Life cycle cost	The total cost of an asset throughout its life, including planning, design, construction, operations, rehabilitation and disposal costs.
Maintenance	All actions necessary for retaining an asset as near as practical to its original condition, excluding rehabilitation.
Model	A mathematical representation of a process used for analysis and planning.
Operation	Active processes utilising an asset, referring, in this context, to electricity use and human resources.
Receiving waters	Watercourse, river, estuary or coastal water into which the outfall of a combined sewer overflow or waste water treatment works discharges (Stephenson & Barta, 2005b).

Rehabilitation	Works to rebuild, or replace parts or components of an asset to restore it to its original condition and/or extend its life (Stephenson et al., 2001).
Suburban	Residential areas located at the edge or fringe of the city, which are characterised by low-density development relative to the city.
Urban	Cities or intensively developed areas.
Useful life	The estimated period of time over which a depreciable asset is expected to be able to be used (Stephenson et al., 2001).

CHAPTER 1

INTRODUCTION

1.1 Introduction

The relatively high cost of providing sanitary sewers is fully justified by the role they play in protecting the community's health, comfort and safety. A sanitary sewer system could be considered essential in sustaining a healthy urban community.

National interest has been awakened to the need for control of pollution in our streams, rivers and coastal waters, and the cost of adequate sewage and waste treatment works has been fully documented. The funds required for the treatment facility itself represent only a portion of the total investment in the collection, transmission, treatment and disposal of municipal wastes.

The modelling and planning of sewer systems is a great responsibility that rests on local authorities, although this task is often contracted out to consulting engineers. The steps involved are not limited to engineering problems, but involve the use of best business practices. Sewer system financing is a challenge to the good business operations of municipalities and the economic judgement of planners and designers who render consultative services to governmental agencies. Knowledge of sewer financing and revenue-producing principles is as important as engineering and construction know-how to ensure that this vital phase of municipal service is maintained in working order for a long and useful life. Cost considerations and comparisons are fundamental aspects of engineering practice.

It is important for planners and designers to have sound estimates of the cost of the sewer system and of how much each phase of the project will influence the overall cost of other proposed projects.

The ageing state of the waterborne sewage infrastructure in South Africa (CIDB & CSIR, 2007), combined with an increase in demand for adequate sanitation services resulting from national growth, has led to a decline in the condition of waterborne sewage systems. Deteriorating waterborne sewage systems have lead, and will continue to lead, to an increase in operation and maintenance costs, safety concerns, and to a lower level of service.

De Swardt and Barta (2008) noted that there are various costs involved when a certain system is implemented and that it is important to understand the initial capital cost as well as the operational and maintenance cost. The summation of these costs would give a life cycle cost for the useful life of the system. It is typical in sewer system master planning in South Africa to consider only the capital cost as constituting the value of the system.

Environmental concerns, including climate change, have been brought to the attention of international bodies, national, provincial, and municipal governments. This has led to international trends to include the cost of the indirect impact on the environment, also known as “carbon cost” as part of the total cost of water and sewer systems (Wu et al., 2008). This so-called “cost” assesses the impact of the particular system on the environment from its construction till the end of its useful life.

This, in essence, means that there are four different “costs” involved in the installation and operation of a sewer system:

- Capital cost (i.e. the cost of constructing new infrastructure)
- Operation costs (i.e. the electricity for operating pumps and the cost of human resources)

- Maintenance and rehabilitation cost (i.e. repair and refurbishment of ageing infrastructure)
- Carbon cost (i.e. the indirect impact on the environment).

The economic input-output life cycle assessment (EIO-LCA) model has been developed to circumvent the data and boundary problems of the life cycle assessment (LCA) method (Herstein, 2009). The EIO-LCA model combines the economic input-output (EIO) models with LCA to produce a complete financial assessment of the overall useful life of the system. EIO models are mathematical tables (matrices) which can be used to calculate the economic output of each section of the life cycle.

1.2 Background and Rationale

Since 1996 the South African population has grown by 650 000 people per annum and is heading for a population of well over 50 million by mid 2011 (Stats SA, 2001a; Stats SA, 2001b). This growth will be centralised in existing and new communities, and in their fringe areas. These areas might be classified as suburban today, but will become fully urbanised in the not too distant future. According to Stats SA (2002) 13.6% of the South African households do not have access to hygienic sanitation; this includes 1 in 5 households that do have access to sanitation facilities in the rural areas. Figure 1-1 gives a percentage distribution of the population’s access to any form of toilet facility. It is evident that flush toilets, and thus waterborne sanitation systems, comprise the largest fraction.

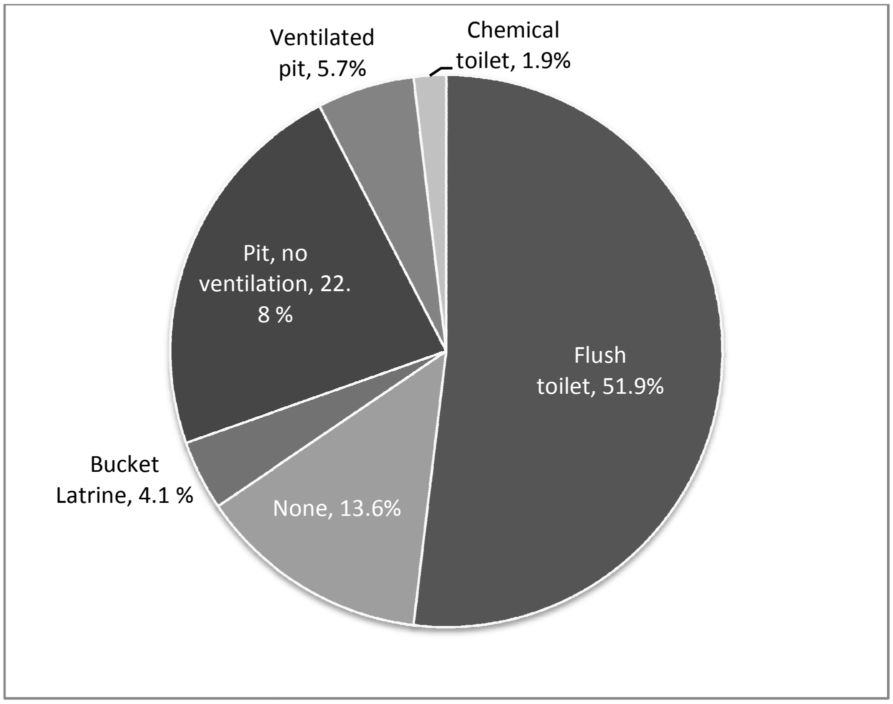

Figure 1-1 Distribution of households by toilet facility (Stats SA, 2001b)

Sewers will be needed where development is expected to take place. More fringe areas will be occupied (and therefore the fringe will expand), re-zoning of existing developments and the densification of existing zones will result in greater communities that must be supplied with adequate sewage disposal (Cohn, 1966).

Collection of sewage will also require the treatment of the waste to prevent the pollution and despoliation of the receiving water resources. These facilities need to be provided and operated with maximum efficiency and economy.

1.3 Objectives

This thesis presents a new approach to optimise the expansion, operation and maintenance of waterborne sewage systems to arrive at system solutions that are cost effective, meet consumer demands and expectations while minimising environmental impacts. The thesis objectives are:

- To understand and predict growth for a certain municipal area.
- To obtain a clear understanding of all the costing implications that surround the decision criteria and structure of WSS.
- To develop optimisation models to assist in cost forecasting.
- To develop a model that interprets complete life-cycle environmental impact.
- To develop a method that aggregates multiple economic impact measures into a single economic impact and environmental impact (EI) index that can be easily understood and interpreted by WSS utility decision makers.
- To develop a multi-objective WSS expansion optimisation approach that considers cost, energy use and environmental impact objectives.

1.4 Contributions

The research contributions made in this thesis are:

- Development of a low-technology tool to assist in WSS capital cost prediction.
- To combine all the objectives of a modern WSS into one optimisation approach using the NSGA-II.

1.5 Layout

This thesis is organised according to the following topics:

The literature review, investigating previous research and publications on topics of relevance to this thesis, is presented in chapter two. The description of an object model for a WSS, wherein the information is found that will populate the optimisation model, is discussed. Furthermore, current optimisation methods and techniques are presented, together with an introduction to financing principles for sewer systems. A thorough description of the genetic algorithms that will be suited to an optimisation problem are presented, together with the chosen genetic algorithm, the NSGA-II, that is to be implemented in this study, together with the reasons for the choice. An overview of the implementation is given and workings are described.

Chapter three discusses the current population growth prediction methods available to the design engineer today. Before any highly complex models to optimise the system can be implemented, there is a need to have a system in the first place. Optimisation can be as accurate and inclusive as possible, but if the system is not used at the capacity that is expected, the optimisation process can be considered null and void.

Chapter four presents a new model developed by the author and GLS Consulting, as part of a larger project by the WRC, on the value estimation of waterborne sewer infrastructure. Current models available were considered, but it was finally decided that a new, easy-to-use, low technology model is needed, as this would be able to assist municipal officials, especially in the poorer municipalities, in getting first order estimates for any given new project. This chapter was presented at the 2010 Water Institute of South Africa (WISA) Conference in Durban. It presents an entirely new model that also considers the aggregation of current prices through the use of price indexes and base timelines.

The biggest challenge in WSS optimisation is the fact that the objectives are contradictory to each other. For example; a smaller pipe (referring to diameter) will have a lower cost, but will also have a lower capacity. For this reason an investigation was launched into the current models available, for the cases of operation, maintenance and rehabilitation minimisation, and environmental impact, as presented in the later chapters of this thesis. Here the models from other literature were modified so to be incorporated into the genetic algorithm framework.

Chapters seven and eight present the implementation method and structure of all the above mentioned objectives within the genetic algorithm technique NSGA-II. This, with the model setup, will conclude the case study in this thesis.

The final chapter gives the conclusions and the findings of this dissertation.

CHAPTER 2

KNOWLEDGE REVIEW

This knowledge review concentrates on topics pertaining to the focus of this study, namely the cost, modelling and planning of a WSS:

- Waterborne sewage systems, with a description of separate and combined systems
- System identification by means of asset registers and object models
- Current methods of sewer system modelling and planning
- Information relevant to costing and cost functions of a sewer system
- Different methods and models proposed for optimisation
- Previous research regarding the application of genetic algorithms
- A thorough knowledge review of multi-objective genetic algorithms and their application to planning and design sewer systems
- An introduction to the hypothetical sewer system Sanitown.

2.1 Introduction

The expansion and continual operation of waterborne sewage systems addresses the need for increased capacity in order to continue meeting current and future needs. This process encompasses the following activities:

- The addition of new system components where there were previously none (e.g. a new development).
- The continuous operation of existing components.

- The rehabilitation and maintenance of existing components.

Most of WSS development and expansion problems are complex, and include a number of possible solutions for a given scenario. Each solution will feature a total capital cost, operation cost, rehabilitation and maintenance cost, and an environmental impact that are unique to the solution. To address this challenging problem, a number of optimisation techniques have been developed to efficiently search for the optimal solution from a large set of possible WSS solutions.

2.2 Waterborne Sewage Systems

A sewer system is the drainage conveyance system that transports wastewater from home and commercial plumbing systems (e.g. toilets, showers, sinks, washers) to a waste water treatment works (WWTW) through an intricate network of pipelines. At the WWTW water is ultimately reclaimed for reuse, and discharged to a receiving water body. The same network is also used to transport industrial sewage to the treatment facilities, although pre-treatment can occur on site to assist in the breakdown, and therefore the transport, of large volumes or poor quality waste water. Figure 2-1 is a schematic representation of a separate sewer system.

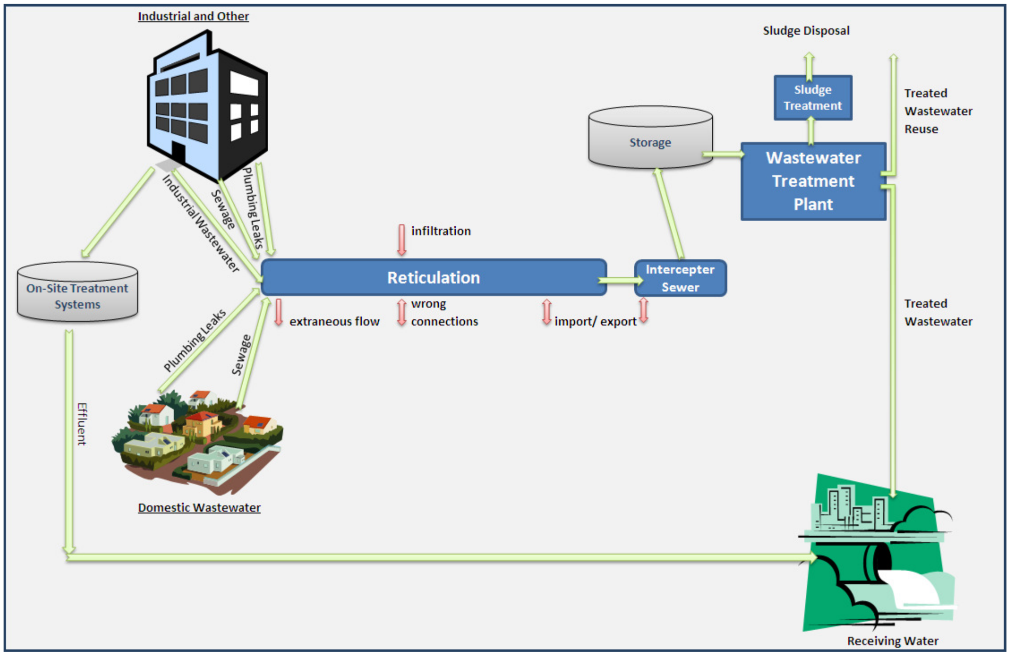

Figure 2-1: Schematic representation of separate sewer system

There are two types of sewer systems that are currently in use in most developed countries, namely separate sewer systems (storm water and sewage are transported in separate pipelines) and combined sewer systems where storm water as well as sewage are transported in the same pipelines (Chadwick et al., 2004). Debates regarding which system is better are often reported in literature (Huang & Borthwick, 2008). In South Africa separate sewer systems are generally in use. However, storm water could enter the sewer system through faulty pipes and manholes and peaks in these separate sewer systems are often noted as coinciding with rain storm events.

Sewer systems are designed to carry the peak dry weather flow so as to provide adequate capacity for the peak rate of sewage, peaks in effluent discharges and a degree of groundwater infiltration. The latter is a relatively constant flow component and could be considered to be a function of sewer pipe length and diameter. An infiltration rate of 0.15 l/metre pipe/metre diameter has been suggested (Stephenson & Barta, 2005a; Stephenson & Barta, 2005b) and is often used locally in sewer system master planning to estimate infiltration rates. It is typical for a sewer system to have the capacity to carry four times the average dry weather flow (Trifunovic, 2006). This additional capacity allows for spare hydraulic load during peak periods as well as for planned future developments (Butler & Davies, 2000). This means that the pipe will seldom run full, providing that there are no wrong connections from surface water drainage systems and that a minimal amount of infiltration is occurring.

Water use and waste patterns within individual households vary moving down the system and have been evaluated in detail (Boxall & Maksimovic, 2009). There is a point where a combination of properties connected, and peak usage in mornings and evenings, results in continuous flows. This means that due to the different travel times there is continuous flow throughout the day, with a notable "base flow" in the sewer pipe, as the network advances closer to the treatment facility (Burstall, 1997).

Variation of water usage throughout the day results in diurnal variation of flow (Butler & Memon, 2006). The peaks are generated by the aforementioned patterns of water usage and the trough occurs in the early hours when the majority of people are asleep. Figure 2-2 gives the unit hydrographs for the different land use scenarios. The peaks are relatively larger at the periphery of the sewage system than at its outlet. The first reason for this is the effect of attenuation of the individual waves discharged from appliances and the second, the effect of different travel times from the many different properties served by the system to a given point.

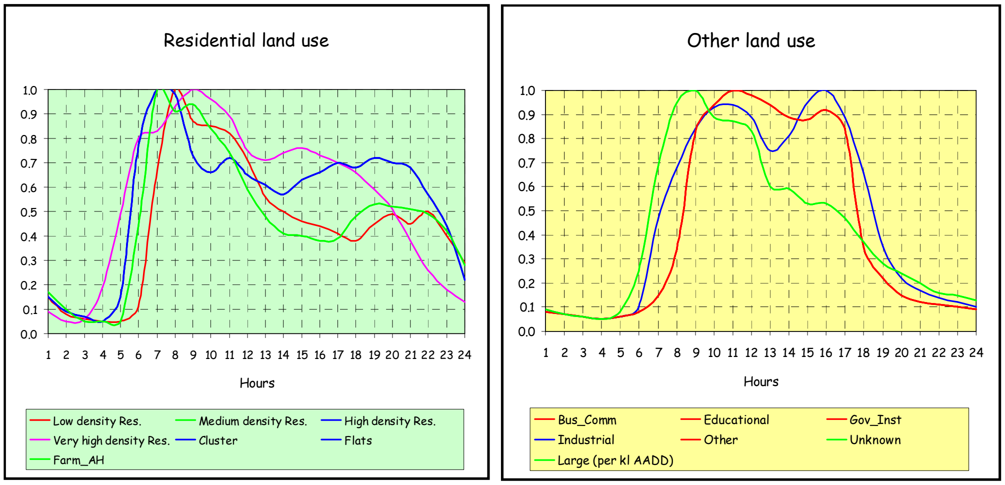

Figure 2-2 Unit hydrographs for different land use (GLS, 2010)

The load includes dissolved and solid organic and inorganic matter from domestic, industrial and commercial premises. The dissolved matter and fine suspended particles are readily conveyed through the sewage system by the water. However, the conveyance of the gross solids is more complex, as presented by May (1993) and depends on the complex relationship between the specific gravity of the particulate, the size and quantity of the particulate and the quantity and the velocity of the water available for transport (ASCE, 1982). In addition, solids may catch on the features within the sewer and cause blockages. These aspects are, of course, critical to the effective operation of a sewer system (Briere, 2007), but a discussion beyond the scope of this limited introduction.

2.3 System Identification, Planning and Modelling

2.3.1 Purpose and Objectives of an Object Model

Identifying and evaluating the current system in place is the first step in optimising and expanding a WSS. There are six general reasons for creating a sewer object model. These reasons and examples of their objectives are presented in Table 2.1 (Haestad et al., 2004):

Table 2.1 Purpose of a WSS object model (Haestad et al., 2004)

Purpose of the Model	Examples of Objectives
Design of new Systems	o Determine optimum configuration o Determine required size of pipes, pumps, wet wells and elevations.
Master Planning	o Identify potential problem areas resulting from growth o Determine location and capacity of new pumping stations o Prepare cost estimates for alternative schemes.
Rehabilitation	o Identify causes of sewer overflows o Assess the hydraulic improvements resulting from replacement or relining of pipes.
Operation and Maintenance	o Analyse downstream flows resulting from pump control strategies o Analyse alternative wet weather flow control schemes o Analyse effectiveness of pump station operation o Determine sections of the sewer system prone to siltation.
Water-Quality Studies	o Determine location, frequency and water quality of sewer overflows o Determine effect of sewer flows on treatment plant operation o Analyse options to reduce frequency and volume of overflows.
Regulatory Compliance	o To demonstrate the system's compliance to regulatory requirements.

2.3.2 Data Requirements and Resources

The project objectives dictate the data requirements. Model data can be obtained from a variety of sources, and the availability and accuracy of the data vary considerably. The table below presents six categories into which data can be classified, the data itself, and the sources from where it can be obtained:

Table 2.2 Object model's data requirements, classification and sources

Data Requirement		Data Sources
Category	Data	
Network Layout	○ X and Y coordinates of each pipe segment and manhole ○ Locations of wet wells ○ Pipe connectivity and lengths ○ Pipe diameters and materials ○ Pipe invert levels ○ Manhole elevations ○ Manhole lid types.	○ Construction drawings ○ Corporate GIS system ○ Asset management systems ○ Work orders ○ Field survey.
Hydraulic Properties	○ Pipe friction factors ○ Pump curves.	○ Manufacturer's specifications ○ Contractor submittals ○ Literature values ○ Field tests.
Sanitary Flows	○ Location of each source ○ Min, max and mean daily flows ○ Diurnal patterns.	○ Construction drawings ○ Maps and aerial photos ○ Census data ○ Growth projections ○ Water billing records ○ Land-use data.
Wet Weather Flows	○ Infiltration rate for each pipe segment ○ Locations of inflows ○ Quantities of inflows ○ Location, dates and quantities of overflows.	○ Field inspection ○ Field measurements ○ Analysis treatment plant flows ○ Hydrological analysis.
Operation Data	○ Settings for pump operation ○ Settings of flow control structures ○ Control strategies ○ Flows and treatment plants ○ Pumped quantities.	○ Interviews with operational personnel ○ Operation records and manuals ○ Field inspection ○ Customer complaints ○ Maintenance records.
Calibration Data	○ Recorded depth and flow rate ○ Frequency and location of overflows ○ Surface elevations ○ Precipitation ○ Rain gauge locations.	○ Field inspections ○ Field measurements ○ Operations records ○ Weather records ○ Flow-monitoring program.

2.3.3 Physical Dimensions

2.3.3.1 Position

The position is defined by the x and y coordinates of each pipe segment and manhole (nodes).

2.3.3.2 Pipes

In a sewerage network model, pipes are links that form the connection between nodes. Many pipe lengths and fittings are combined into one segment linking two nodes. The pipe links in the model should have similar characteristics, i.e. in terms of diameter, material and hydraulics, throughout the entire length.

The following are the attributes of pipes in a sewer network (Haestad, Barnard, Walski and Harold, 2004):

- *Diameter*

  It is preferable to know the inside diameter of the pipe, but in practice pipes are normally described by their nominal diameter. The wall thickness is then normally supplied and can be used to calculate the inside diameter. It is also important to note that the diameter of the pipe can change as the pipe gets older (due to corrosion).

- *Length*

  The pipe length is the distance between the nodes, usually the manholes, at each end of the pipe segment.

- *Material*

  Pipe material is classified as either rigid (asbestos cement, concrete, vitrified clay and cast iron) or flexible (ductile iron, steel, polyethylene and polyvinyl chloride).

It is common that metallic pipes are lined with some type of lining to prevent corrosion and reduce the roughness of the pipe, in order to enhance hydraulic flow. These linings can be added on the inside of the pipe during manufacture or can be added to older, existing pipes. If a pipe has been rehabilitated with a lining, the diameter in the model should reflect the new inside diameter.

- *Roughness*

  Pipe friction can be accounted for by Manning's n, Chezy's k, or any other standardised roughness coefficient. In many cases in sewer pipe flow, the sewer pipe does not flow full. For these scenarios the roughness coefficient is also a function of the depth of flow in the pipe.

- *Shape*

  Most sewer pipes are circular; however, older systems or major main lines may use egg-shaped, horseshoe, or rectangular pipes. Also, vertical elliptical pipes are sometimes used when the flow depth in the pipe is very low.

- *Invert Elevation*

  The pipe invert is the elevation of the inside bottom of the pipe. This can, in some cases, be calculated by the model based inverts of the other pipes connected to the same manhole. In most models the slope is considered constant between two nodes.

- *Grease, Sediment, Roots and Sags*

  Potential problems in the hydraulics of the sewage pipeline can be caused by grease, sediment, roots and sags. Grease from the wastewater can build up on the sides of the pipe, thereby reducing the inside diameter and the area available for sewage flow.

- *Inverted Siphons*

  Any designed dip in a gravity sewer is referred to as inverted siphon. This occurs when the sewer must pass under structures such as other pipes, highways, subways, a river, or across a valley. Characteristically, the pipeline is below the hydraulic grade line and is always filled with sewage and under pressure. An inverted siphon is modelled hydraulically by accounting for the entrance losses, pressure flow through the siphon, exit losses, and a transition to open channel flow.

2.3.3.3 Manholes

Manholes are placed in a sewer system to provide access for inspection, maintenance and emergency service. The following are the attributes of manholes in a sewer network (Haestad et al., 2004):

- *Invert Elevation*

  The manhole invert is usually defined as the elevation of the inside bottom of the pipe entering the manhole. This term can also, in other instances, be used to represent the bottom of the pipe in the centre of the manhole.

- *Rim Elevation*

  The rim elevation is typically at the ground elevation when the sewer is located in the street, although the manhole rim may be either buried or elevated above the ground level.

- *Structure Size*

  Manholes are normally cylindrical, with inside dimensions large enough to allow room for maintenance and inspections.

- *Drop Manholes*

  It is often necessary that a pipe enters the manhole at an invert level much higher than the main sewer pipe leaving the manhole. In these instances it is undesirable to let the sewage fall freely to the bottom of the manhole, so incoming sewage is transported down a vertical pipe to the bottom of the manhole before entering the outgoing sewer pipe.

2.3.3.4 Pumps

In a wastewater collection system, pumping stations are placed where the hydraulic grade line must be raised. Since sewage flows primarily by gravity, a pump transports it from a low elevation to a higher elevation. The sewage then flows away, again by gravity, to the next pumping station or until it reach its destination. The following are the attributes of pumps in a sewer network (Haestad et al., 2004):

- *Pump Curves*

  A pump is classified by its pumping head, efficiency and power requirements at various flow rates. The pump head performance curve describes the pump’s ability to pump sewage against a pump head at a constant impeller speed.

- *Pump Status and Controls*

  The pump status in a pumping station is normally controlled by the water level in the adjacent wet well on the upstream side, although it can also be controlled by the condition on the downstream side.

2.3.3.5 Wet Wells

Pumping stations need wet wells in which to store water before it is pumped. Some wet wells have screens to help protect the pumps against rags that can clog the pump, damage pump seals or increase head loss. The following are the attributes of wet wells in a sewer network (Haestad et al., 2004):

- *Minimum and Maximum Level*

  In designing a wet well, the key inputs are the minimum and maximum water level for each pump and the wet well volume. The pumps are controlled by a minimum level control switch which turns off the pump when this level is reached.

- *Volume*

  The active volume in the wet well is the volume of water between the minimum and maximum water levels.

2.3.4 Capacity

2.3.4.1 Sources

Wastewater collection systems are designed to collect and transport sewage from domestic, commercial and industrial sources. However, there can also be additional infiltration into the sewer system from the ground through defective pipes, pipe joints, connections, or manhole walls. Inflow can also be water discharged into the sewer from other sources such as building drains, drains from wet or swampy areas, manhole covers, cross connections, catch basins, or surface runoff.

2.3.4.2 Types of Conveyance

Most sewer systems are designed to operate partially full, but there are, in total, five types of flow conditions that exist in a collection system:

- Partially full gravity flow (there is a free water surface in the pipe)
- Surcharged gravity flow (the depth of flow in a gravity pipe is controlled downstream)
- Pressure flows in force mains (sewage is pumped along stretches where gravity flow is not possible)
- Pressure sewers (each end user has a pump that discharges to a pressure sewer)
- Vacuum sewers (flow is pulled through the system by vacuum pumps).

Although most sewer systems fall into the first category, systems can be a combination of some or all of the categories.

2.3.4.3 Gravity flow hydraulics

Table 2.3 gives the inputs, which can be either mathematically calculated or physically measured, that need to be found in order to develop a complete object model of the overall system as regards the hydraulic capacity:

Table 2.3 Object model hydraulic inputs

Gravity Flow Hydraulics	
Parameter	Inputs
Fluid Properties	○ Viscosity ○ Fluid compressibility ○ Vapour pressure ○ Density and specific weight.
Fluid statics and dynamics	○ Static pressure ○ Absolute pressure ○ Gauge pressure ○ Velocity and flow ○ Reynolds number ○ Velocity profiles.
Fundamental laws	○ Conservation of mass ○ Conservation of energy ○ Conservation of momentum.
Hydraulic Variables	○ Slope ○ Depth of flow ○ Flow rate ○ Velocity.
Energy and head losses	○ Roughness coefficients.
Hydraulic elements	○ Open-top cross sections ○ Closed-top cross sections ○ Noncircular cross sections.
Roughness coefficients	○ Roughness coefficients.
Specific energy and critical flow	○ Specific energy ○ Froude number ○ Sub- and supercritical flow ○ Hydraulic jumps ○ Flow profiles ○ Backwater curves.
Hydraulics of flow control structures	○ Orifices ○ Weirs ○ Gates.

2.4 Sanitown

Sanitown is a generic hypothetical sewer system model for a separate sewer system (De Klerk & Jacobs, 2010). The design of this model is based on the same concepts that were developed by Walski et al. (1987) in the development of the hypothetical water network model known as Anytown. The Anytown model was developed to serve as a benchmark for hydraulic analysis and cost optimisation of water distribution networks. The publication of this benchmark problem for water distribution systems set the scene for water researchers to discuss and investigate different approaches to the problems of water network design. De Klerk et al. (2010) identified the same need for comparing the optimisation techniques and models for waterborne sewage systems.

Sanitown presents a conceptual description of a hypothetical model for sewer system analysis, which includes input parameters and topology that were carefully selected to include typical problems encountered with the hydraulic modelling and master planning of sewer systems. The Sanitown system is indicated in Figure 2-3 (See Appendix A for pipe sizes).

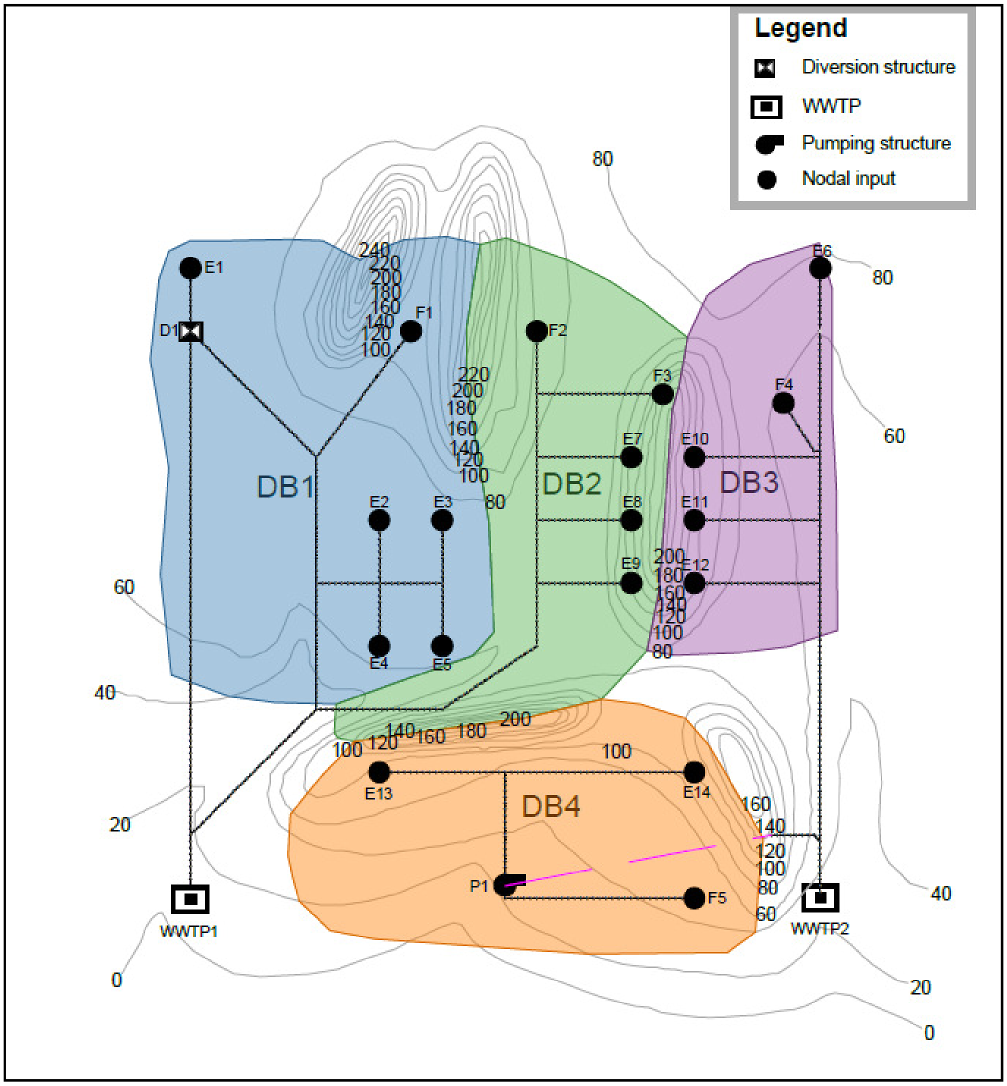

Figure 2-3 Sanitown benchmark model (De Klerk & Jacobs, 2010)

The Sanitown model forms a benchmark for waste water systems so that waste water researchers can discuss and investigate different approaches to design problems. It allows for the comparison of optimisation techniques and models for waterborne sewage systems; expansion problems can also be tested and evaluated on the future scenario supplied by De Klerk et al. (2010).

2.5 Engineering Economy

According to Sullivan et al. (2005) an engineering economy study is accomplished using a structured procedure and mathematical modelling techniques. The economic results are then used in making a decision, a situation that normally includes other engineering knowledge and input.

Presented in Figure 2-4 are the seven steps of a basic economic analysis:

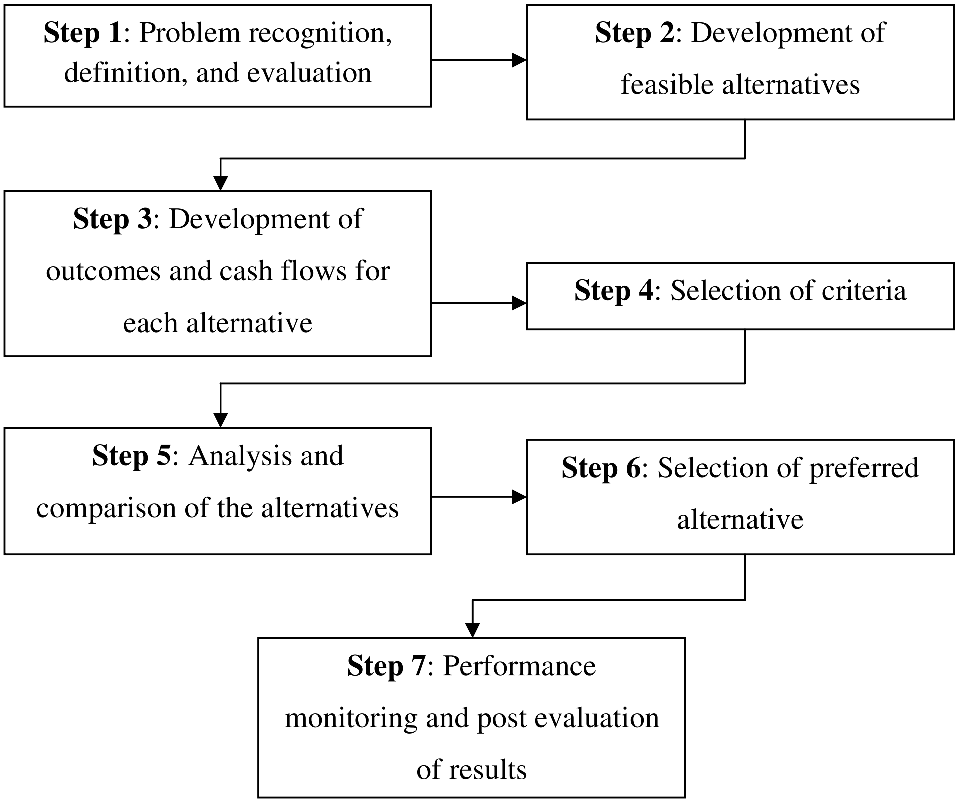

Figure 2-4 Steps of economic analysis

2.6 Optimisation Methods and Models

2.6.1 Introduction

WSS expansion and rehabilitation projects involve the enhancement of system capacity through resizing, the addition of pipes where they did not previously exist (as in new developments), the cleaning and lining of existing pipes and the addition of pumps and storage sumps. Having increased system capacity, the system is better equipped to handle expected consumer demands and maintain a high level of service.

Although expansion and rehabilitation of a WSS serves the function of decreasing operation and maintenance costs by increasing hydraulic efficiency, the capital (initial) cost for these programmes is often substantial. Municipalities are responsible for the financing of these programmes or projects, but with stringent budgetary restraints. In addition to these restraints the municipalities must ensure that the given end product is adequate to meet the demand, sometimes in exceptional conditions, e.g. in storm situations (where infiltration is generally higher).

2.6.2 History of Optimisation Approaches

The earliest optimisation approaches (perhaps with regard to water distribution) were single objective optimisation approaches. The objective was typically to minimise the overall cost of the system. Savic and Walters (1997) found that there were four categories for the single-objective optimisation approaches. These were the enumeration approach, linear programming, steepest descent and stochastic search approaches.

However, their application was time consuming, complex and often failed to find the optimal global solution. What was found was that the only efficient, simple and powerful single-objective optimisation method that could be applied was through the use of genetic algorithms (Simpson et al., 1994).

2.6.3 Brief Introduction to Genetic Algorithms

A genetic algorithm (GA) is a search algorithm based on the natural selection and mechanisms of population genetics (Holland, 1975; Goldberg, 1989). Genetic algorithms differ from the traditional approaches of existing optimisation techniques. The simple idea of a GA search has its roots in the biological processes of survival and adaptation. The result is an effective algorithm with the flexibility to search complex spaces such as the solution space for the design of a pipe network (Simpson et al., 1994).

2.6.4 Genetic Algorithms in Single-Objective Optimisation

The genetic algorithm is an optimisation tool that is based on the natural phenomenon of evolution, whereby the strongest, or fittest, individual of a population has the greatest chance to survive and reproduce. Goldberg (1989) has found that when applied to the single-objective least-cost expansion problem, genetic algorithms efficiently search a space to identify the best-fit solution, e.g. lowest cost, through simulated versions of genetic selection, crossover and mutation (to be discussed later in detail).

It is, however, still possible that the global optimal solution will not be found, as the genetic algorithm searches the solution space efficiently, but does not consider every single possible solution (Savic & Walters, 1997). Regardless of this, it has been found that genetic algorithms will in most cases supply the user with the optimal solution, or at least a solution near the global optimum.

This thesis considers the multi-objective genetic algorithms (MOGA), which are conceptually similar to single-objective genetic algorithms (SOGA).

2.6.5 Genetic Algorithms in Multi-Objective Optimisation

Walski (2001) has noted that cost objectives should be considered alongside additional objectives such as environmental impact and hydraulic reliability. Multi-objective genetic algorithms, also known as a Pareto based technique, have been used extensively in problems concerning water distribution system expansion. Their mathematical application to sewer system optimisation is very similar; there are however, considerable differences in the constraints that are installed in the model.

Conceptually multi-objective genetic algorithms are nearly analogous to single-objective genetic algorithms. The difference between these two optimisation approaches is that the MOGA considers two or more objectives where the SOGA considers only one (e.g. cost minimisation). MOGA optimisation is designed to balance two or more objectives by developing a set of optimal solutions.

2.7 Genetic Algorithms as Optimisation of Sewer Systems

2.7.1 Overview

In water distribution systems (WDS) there has been a great deal of research in evaluating multiple solutions and competing objectives in expansion problems (Dandy et al., 2008; Kapelan et al., 2006; Wu and Walski, 2005). A multi-objective optimisation balances competing objectives to identify feasible solutions that simultaneously comply with all objectives. Although most of the former research has been conducted with the focus on WDS, the principles can also, with some adjustments, be used to evaluate and optimise a WSS.

Multi-objective genetic algorithms (MOGAs) can be applied extensively to WSS scenarios. MOGAs simulate the evolutionary processes of genetic selection, crossover and mutation to arrive at the optimal solutions to the scenario in a computationally efficient manner. The result is a number of suitable solutions that balance all the given objectives. Stakeholders can use these optimisation results in their decision making process to find a solution to best fit their concerns and priorities. Multi-objective optimisation and genetic algorithms and their application will be further discussed in the following chapters.

Srinivas and Deb (1994) mathematically stated the multi-objective problem as follows:

Objective functions:

Minimise or maximise $f_i(\vec{x})$ $i = 1,2, \dots, n$

Constraints:

Subject to $g_j(\vec{x}) \leq 0$ $j = 1,2, \dots, p$

$h_k(\vec{x}) = 0$ $k = 1,2, \dots, q$

where n = number of objective functions

p = number of inequality constraints

q = number of equality constraints

Herstein (2009) summarised their application and found that the parameter $\vec{x}$ is a vector featuring decision variables $x_1, x_2, \dots, x_w$, where w is the total number of decision variables, also called genes in a genetic algorithm, each of which must be chosen from a list of possible values (e.g. commercially available pipe diameters). Together, these w decision variables (or genes) make up one system solution, also called a chromosome in a genetic algorithm. A chromosome consisting of w genes is illustrated in Figure 2-5. Each solution is evaluated by the genetic algorithm to determine the value of its n objective functions.

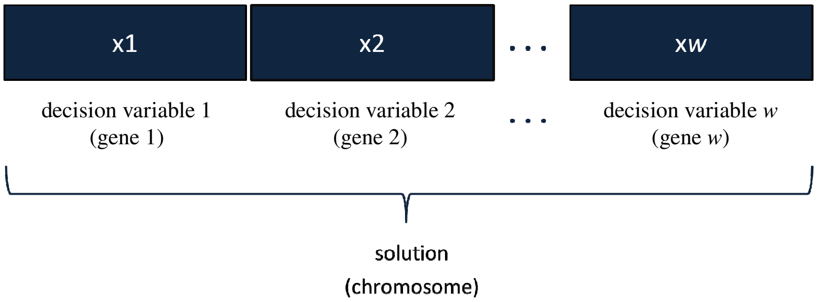

Figure 2-5 Chromosome layout of a genetic algorithm solution with *w* variables

For example, suppose that ten new pipes must be added to an existing system. In this problem, therefore, a single solution or chromosome has 10 decision variables (*w*). The diameter of a new pipe is selected from 5 commercially available pipe diameters. The total enumeration of possible solutions is thus the number of commercially-available pipe diameters for each new pipe raised to the power equal to the number of new pipes added, or

possible solutions.

Furthermore, the system is to be optimised with two objectives:

- Minimise pipe cost
- Minimise operating cost.

Each unique system solution (chromosome) will feature a different combination of 5 pipe diameters (genes) and will correspond to unique values of pipe cost (objective 1) and operating cost (objective 2).

2.7.2 Pareto-Optimal Front

Multi-objective optimisation algorithms generate a set of solutions called the Pareto-optimal front, which consists of non-dominated solutions (Srinivas & Deb, 1994). In the scenario where all objectives are to be minimised, there will be one solution (e.g. solution A) that dominates another solution (e.g. solution B). This means that all the objective function values of solution A are either less than or equal to those of solution B, or at least one of the objective function values of Solution A are strictly less than those of solution B. Therefore the objective function value of a Pareto-optimal solution cannot be improved without compromising at least one of the other optimising objectives. In a MOGA, comparison of solutions occurs in pairs and the conditions for dominance create situations in which neither solution dominates the other, thereby resulting in multiple non-dominated solutions and, ultimately, the Pareto-optimal front (Srinivas & Deb, 1994).

Figure 2-6 shows the concept of dominance. For this example there are two objectives: Objective 1 and Objective 2. These two objectives have been minimised, resulting in the Pareto-optimal front. Solution A and Solution C reside on the Pareto-optimal front, therefore they are considered non-dominated solutions. Solution A dominates Solution B because Solution A is a better option in Objective 1, with similar optimisation values in Objective 2, as compared to Solution B. Solution C also dominates Solution B, because Solution C is an improvement on Objective 2 with no change in Objective 1. As a result, Solution B is dominated and thus does not form part of the Pareto-optimal front.

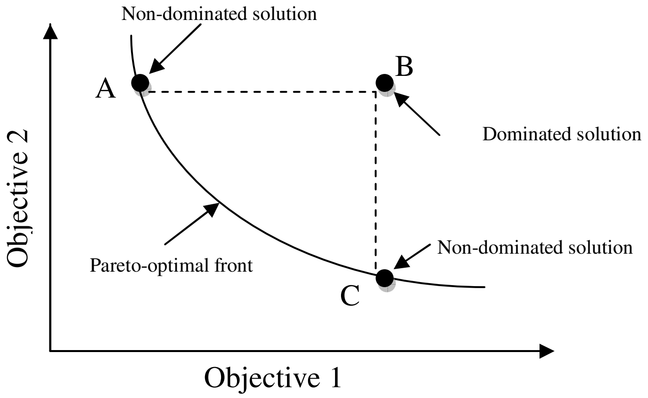

Figure 2-6 Pareto-optimal front for multi objective optimisation

The Pareto-optimal front allows decision makers to choose from a set of non-dominated solutions, rather than a single optimal solution (as is the case in SOGAs). Further, MOGA optimisation allows decision-makers to analyse solutions in a post-optimisation process and choose those feasible solutions from a Pareto-optimal front that best meet the overall needs of stakeholders (Cheung et al., 2003).

2.7.3 History of Evolutionary Multi-Objective Optimisation

During the mid-1980s the first studies on evolutionary multi-objective optimisation (EMO) were published. Since then a number of Pareto based techniques have been developed:

- 1994: Niched Pareto Genetic Algorithm (NPGA) (Horn et al.)
- 1994: Non-dominated Sorting Genetic Algorithm (NSGA) (Srinivas and Deb).

These formed the basis for further development and demonstrated the capability of EMO algorithms to approximate the set of optimal trade-offs in a single optimisation run. These approaches did not incorporate elitism explicitly, but the importance of this concept in multi-objective optimisation was recognised and supported experimentally (Parks and Miller, 1998; Zitsler et al., 2000). The elitist multi-objective evolutionary algorithms (MOEA) that were developed were:

- 1999: Strength Pareto Evolutionary Algorithm (SPEA) (Zitsler & Thiele)
- 1999: Pareto Archived Evolution Strategy (PAES) (Knowles & Corne).

These techniques clearly outperformed their (non-elitist) predecessors (Jaszkiewics, 2000). Following the development of the elitist principle, and new insights into the behaviour of EMO algorithms, the understanding of the basic principles and the main factors of success in EMO was improved (Laumanns et al., 2001). Algorithms that have been developed, and more recently proposed, are:

- 2000: Pareto Envelope-based Selection Algorithm (PESA) (Corne et al.)
- 2001: Strength Pareto Evolutionary Algorithm 2 (SPEA2) (Zitsler et al.)
- 2002: Non-dominated Sorting Genetic Algorithm (NSGA-II) (Deb et al.).

2.7.4 Comparison of MOEAs, and their suitability to WSS

The Strength Pareto Evolutionary Algorithm, SPEA, was introduced in 2000, in which selection and diversity maintenance are controlled via a simple layer hyper-grid based scheme (Corne et al.). The Strength Pareto Evolutionary Algorithm 2 (building on the base-line principles of its predecessor, SPEA) followed soon after, which incorporated, in contrast to its predecessor, a fine-grained fitness assignment strategy, a density estimation technique, and an enhanced archive truncation method (Zitsler et al., 2001). These two methods were similar in the sense they both used a small ‘internal population’ and a usually larger ‘external population’ (The external population is the archive which stores the current approximation to the Pareto front, and the internal population is new candidate solutions vying for incorporation into the archive).

The Non-dominated Sorting Genetic Algorithm (NSGA) proposed by Srinivas and Deb in 1995 was one of the first evolutionary algorithms that gave a large number of alternative solutions lying near or on the Pareto optimal front. However, over the years, the main criticism of the NSGA approach has been as follows:

- High computational complexity of non-dominated sorting.
- Lack of elitism.
- Need for specifying the parameter.

The authors of the NSGA addressed these issues and have developed a much improved version, the NSGA-II. This version will be discussed later in full, under section 2.8.

Although all three modern optimisation genetic algorithms were found to be suitable for optimisation of WSS, there were some instances in which certain methods were chosen above the others:

- PESA was found to have the fastest convergence (due to higher elitism intensity), but was also found to have some problems due to not always keeping the boundary solutions (Zitsler et al., 2001).
- In higher dimensional objective spaces SPEA2 has some advantages over PESA and NSGA-II (Zitsler et al., 2001), but these are not necessarily required for WSS optimisation.
- NSGA-II has advantages over PESA and SPEA2 in its simple and effective constraint handling techniques (Farmani et al., 2005).

This resulted in the choice of NSGA-II over any other MOEA. It was founded that advantages were:

- The accelerated speed of the non-dominated sorting approach.
- The ability to preserve good solutions throughout the evolution process.
- No need for the *a priori* specification of parameters.

The NSGA-II has also been proven to be efficient and effective in WDS optimisation. Farmani et al. (2005) used this improved non-dominated sorting genetic algorithm method to handle three objectives, namely, total cost of installation, expansion and rehabilitation (capital expenditure and pumping costs), resilience index and minimum surplus head in arriving at the optimal expansion and rehabilitation strategy for the “Anytown” network. It was found that NSGA-II would be appropriate for water distribution network problems involving constraints, since it is found to satisfy the primary goals of Pareto multi-objective optimisation, namely, closeness to the global Pareto-optimal front and diversity among the solutions in the front. Herstein et al. (2009) also found it suitable by using the NSGA-II to incorporate the environmental impact index into the optimisation for the “Anytown” network.

2.7.5 Summary

The evaluation and compilation of the existing system and its components are the first processes to be tackled in the task of optimising and expanding a WSS. The physical and hydraulic data that populate the object model can be obtained from an assortment of sources, and form the platform on which new models will be based.

Multi-objective genetic algorithms have been used extensively in the optimisation of water distribution systems. This has brought forward the notion that the same principles can be applied to WSS, with changes to the input parameters and constraints. MOGAs have enabled researchers and practitioners to incorporate multiple objectives to balance cost, performance, reliability and, recently, environmental impact. The NSGA-II has been widely adopted in the field of distribution system analysis due to its efficient and straightforward sorting and constraint-handling characteristics.

2.8 Non-dominated Sorting Genetic Algorithm II (NSGA-II)

2.8.1 Introduction and Overview

The NSGA-II is the revised version of the Non-dominated Sorting Genetic Algorithm (NSGA) (Srinivas & Deb, 1994) and is more efficient than its predecessor. It employs a crowded tournament selection operator to keep diversity. In the elitist mechanism of NSGA-II, it neither uses an external memory nor does it specify any extra niching parameters, as most other algorithms have to do. Instead, the elitist mechanism consists of combining the best parents with the best offspring obtained. Because of its elitist approach and fewer parameters being required, NSGA-II has become one of the best multi-objective optimisation algorithms (Zhang, 2009).

It has been argued in the previous sections that NSGA-II is an acceptable method for optimisation of WSS, due its efficient and effective manner of handling highly constrained, discrete and non-linear optimisation problems. The working of this method is illustrated in Figure 2-7.

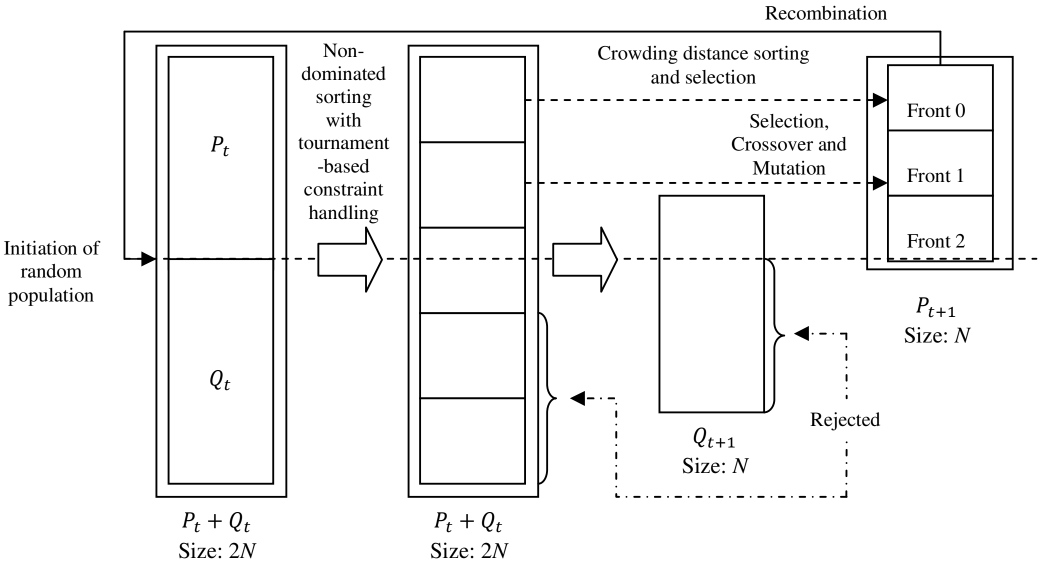

Figure 2-7 Overview of the NSGA-II procedure (Deb et al., 2002)

The following sections provide the process details and workings of the NSGA-II as presented by Deb et al. (2002) and as summarised by Herstein et al. (2009).

2.8.2 Initial Population

Before any genetic algorithm begins its search, an initial population must be generated. The initial population, comprising system solutions called chromosomes (as was described in section 2.4), is generated randomly to ensure diversity in the starting population. The pre-specified population size *N*, is held fixed throughout the optimisation run. Different from any other MOEA is the fact that the population size of the NSGA-II is double the normal random population size, therefore 2N. This is to further ensure diversity in the initial population (Deb et al., 2002).

2.8.3 Non-dominated Sorting of the Initial Population

Figure 2-7 depicts the first generation, t, of the first population P_t, of size *N*, and the second population, Q_t, of size *N*. This initial double population is sorted into fronts with the non-dominated sorting method. The basis of this procedure is to evaluate the objective functions of each solution in the initial population relative to other solutions in the initial population, organise the solutions according to their dominance over one another, and choose a population, P_{t+1}, of size *N* from the initial population, of 2*N* (Herstein et al., 2009).

Herstein et al. (2009) presented an example (Figure 2-8) of the non-dominated sorting of population of five solutions into three fronts.

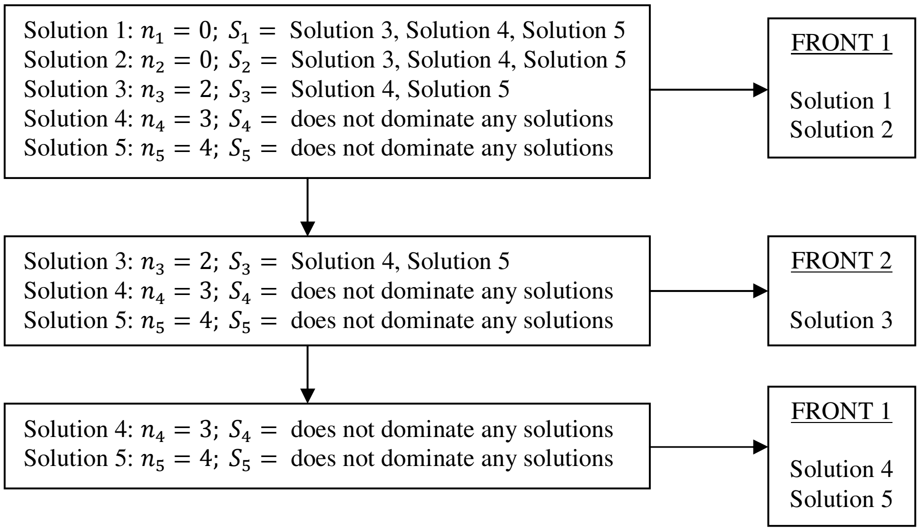

Figure 2-8 An example of the NSGA-II non-dominated sorting procedure

The procedure begins by evaluating each solution, p, in the initial population to determine the number of solutions, n_p, that dominate each solution p and a set of solutions, S_p, that are dominated by p. All solutions with n_p= 0 will be in the first non-dominated front (front 0) and each of these front 0 solutions will feature its own set S_p. For each member of front 0, the value of n_p for each solution in the set S_p is reduced by one. All solutions in S_p with n_p = 0 will be in the next non-dominated front (front 1). This de-incrementing procedure continues for each consecutive front until all solutions have been placed in a front (Front 2, Front 3, etc.) (Deb et al., 2002).

2.8.4 New Population and Crowding Distance

Chosen from the initial double population, $P_t + Q_t$ with 2*N* population, a new population comprising non-dominated selected members P_{t+1} is found, with population size *N*. This process is illustrated in Figure 2-7. This population P_{t+1} can comprise only *N* population members. This means that *N* solutions are chosen from the initial double population $P_t + Q_t$, starting with the first front, front 0, and continuing to the next fronts until *N* solutions have been chosen for the new population, P_{t+1}.

The crowding distance is a measure of how similar a solution is to another solution in the same front when all objective functions are compared. A longer crowding distance denotes a solution that is further away from other front solutions and these solutions are preferred, as they preserve diversity in the newly chosen population. The crowding distance of each solution in the last chosen front is calculated and the front is organised in descending order of crowding distance. The solutions from the last chosen front with the largest crowding distance values are chosen for the population P_{t+1} and the other front solutions are discarded (Deb et al., 2002). In Figure 2-9 the crowding distance of the *i*-th solution in the front is the average side lengths of the cube depicted.

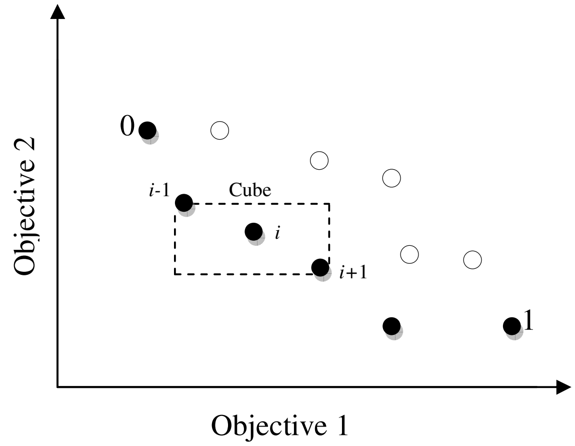

Figure 2-9 Crowding distance calculation

2.8.5 Tournament Selection

At this stage the selection process has identified the fittest members of the initial population. To further improve the population, the resulting population is subject to genetic operations of selection, crossover and mutation to create a new population.

Tournament selection randomly chooses a set of individuals and picks out the best for reproduction. The number of individuals in the set usually equals two, but larger tournament sizes can be used in order to increase the selection pressure. The dominant individuals that are chosen then continue on for further operations such as crossover and mutation, and the process is repeated for the rest of the population members. Members are first shuffled and then compared, two at a time, until all members have been compared once. The population is then shuffled a second time and each member is compared again, to arrive at a selected population of size *N*. The result of the selection process is a new population with some of the best randomly chosen members of the population P_{t+1} $(\text{Goldberg} \,\&\, Deb, 1991)$. Figure 2-10 depicts tournament selection without replacement, featuring a tournament size of two for simplicity.

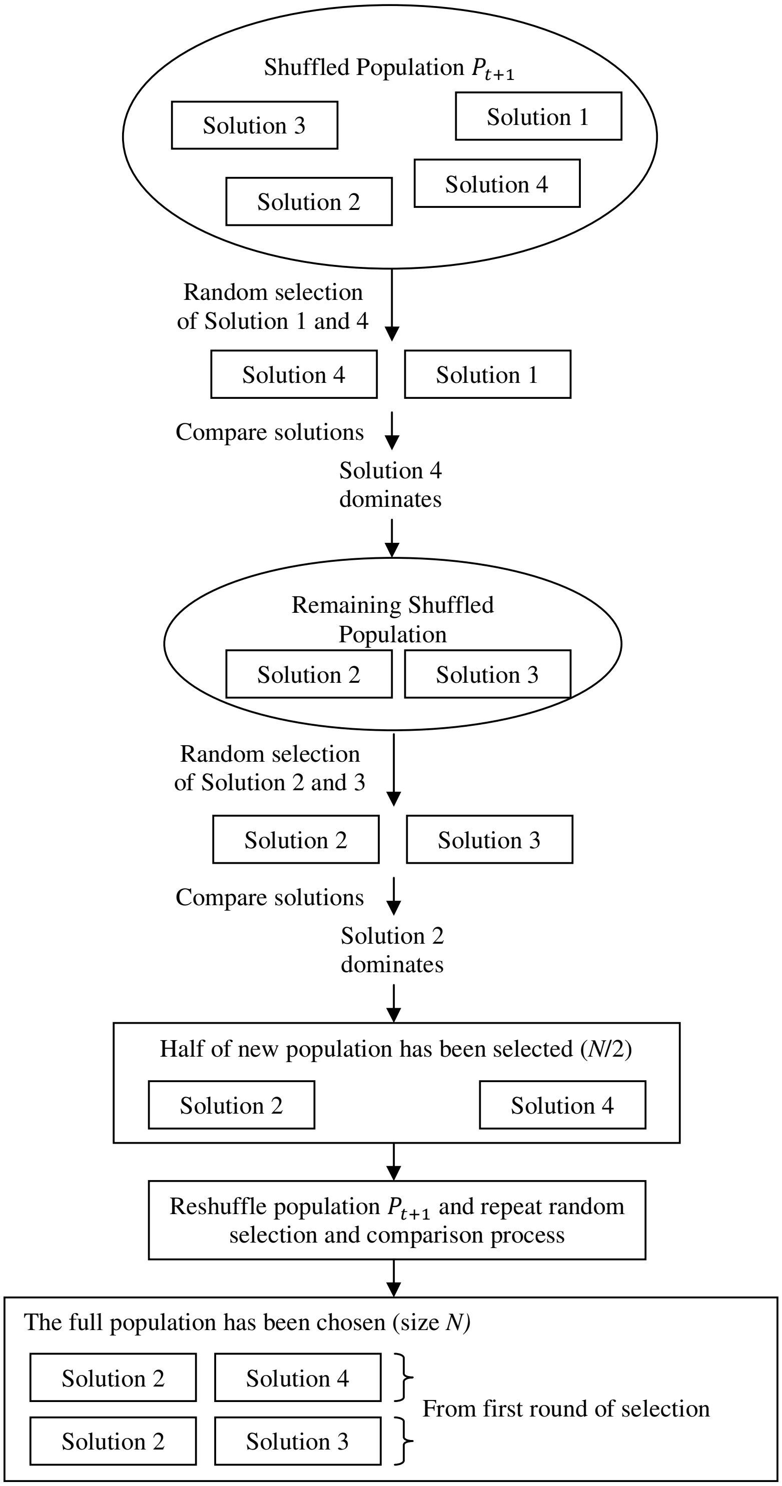

Figure 2-10 NSGA-II tournament selection without replacement (Herstein, Fillion and Hall, 2009)

2.8.6 Two Point Crossover

Crossover describes the process by which two parent population members are combined, or crossed, to form two new offspring population members, with each offspring carrying a part of the parent's solution. Two point crossover (the string being broken at two points with the middle section of code switched), was found to be more effective than one point crossover (Halhal et al., 1997).

Halhal et al. (1997) described the process as follows; the two-point crossover process randomly chooses two members, or parents, from the newly selected population, splices each of their chromosomes (solutions) at two randomly chosen crossover sites, and switches the genes (decision variables) between these sites to create two new children each containing part of both parental chromosomes.

2.8.7 Mutation

Occasional random alteration of solutions protects the genetic algorithm process against premature loss of potentially useful genetic material; this ensures additional solution diversity. A mutation operator introduces random solutions into the population that may not have been created through the selection and crossover processes. This can result in a better solution than those currently in the population.

Figure 2-11 shows the selective mutation process, which randomly selects a decision variable of a solution from a child member and replaces it with a random variable within a specified range. Mutation of each solution in the child population occurs with a pre-specified probability (Herrera et al., 1998).

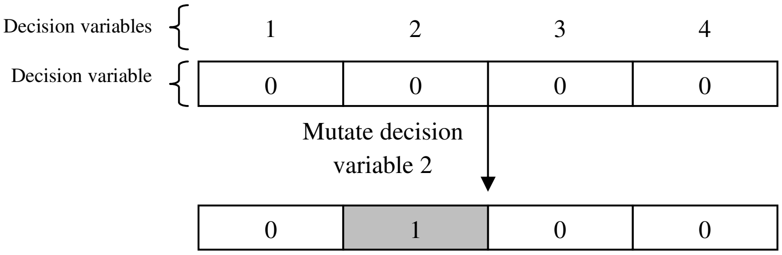

Figure 2-11 Selective mutation process

2.8.8 Recombination

Recombination, or re-evaluation, is the iteration process after the selection, crossover and mutation processes have been completed and a population Q_{t+1} has resulted (with population size *N*). Once one generation Q_{t+1} has been conceived, it is combined with the population P_{t+1} to create a population ($Q_{t+1} + P_{t+1}$) with a size of 2*N*. This combined population is subject to another non-dominated sorting, selection, crossover and mutation. Therefore, the resulting population consists of the best solutions from the newly formed population as well as best solutions from the previous population, which may have been lost through the various operations.

The process is repeated in subsequent generations to ultimately arrive at the Pareto-optimal front. Literature (Wu and Walski, 2005; Kapelan, et al., 2006; Dandy et al., 2008) suggest that for NSGA-II-based WDS expansion optimisation models (with similar variables as in WSS) convergence is often observed within 200 generations.

2.8.9 Constraint Handling

Deb et al. (2002) has proposed a constraint handling approach. This constraint-handling method uses the binary tournament selection, where two solutions are picked from the population and the better solution is chosen. In the presence of constraints, each solution can be either feasible or infeasible. Thus, there may be at most three situations:

- both solutions are feasible
- one is feasible and other is not
- both are infeasible.

Solution *i* is said to have constrained-domination over Solution *j*, if any of the following conditions is true:

- Solution *i* is feasible and Solution *j* is not.
- Solutions *i* and *j* are both infeasible, but Solution *i* has a smaller overall constraint violation.
- Solutions *i* and *j* are feasible and Solution *i* dominates Solution *j*.

The effect of using this constrained-domination principle is that any feasible solution has a better non-domination rank than any infeasible solution. All feasible solutions are ranked according to their non-domination level based on the objective function values. However, between two infeasible solutions, the solution with a smaller constraint violation has a better rank (Deb et al., 2002).

CHAPTER 3

SPATIAL DEVELOPMENT AND POPULATION GROWTH

3.1 Introduction to Municipal Spatial Development Framework

Planning the future begins with an understanding of the way things are right now: the place, the people, and the social and economic forces underlying the trends that shape the development of any municipal area.

Change and growth are inevitable, and development pressures are a given. Nevertheless, a municipal government with foresight and insight can guide and manage public and private development to ensure the best possible outcome for the city and its people. This best possible outcome necessarily includes the protection and enhancement of the city's key economic, social and environmental resources and assets, and the extension of these economic, social and environmental opportunities to everyone in the city (City of Cape Town, 2009)**.**

The overall intention of the Spatial Development Framework (SDF) is to guide and manage urban growth, and to balance competing land use demands by putting in place a long term, logical development path that will shape the spatial form and structure of the municipal area.

3.2 Legislative Value

In terms of the South African Municipal Systems Act (Act 32 of 2000), every municipality is required to formulate a Spatial Development Framework as a part of its Integrated Development Plan (IDP).

Taking into account the current pattern of land use and the nature of development in the municipal area, a Spatial Development Framework is required to describe in words and illustrations how the municipality sees desirable future patterns of land use and development in its area of jurisdiction. In essence, it is the municipality's spatial "vision" of what the area will look like in years to come.

The Spatial Development Framework is a legally enforceable component of the IDP, which indicates both to the municipality (councillors and officials) and to the public (developers and land owners) where certain types of land use and associated developments are permissible, and where certain activities are unlikely to be permitted. As such, it forms the basis for land use management and serves as a guideline to inform the municipality in its decisions on land development (new development and changes to existing land uses) in its area of jurisdiction.

3.3 Population Growth Projections

3.3.1 Introduction

Before the commencement of any project the design engineer needs to estimate the size of the population, so that the planned system will be adequate throughout the design life (also referred to as the design period). Depending on the priorities of the municipality, there are typically two types of population projection:

- short term projection, from 5 to 10 years
- long term projection, from 10 to 50 years.

Making longer term projections is a significant challenge, due to the large number of uncertainties involved in predicting the distant future. In this case the only viable option is to rely on past growth curves to predict trends, although economic and social factors can adversely affect the growth in municipal areas.

Growth prediction models can be instrumental to the opinion formed by the design engineer regarding the future growth of a certain area, which can then be clarified by interviews with responsible authorities, examination of the city or town's technical service files, and information gathered from professionals in other fields (urban planning, economics, demography and sociology) (Briere, 2007).

3.3.2 Sources of Information

There is a wide range of sources available to assist the design engineer to better estimate population growth:

- national and provincial census
- immigration and emigration data
- birth and death statistics
- historic urban planning documents.

3.3.3 Population Growth Models

3.3.3.1 Introduction

In a finite environment, and considering the social and economical factors and the available food supply, the behaviour of the human population is similar to the behaviour of a bacterial population living in a confined environment where resources are limited (Briere, 2007), see Figure 3-1. The different stages of growth are indicated on the graph.

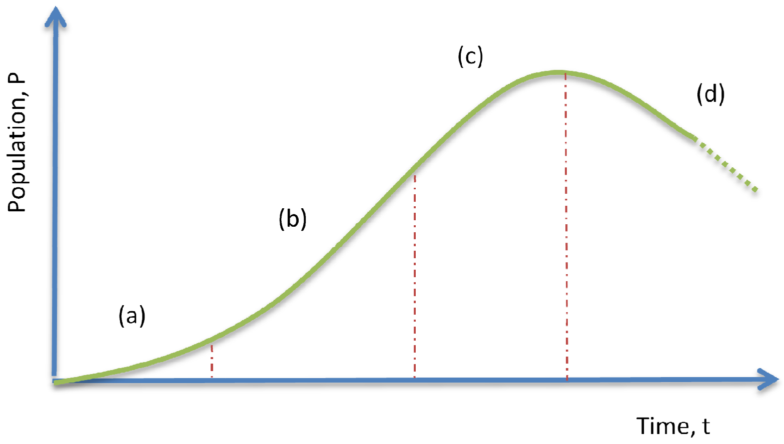

Figure 3-1 Evolution of bacterial population in a confined environment: a) initial adjustment period; b) rapid growth; c) slowed growth; d) decline

It is important, in the case of a town or city, to note that before the period of declining growth, equilibrium can be achieved by using (recycling) the organic wastes and natural fertilisers that allow for a constant food supply. This allows the population of an urban area to tend to its maximum (saturation). Most long term projection methods attempt to evaluate the growth according to this type of curve.

When historical data is analysed care should be taken to detect extraordinary events that may have influenced population growth, but which have little chance of reoccurring; these events may induce projection errors (Briere, 2007).

The following six different growth projection models are those noted by Briere (2007).

3.3.3.2 Graphic Extrapolation

Graphic extrapolation is the method by which extrapolations are made from the growth curve of the population (Figure 3-2). Past events that have influenced population variations are used for population predictions in the years to come.

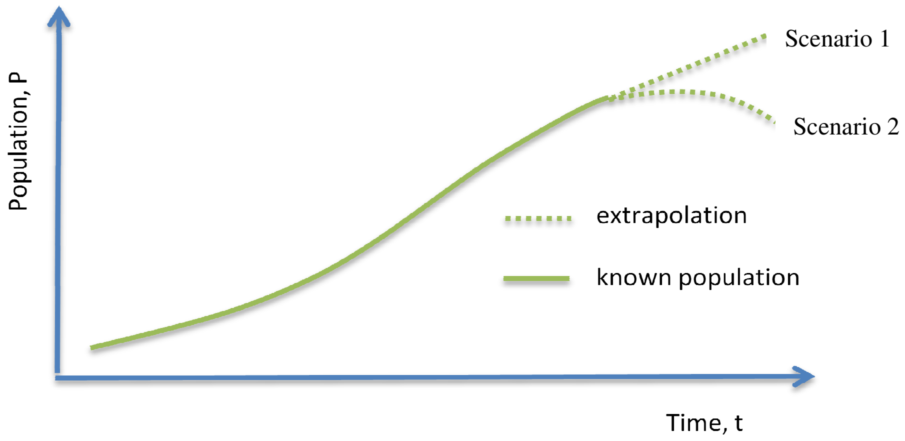

Figure 3-2 Graphic extrapolation of population growth

3.3.3.3 Comparison of Population Growth in Different Cities

The population growth curve of a city where the population is to be estimated is compared to cities that have shown similarities in terms of population status in the past. If three cities or urban areas evolved in similar fashion, but at different times, the demographic growth of city no.2, for example, can be projected by assuming that it will correspond to the average growth of the other two cities (as indicated in Figure 3-3). However, it is important that the cities have similar social and economic characteristics for the periods under consideration.

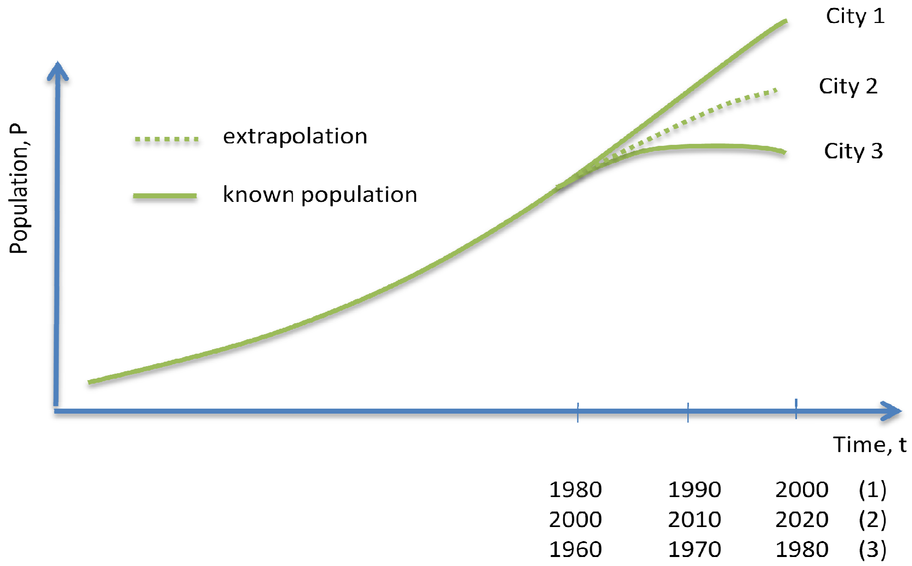

Figure 3-3 Population evolution projection of city no. 2 by graphic comparison with cities no. 1 and 3

3.3.3.4 Projections Based on Arithmetic Growth

The growth of a population is said to be arithmetic when the growth rate, dP/dt, of the population is constant, i.e.:

— (3-1)

therefore

(3-2)

thus

(3-3)

where P = population

t = time

= arithmetic growth rate constant

Equation 3-3 could be represented by a straight line as indicated by the extrapolation in Figure 3-4.

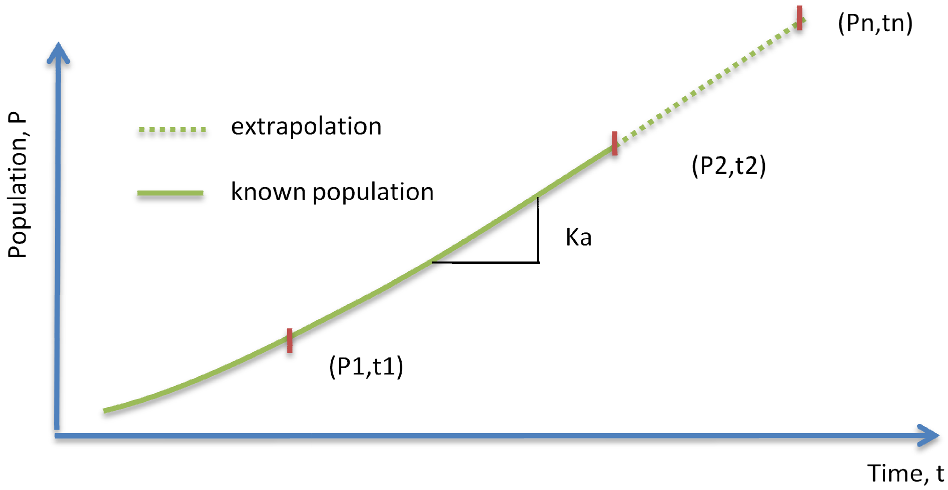

Figure 3-4 Arithmetic population growth projection

is calculated by known populations, i.e.:

______ (3-4)

and

$$P_n = P_2 + K_a(t_n - t_2) \tag{3-5}$$

where t_n = year for which population is projected
P_n = population for the year t_n
P_2 = known population for the year t_2

Population projection using the arithmetical growth method is well suited for older established cities and regions where development has stabilised, as is often the case in rural agricultural communities (Briere, 2007).

3.3.3.5 Projections Based on Geometric Growth

The growth of a population is said to be geometrical when the growth rate, dP/dt is proportional to the population itself, i.e.:

$$\frac{dP}{dt} = K_g P \tag{3-6}$$

therefore

$$\int_{P_1}^{P_2} dP/P = K_g \int_{t_1}^{t_2} dt \tag{3-7}$$

thus

$$ln(P_2) - ln(P_1) = K_g(t_2 - t_1) \tag{3-8}$$

where = geometric growth rate constant

The graphic representation of the logarithm variation for population P, as described as a function of time, is a straight line with a gradient of (see Figure 3-5).

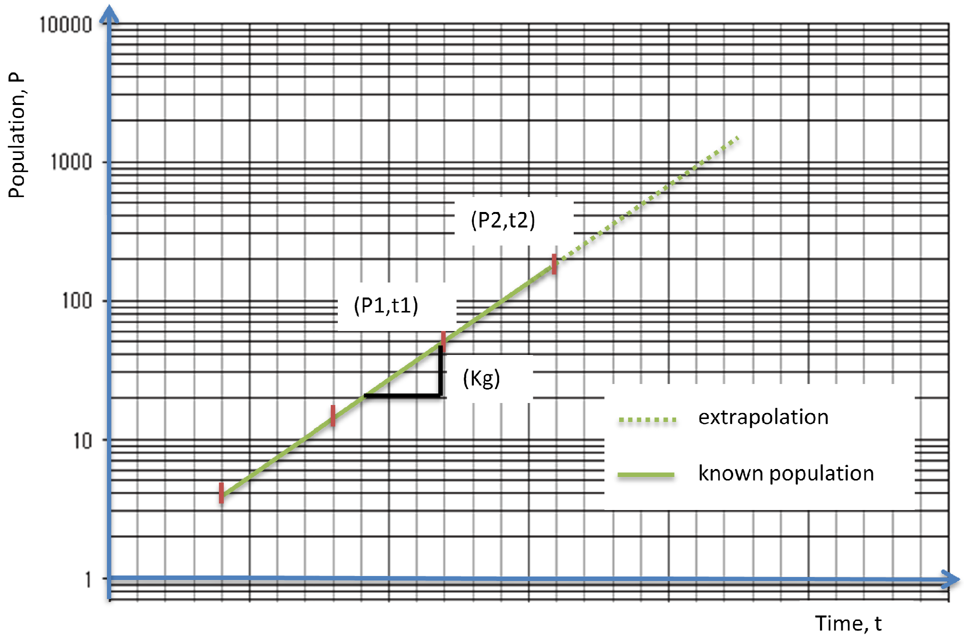

Figure 3-5 Geometrical growth projection

3.3.3.6 Logistical Projections

Logistical projection is a long term projection method that relies on the previously stated hypothesis (section 3.3.3.1) that a given community goes through three distinct stages of growth; a slow start, followed by rapid growth, and then a gradually slowing as the population tends to saturation (see Figure 3-6).

This method is appropriate for situations in which the population of a given community is known over a certain number of years. Three populations, P1, P2, and P3 are evaluated at regularly spaced intervals .

Population P1 corresponds to the slow growth period, P2 to the rapid growth period, and P3 to the period of decreasing growth-rate period.

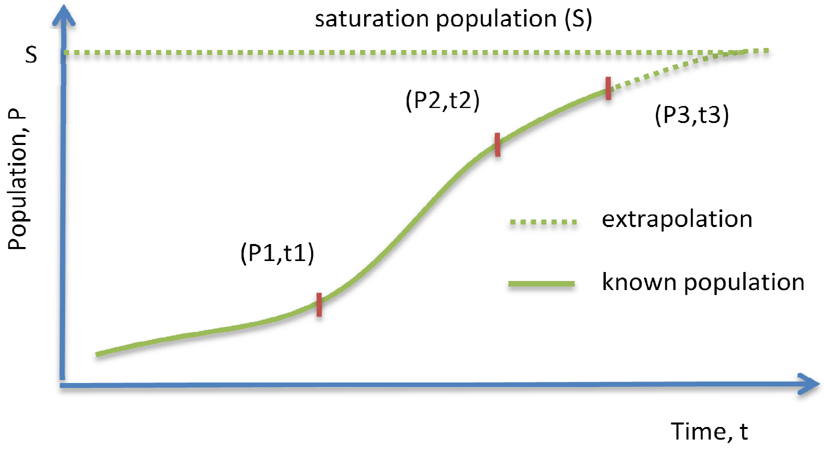

Figure 3-6 Projection of population growth using the logistic method

Population is then calculated at time using the following equation (Briere, 2007):

(3-9)

where

(3-10)

and

(3-11)

$$b = \frac{1}{n} \ln \left[\frac{P_1(S - P_2)}{P_2(S - P_1)}\right] \qquad (3\text{-}12)$$

and t_n = time elapsed from beginning of logistical growth

3.3.3.7 Projections Based on Decreasing Growth Rate

During the third and last phase of population growth as presented in Figure 3-1 in section 3.3.3.1, growth tends to a maximum, previously defined as saturation population, S (see Figure 3-7). This growth can be modelled by assuming that the growth rate is a function of the difference between the saturation population, S, and the current population, P, i.e.:

$$\frac{dP}{dt} = K(S - P) \qquad (3\text{-}13)$$

where S = saturation population

K = decreasing growth rate constant

this means that

$$\int_{P_1}^{P_2} \frac{dP}{S - P} = K \int_{t_1}^{t_2} dt \qquad (3\text{-}14)$$

therefore

$$-ln\left[\frac{S - P_2}{S - P_1}\right] = K(t_2 - t_1) \qquad (3\text{-}15)$$

thus

(3-16)

i.e. that

(3-17)

therefore, in general

(3-18)

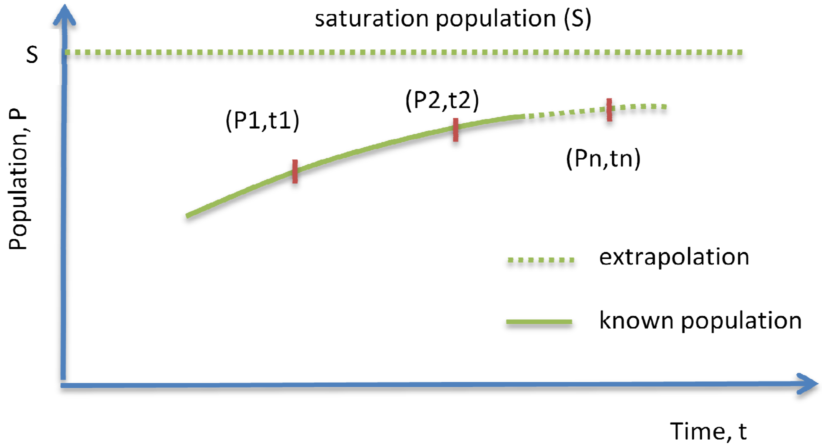

Figure 3-7 Projection of population growth when the growth rate is decreasing

The projection method is appropriate for communities approaching saturation population (Briere, 2007).

3.3.4 Population Densities

Population densities are generally expressed as the number of persons per square kilometre. Population densification is that scenario in which there is an increasing number of people living in the same space. New apartments and land re-zoning can often lead to this. The obligation rests on the design engineer to design to accommodate this densification phenomenon.

3.3.5 Design Period

In a WSS the facility must be designed to adequately serve the community to meet its current and future needs. The design period refers to the number of years between the time a structure is first put into service until the day it no longer meets the needs of the community. This period is usually calculated by taking the following considerations into account:

- Investments
- Maintenance and Operation costs
- Possibility of expansion.

Table 3.1 shows the design periods for structures in WSS as suggested by the CIDB (2007). However, these values vary from one source to another. The values in Table 3.1 are considered quite typical.

Table 3.1 Design periods for WSS facilities

Facility	Characteristics	Design Period (yrs)
Secondary pipes smaller than 375mm dia.	Construction and doubling easy	20-25
Collecting and intercepting sewers, outfalls	Extension difficult and costly	30-50
Pumping station	Easily extended	10-20
Entrance pumps at treatment facility	Replacement easy and cheap; rapid wear	5-10

3.4 Chapter Summary

A spatial development framework (SDF) is a crucial part of the expansion and densification optimisation of any municipal area. It provides a guide to municipal officials, engineers, land developers and home owners, and manages urban growth. The fact that it is a legally enforceable component of the IDP ensures that it balances competing land use demands and shapes the spatial form and structure of the municipal area.

Current population growth prediction methods are widely available and relatively easy to use and understand. The tricky part of predicting the future growth of any area is to know which model to implement and then to obtain accurate input values, given the uncertainties inherent in spatial development. This chapter has provided an overview of all the models available and some insight as to when each is applicable.

CHAPTER 4

COST AND COST FUNCTIONS

4.1 Overview

Infrastructure costs are a crucial part of sewer system master planning, since the unit costs are required during the optimisation stages of the analysis. It is very important, especially in the preliminary stages of any project, to have relatively accurate estimates of the infrastructure cost. The item costs for previous projects across South-Africa were collected by GLS Consulting (2010) as part of this study, from both consultants and actual tender documents, and the typical cost for certain conditions was determined. This data was used as the basis for the model developed. Numerous factors were taken into consideration to develop a unit cost value. These values were, for example, grouped according to a wide range of pipe diameters and common pipe materials, in the case of pipes.

A model was developed as part of this thesis to predict the unit value of the various sewer elements, including the gravity pipes, rising mains and pump stations. The cost functions presented in this thesis are used for practical application by specialist consultants in view of system optimisation and cost estimation in sewer networks. The costs are time dependent and serve as an illustration of the unit costs for sewer system components at the time of this study. Later in this chapter construction cost indices will also be discussed and applied, together with the optimisation formulas that are to be incorporated into the NSGA-II.

4.2 Introduction to Construction Cost

Construction cost in general is equal to the sum of the following:

- Materials (M_1) (concrete, steel, PVC, lumber or iron used in the construction)
- Machines (M_2) (process equipment and contractor's equipment used in construction)
- Men (M_3) (skilled and common labour employed during construction)
- Money (M_4) (overhead charged and profit earned during construction)

Or

$$Construction\ cost = M_1 + M_2 + M_3 + M_4 \qquad (4\text{-}1)$$

4.3 Unit Cost Functions for Value Estimation of Waterborne Sewage Infrastructure

4.3.1 Limitations Applicable to This Model

Normalising the Rand value presented in this thesis was initially considered, but after various workshops held by the author with various Municipalities across South Africa it was decided to maintain the more basic approach to present value in Rand terms. This is, of course, a limitation in that the value would soon become out-dated. In view of the low-technology application of these cost functions it was considered too complex from a viewpoint of application to derive functions that would be based on some normalised value – that would have to be converted back to Rands for the sake of practical application. However, although the Rand value was kept at the value at the date of this study, later on in the chapter there will be a discussion on indices that will assist in bringing the cost values up to date. An example of this procedure will be shown in the case study.

Another limitation, resulting from the simplistic nature of the product sought, is the fact that the cost functions are based purely on capital cost, as the name of the model states. Operations and maintenance costs are not included here. This could be viewed as a limitation, in that these functions cannot be applied to optimise total cost during master planning. However, when a local authority reaches the point where such optimisation is needed, a specialist consultant could arguably be appointed to conduct a more detailed analysis. These functions based on capital cost are handy to provide estimates of sewer infrastructure replacement value and could also act as a method to verify budgets and estimated tender prices – typically provided by engineering consultants – for the construction of new infrastructure.

In the set-up of the unit costs, the administration and general preliminary costs for a project are not included in the calculations, as these values are project specific.

4.3.2 Model Use in WSS Optimisation

The cost functions presented in this chapter have been developed over a number of years by specialist consultants (GLS, 2010) and are widely used locally to estimate sewer infrastructure cost. The intention for this costing model is to give municipal employees a quick and easy means to obtain an estimate of the costs of the system for a project based on specific input parameters.

However, the findings in this model (especially referring to the development of equations 4-2 to 4-11) can be used to determine the initial investment component of WSS optimisation. This will be demonstrated on the Sanitown model later in this thesis.

4.3.3 Cost Influencing Factors

Through a sensitivity analysis that was conducted, it was found that for pipes, the main cost influencing factors in this study are considered to be the pipe diameter and the type of surface to be reinstated. Construction in roads is more expensive than that in the road reserve (at the side of the road), while construction in an open space is relatively cheap compared to the first two mentioned.

An interesting result, in agreement with practice, is that gravity sewers are generally more expensive than rising mains of the same diameter, despite the fact that the pressure class and cost of the pipe itself is higher for the rising main than the gravity sewer (due to the thicker pipe wall). The two reasons for the higher cost of gravity sewers are the deeper trenches needed to maintain a suitable gradient (and avoiding other services along the way) and also the presence of manholes at regular intervals. An interval of 90 m is normally suggested (CSIR, 2000), implying that manhole cost could add substantially to the pipeline cost. The cost for manholes, bends and couplings are averaged across the length of the pipeline to produce the unit cost function.

In the case of pumps the civil works, mechanical and electrical works are addressed separately, arriving at an estimate for the pump station cost based on the total capacity.

4.3.4 WSS System Cost Estimation Model

4.3.4.1 Development and Methodology

Four workshops were held with various Municipalities in the Western Cape and Central Karoo during November 2009 as part of this project to test the possible application of the cost functions as a low technology tool. The target municipalities were the smaller and, in effect, poorer municipalities that did not necessarily have the knowledge base or even access to computers to do an accurate sewer system costing or master planning. In some cases comprehensive sewer master plans had been compiled by specialist consultants, but the application and usefulness of the cost functions were tested nonetheless.

A clear need was identified for a tool such as the one presented here, particularly since it could be presented in hard copy format (e.g. as a poster) which would be easy to use. The fact that a Rand value was presented was noted to be particularly handy and easy to understand. Various options to keep the cost functions up to date were obtained during these workshop sessions. For ease of use the values are given as a Rand per meter value for a certain type and size of pipe (i.e. uPVC, concrete, or steel) and depending on the area in which it would be constructed (i.e. public open space (POS), road reserve, or in the road).

The model was developed by using actual values given in successful tender documents submitted by civil construction companies. The values that cover the excavation, the preparation of the trench bottom, backfilling and reinstatement of surfaces were averaged across tenders from a wide assortment of civil construction companies to obtain the first-order estimate of the cost.

For the computation of quantities the excavation is measured as if taken out with vertical sides, regardless of whether the sides are sloping (as is the standard in tendering processes). The measurement of and payment for earthworks for a pipe trench is that the rates which were tendered shall cover the cost of the excavation and the re-use of the excavated material for backfilling and disposal of any surplus material along the route of the pipeline. The rate for the preparation of the trench bottom (bedding cradle and specific fill blanket) shall cover the cost of the handling, placing, and the compaction of the bedding materials in addition to any other cost associated with the laying of the pipeline. The cost of the reinstatement of surfaces is subject to the type of surface that was previously in place – prior to construction.

The model makes provisions for a pipeline underneath three surface types, displayed in Table 4.1, which are also considered to be the main cost influencing factors:

Table 4.1 Surface conditions to be reinstated

Surface Condition	Description
Public open spaces	These areas are normally covered in either dirt or grass which is relatively inexpensive to reinstate to its former condition. The materials removed can be salvaged through the excavation period and replaced after backfilling has occurred.
Road reserves	This area refers to the space that is normally in-between the roads and the local properties. There is a higher cost involved, compared to public open spaces, when excavating in these areas. This is due to the high likelihood of other pipes and services that are found in the same area.
In roads	When excavation for a pipeline occurs on a road or a segment of a road the contractor has to undertake higher costs for reinstatement of the road layers and surface after excavation.

The costs for every aspect of the system are then computed and added together to determine the overall cost of the infrastructure element. The total cost is then divided by the length in meters to determine the value of the pipe installation per meter length, thus providing the functional unit. These represent the average values per meter length for a certain size and type of pipe. The values were determined for each of the three types of surface cover that was previously mentioned.

The cost of the construction of pump stations was developed similarly to the development of the cost functions for sewer mains, i.e. by averaging the cost of actual accepted tenders. The value derived was for the pump operating at 65% efficiency.

4.3.4.2 Gravity Pipes

In instances where the water flows under gravitational force, the most commonly used pipe material is either uPVC or concrete. The model is based on the assumption that for diameters from 100 mm to 450 mm uPVC pipes will be used, and for diameters from 450 mm up to 1.8 m concrete will be utilised.

The graphs in Figure 4-1 depict the different diameters available in the model, with the corresponding Rand per meter value for the three different types of cover conditions.

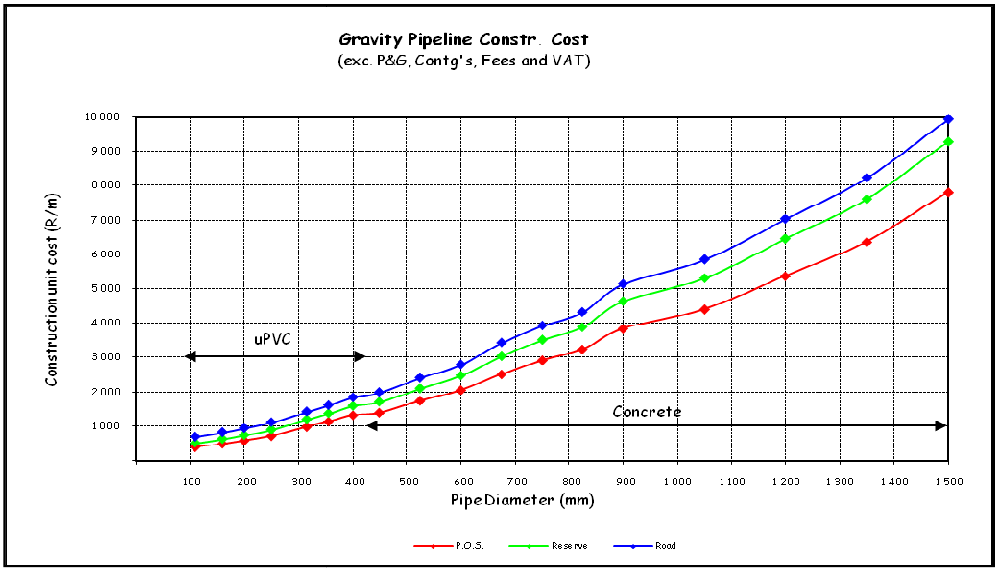

Figure 4-1 Gravity Pipeline Construction Cost (Bester et al., 2010)

The data plotted in Figure 4-1 was used to compile three different equations for the different types of land cover:

For Public Open Space areas:

$$\text{Cost} = \text{L} * (0.0024\text{D}^2 + 2.8788\text{D} + 300) \qquad (4\text{-}2)$$

For Reserve areas:

$$\text{Cost} = \text{L} * (0.0024\text{D}^2 + 2.4544\text{D} + 190) \qquad (4\text{-}3)$$

For Road areas:

$$\text{Cost} = \text{L} * (0.0021\text{D}^2 + 1.9783\text{D} + 154) \qquad (4\text{-}4)$$

where: Cost = value in Rand
L = total length of pipeline (m)
D = nominal pipe diameter (mm)

It was found is that the comparative costing of the construction of a pipeline in a road reserve area will be about 20% higher than for public open spaces, and in the road about 13% higher than in a road reserve area on average.

4.3.4.3 Rising Mains

In some instances the water needs to be pumped to a higher level, and here use is generally made of two types of pipe materials, i.e. uPVC or steel. The model is based on the assumption that for diameters from 100 mm to 450 mm uPVC pipes will be used, and for diameters from 450 mm up to 1.0 m steel will be utilised.

Figure 4-2 depicts the different diameters available in the model, with their corresponding Rand per meter value for the three different types of land cover conditions.

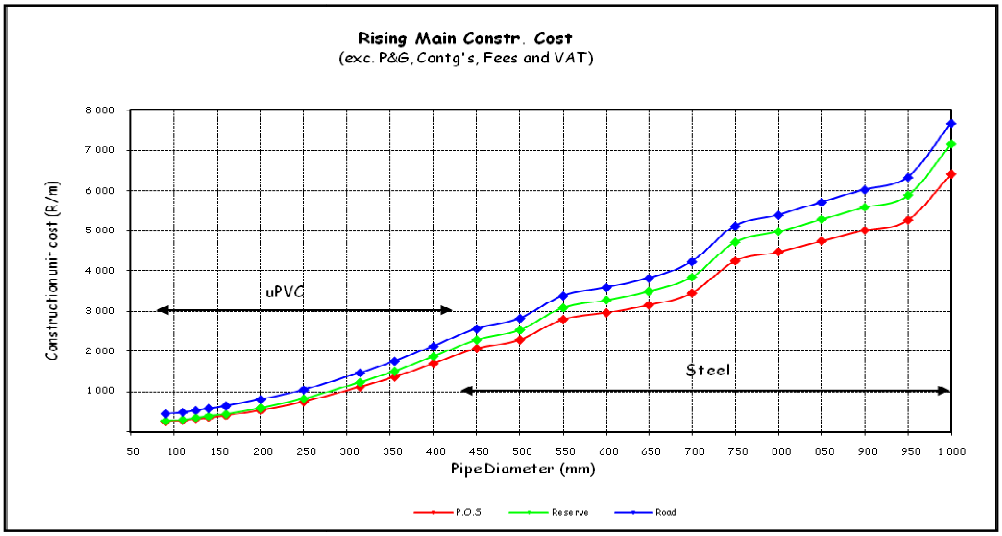

Figure 4-2 Rising Main Construction Cost (Bester et al., 2010)

The data plotted in Figure 4-2 was used to compile three different equations for the different types of land cover:

For Public Open Space areas:

(4-5)

For Reserve areas:

(4-6)

For Road areas:

(4-7)

where the parameters have the same meaning as before.

It was found that the comparative costing of the construction of a pipeline in a road reserve area will be about 10% higher than for public open spaces, and in the road about 9% higher than in a road reserve area on average.

4.3.4.4 Pumping Stations

Three major cost influencing factors in the construction of pump stations were noted. These include:

- The cost of civil works to erect the building to house the pumps; these normally include the covering structure of the pumps, the supply sumps, and the inlet structure.
- The cost of the intricate pipe networks leading the water to and from the pumps to the main line, together with the various necessary valves and auxiliary equipment.
- The cost of the mechanical and electrical components of the pump station. These include the pumps, the control and monitoring equipment, flow meters and measurement devices.

The graphs in Figure 4-3 portray the three different costs involved in the construction of a complete pump station, in proportion to the pump capacity. The total cost for the pump station is shown, for pumps operating at 65% efficiency.

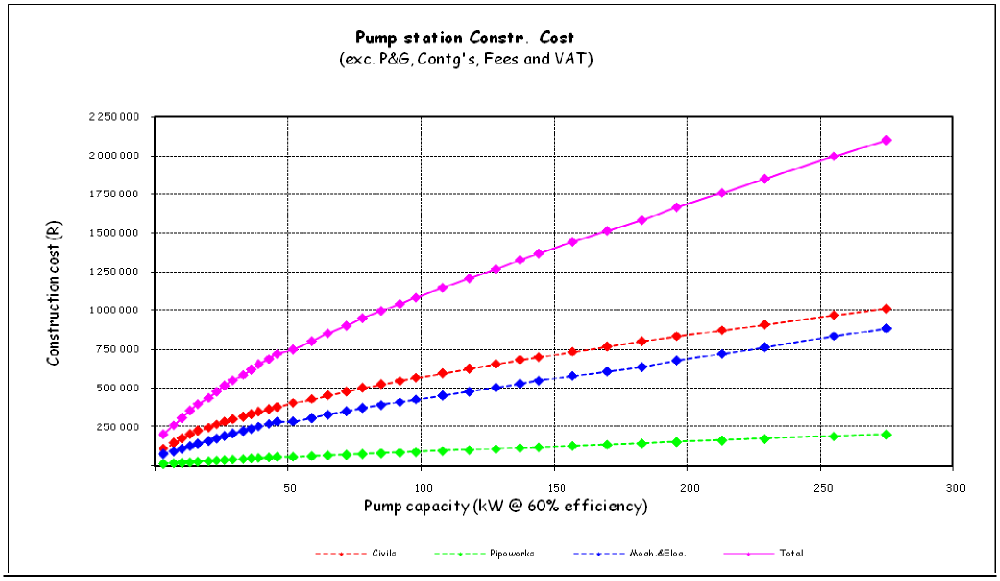

Figure 4-3 Pump Station Construction Cost (Bester et al., 2010)

The total cost for a pump station under the parameters stipulated can be described by the formula:

Civil works:

(4-8)

Pipe works:

(4-9)

Mechanical and Electrical:

(4-10)

Total pumpstation cost:

$$\text{Cost} = 91169 * \text{PC}^{0.5444} \tag{4-11}$$

where $Cost$ has the same meaning as before, and PC represents the total volume of water that can be pumped (l/s).

4.4 South African Tendering Process

A tender is an offer to perform a certain obligation, together with actual performance or evidence of present ability to perform the aforementioned obligation. Construction refers to the process that comprises the building of infrastructure, e.g. the construction of a WSS. This requires the interactions of various bodies with different types and levels of expertise.

The system of tendering, contracting and executing of contracts is the driving force behind a free enterprise system. The motive for these systems is profit generation. Although this process forms a crucial part of the cost evaluation and procurement process, it falls outside the scope of this report, refer to Appendix B for a clear elucidation of the South African tendering process.

4.5 The Construction Cost and Price Index Number

4.5.1 Overview

The construction cost index (CCI) is a business cycle indicator showing the trend in the costs incurred by the contractor in the construction process (Eurostat, 2010). The CCI can be regarded as a combination of component costs indices (material, fuel, plant and labour costs) which show the developments in the price of the main factors of production used in the construction process.

Figure 4-4 shows the cash flow diagram attributed to the construction industry. The CCI (see A in the diagram) shows the trend in the costs incurred by the contractor in carrying out the construction process; this is also referred to as a “factor price index” or a “construction input price index”. The output price index (see B in the diagram) shows the development of prices paid by the client to the contractor; which is also referred to as a “producer price index” (PPI). The CCI measures the relationship between the costs, at constant technology and constant input mix, which are associated with the implementation of a fixed amount of construction work.

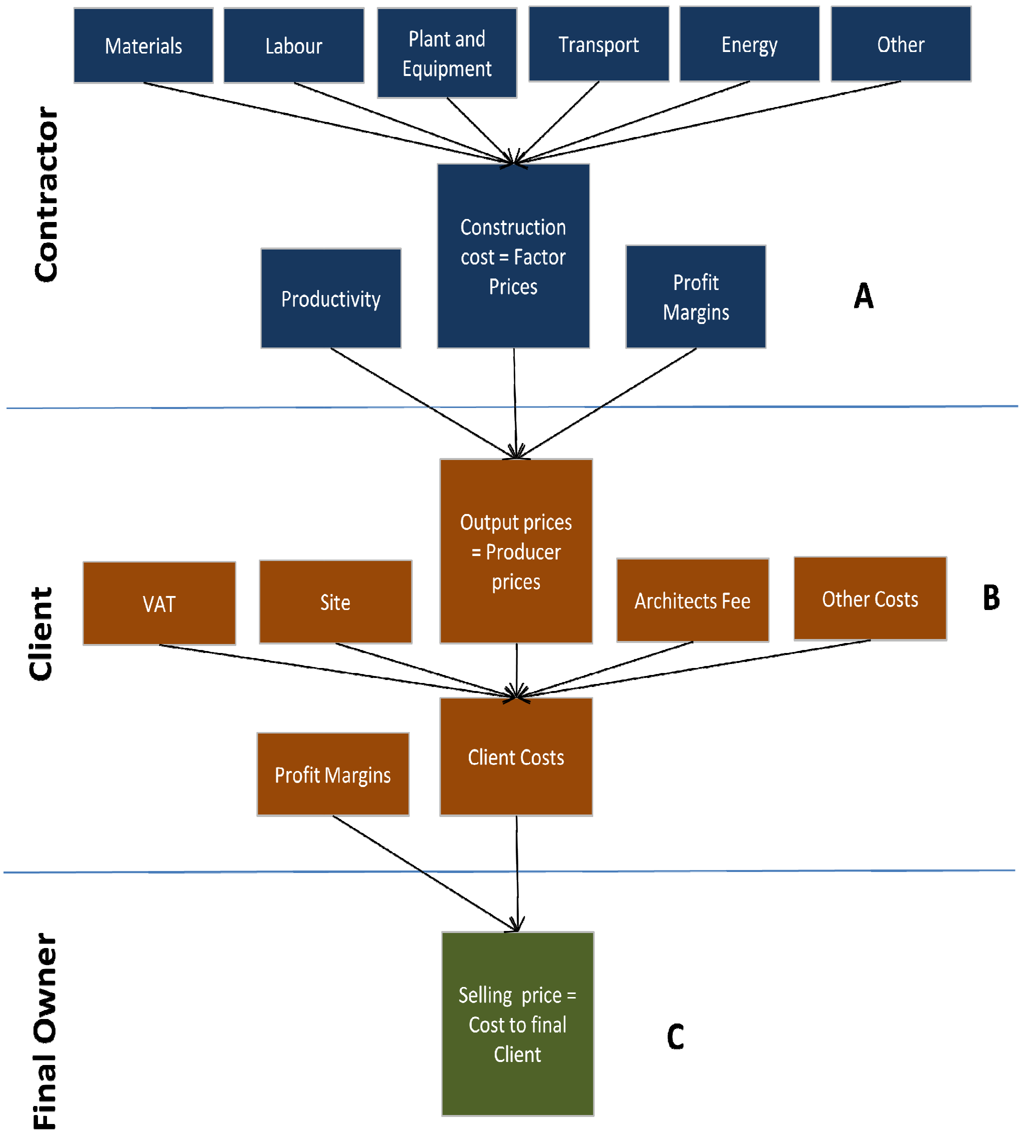

Figure 4-4 Construction cash flow diagram

These two indices can be distinguished from the “selling price index” (item C in the diagram above) which measures changes in the price paid by the final owner of the output to the client. It includes the price of the land, architect’s fees and client’s margins.

4.5.2 Aggregation of Construction Costing Indices

The CCI is made up of aggregated price indices for materials, labour costs and other types of cost. For any given reference period, the construction cost index is calculated as the weighted sum of the material, labour, fuel, and plant costs indices for the construction sector (Figure 4-5).

The component costs index (material costs and labour costs) shows the price developments of production factors used in the construction industry. Plant and equipment, transport, energy and other costs are also components of the construction costs.

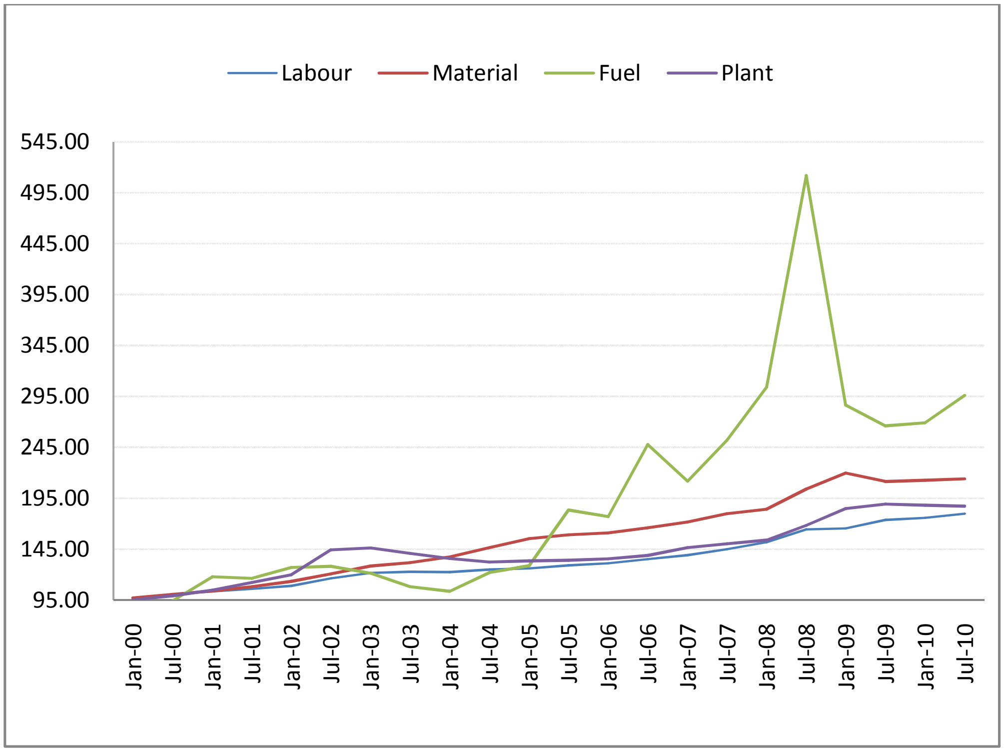

Figure 4-5 Construction cost index derived from SAFCEC (2010)

The material costs index is calculated using materials prices. Prices of materials should be based on actual prices rather than list prices. They are also based on a sample of products and suppliers.

The labour cost index for the construction sector should cover wages and salaries and social security charges for all persons employed in the construction sector. Social security charges include:

- Statutory social contributions payable by the employer.
- Collectively agreed, contractual and voluntary social contributions payable by the employer.
- Imputed social contributions (social benefits paid directly by the employer).

4.5.3 Computation of a CCI

A price or cost index number is the ratio of the sum of the prices or the cost of a product or services in a given period divided by the sum of the prices or costs for similar products or services for a base period. A price index differs from a cost index in that a price index is influenced by the prices of factors, whereas a cost index is influenced by the prices and quantities of factors entering the “standard product” at two different periods. The calculation of the construction price index is as follows:

$$CPI = \frac{P_{1_a} + P_{2_a} + P_{3_a} + \cdots P_{n_a}}{P_{1_b} + P_{2_b} + P_{3_b} + \cdots P_{n_b}} * 100 = \frac{\sum P_a}{\sum P_b} * 100 \qquad (4\text{-}12)$$

where CPI is the Construction Price Index

$P_{1_a}, P_{2_a}, P_{3_a}, \dots, P_{n_a}$ are the prices of the factors making up the "standard product" of construction, "a" is any given construction period, and "b" is the base period of construction. The construction cost index is calculated as follows:

$$CCI = \frac{P_{1_a}Q_{1_a} + P_{2_a}Q_{2_a} + P_{3_a}Q_{3_a} + \cdots P_{n_a}Q_{n_a}}{P_{1_b}Q_{1_b} + P_{2_b}Q_{2_b} + P_{3_b}Q_{3_b} + \cdots P_{n_b}Q_{n_b}} * 100 = \frac{\sum P_a\, Q_a}{\sum P_b\, Q_b} * 100 \qquad (4\text{-}13)$$

where CCI is the Construction Cost Index

$P_{1_a}, P_{2_a}, P_{3_a}, \dots, P_{n_a}$ are the same as for equation 4-12

$Q_{1_a}, Q_{2_a}, Q_{3_a}, \dots, Q_{n_a}$ are the quantities of the factors making up a "standard product" of construction.

For the purpose of this report only the use of a fixed base, weighted cost index, which is believed to be a substantially accurate indication of the purchasing power of the funds invested in sewer construction are considered (US Department of Interior, 1968; Eurostat, 2010).

4.5.4 Background

Sewers are defined as a series of pipes and conduits including necessary appurtenances that collect and carry sewage from its point of origin (residences, business buildings and industrial institutions) to the point of final discharge, excluding building sewers and treatment facilities.

The construction cost index herein developed is designed to measure the rise and fall of costs for the specific commodity "sewer construction". The table below displays the sources available for the development of a CCI.

Table 4.2 Sources for the development of a CCI

Expense	Sources
Materials	Price lists, Producer Price Index, Statistical offices of trade chambers, Wholesale prices
Labour	Collective agreements, Labour cost survey
Equipment	Producer Price Index for machinery
Energy	Producer Price Index, Wholesale price index

In summary: the construction cost index is the ratio of construction cost, at a specific time, to a base period construction cost.

4.5.5 Assumptions and Base Data for Index

The primary assumptions made for a price cost index are normally as follows:

- The hourly output of labour remains the same, in spite of changing wage rates.
- Quantities and kinds of material used in construction remain constant and available during the period under study.
- Modern construction techniques are employed over the entire period.

In view of these assumptions an index may be used for:

- Estimating construction costs at various times
- Comparing present costs with costs of similar projects of previous years
- Verifying other cost data
- Forecasting future cost trends.

The Base year for the CCI developed in this thesis is the year 2000. That means that 2000's index number is 100 for all the types of cost indices.

4.5.6 Weighting

This index is not designed to reflect right of way or land, engineering, legal, or fiscal costs; nor does it allow for errors, omissions and changes occurring after a contract award. It does include:

- Material cost
- Contractors plant cost (contractors equipment and supplies used in construction but not incorporated in the finished project)
- Labour cost
- Overhead and project cost associated with the project.

4.6 Chapter Summary

A model was developed to predict the unit value of the various sewer elements including the gravity pipes, rising mains and pump stations. This model can be used by municipal officials to obtain a first order estimate of the number of resources that need to be asserted in the construction of a WSS. The values are given in Rand value and, as a consequence, have given rise to the need for a method to keep the model up-to-date and applicable.

The construction cost index is a business cycle indicator showing the trend in the costs incurred by the contractor in the construction process. The CCI can be regarded as a combination of component costs indices (material, fuel, plant and labour costs) which show the developments in the price of the main factors of production used in the construction process. These index increases can be used to bring the aforementioned models up-to-date.

CHAPTER 5

OPERATION, MAINTENANCE AND REHABILITAION

5.1 Introduction

This thesis considers all the objectives that are to be minimised in the cost effective procurement of a waterborne sewage infrastructure. In the previous chapter the installation costs of a system were considered; in most cases municipal officials consider only the installation cost (initial investment) of the system, as this can easily be assessed in budgetary situations. There is a presumption that most operation, maintenance and rehabilitation strategies for a given project are all very similar in cost and that therefore, if the financial implication is the concern, the initial investment for the system is the main concern. The design engineers have a responsibility to give guidance on certain alternatives that might reduce the operation, maintenance and rehabilitation cost, and thereby produces an overall cost effective solution. It should also be made clear that in order for the system to have a long and useful life more financial resources will have to be asserted to keep the system running at its designed capacity.

Where operation cost is concerned, the cost of electricity for operation of pumping stations will be considered. Appendix D gives an example of the weight that the operation cost carries on the overall economic expenditure on the useful life of the system.

Maintenance and Rehabilitation forms a crucial part of the success of the overall useful life of a WSS. The expenditures here are considered an investment on the system; a model presented in this chapter may be considered an indication of the costs that will be involved in keeping the system operational at an adequate capacity.

5.2 Pumpstation Operation

5.2.1 Pumping Cost

Pumping power is calculated for each hour with the brake horsepower equation:

$$P = \frac{\gamma Q h}{\eta} \tag{5-1}$$

where P = brake horsepower in kW
γ = unit weight of water (9.802 kN/m^3)
Q = pump discharge in m^3/s
h = pumping head in m
η = pumping efficiency of 65%

The kilowatt value is then multiplied by the applicable Eskom tariff to determine the hourly cost of the operation of the pumpstation. The values are then added together to find the daily cost, and further to find the monthly cost. For industrial use Eskom has different seasonal rates. Appendix C shows Eskom's industrial rates.

An example of the comparison of the operational cost over a thirty year period compared to the installation cost of the Sanitown model is demonstrated in Appendix D. Here it is shown that it can sometimes be irresponsible for municipal decision makers to consider only initial investment as a benchmark for comparison criteria in the decision of a WSS.

5.3 System Maintenance and Rehabilitation

5.3.1 Maintenance and Rehabilitation Framework

To understand the financial implications that general maintenance and rehabilitation pose, it is important first to understand the proposed framework (Table 5.1) for a sewer maintenance and rehabilitation programme on which financial models are based. This framework is based on the premise that a sewer maintenance and rehabilitation program must address each of three functional objectives:

Table 5.1 Maintenance and rehabilitation framework

Capacity restoration	This function is aimed at reducing infiltration and inflow to restore and maintain available system capacity and to control wet-weather sanitary sewer overflow (SSO).
Damage repair	This function is aimed at repairing structural damage and failures in the system that are the result of wear, corrosion, age, and/or construction-related damage.
Maintenance reduction	This function is aimed at repairing portions of the system that are subject to known, repeated maintenance problems resulting from conditions such as root intrusion, offset joints, pipe sags, improper service connections, and other system deficiencies.

To be effective in meeting each of these functional objectives, a sewer rehabilitation programme must evaluate the system condition and identify where rehabilitation is needed with respect to each objective. The relative emphasis on each of these areas will vary, depending on system conditions and short-term objectives. However, a successful long-term programme must address each objective to maintain good system performance in a cost-effective manner.

A financial evaluation should be conducted to determine the sections of the system for which the financial return on an investment in rehabilitation is greater than the cost of the investment.

5.3.2 Maintenance and Rehabilitation Cost

According to the National Infrastructure Maintenance Strategy's (NIMS, 2007) "Infrastructure Maintenance Budgeting Guideline", "maintenance" is used as a generic term embracing planning, budgeting and implementation of repair, planned maintenance, rehabilitation and replacement of infrastructure to achieve an optimal level of service provided by the infrastructure.

The cost of maintenance of an infrastructure asset is determined not just by the size, nature and capacity of that infrastructure, but by its fitness for purpose, how well it was designed, materials specified and used, the quality of construction and, very importantly, how well it has been operated and maintained in the past (CIDB, 2007).

Decisions are, nevertheless, frequently taken in order to "save cost" at planning, design or construction stage, despite it often being possible to show that these will increase costs of operation throughout the life of that asset, to the extent that they far exceed the initial "saving". It might, for example, be that the choice of less durable construction materials is the direct cause later, of having prematurely to refurbish or even replace the infrastructure. Similarly, injudicious design, or poor construction workmanship, if not detected and timeously corrected, will lead to operational problems with resultant significant costs. Furthermore, design and construction that does not take into account practical operation and, particularly, maintenance issues may result in costly errors (CIDB & CSIR, 2007).

The CSIR and CIDB (2007) recommend to municipal officials an annual maintenance budget of 4-8% average of the total replacement cost for the maintenance of sewer infrastructure (given a 20-30 year life span). In applying this information it should be noted that the maintenance cycle for each asset is not static each year. Typically the maintenance cycle requires the following components:

- Normal annual maintenance
- Emergency maintenance (for example a burst water pipe as a result of a severe storm)
- Periodic refurbishment (for example relining of pipes).

The budget estimate caters for the above three elements. However, the following components which are not catered for in the annual 4-8% budget will also need to be taken into account with respect to the total life cycle costing:

- Major rehabilitation, in order to extend the life of an asset, which is not the same as periodic maintenance
- Replacement of the asset at the end of its useful life
- Disposal of the asset, which may require demolition and environmental rehabilitation.

5.4 Chapter Summary

Operation cost forms a significant part in the economic life-cycle of a WSS, but with efficient design and foresight these costs can be minimised, be it at a larger initial investment. Design engineers have the responsibility to inform their clients of the optimal long-term solution.

Maintenance and rehabilitation are considered an investment in the system and, without adequate maintenance and rehabilitation programmes, the system will not perform at its optimum.

This chapter has given insights into the costs involved in keeping the system operational and the weight they assert on the overall economic life-cycle expenditure of this infrastructure.

CHAPTER 6

ENVIRONMENTAL IMPACT AND CARBON COST

6.1 Introduction

Increasingly, municipal decision makers are considering the environmental impact in the design and construction of waterborne sewage infrastructure. Climate change is leading to awareness in the general public and, as a result, the environmental impacts of expanding and operating a WSS are being considered alongside hydraulic design and cost implications.

Engineering researchers and practitioners are starting to recognise the need to design networks to make them more compatible with their natural and social environments (Herstein et al., 2009). The materials used in a waste water network (pipes and pumps) must be extracted, constructed, produced and manufactured. Pumping water consumes electricity, and that has certain environmental implications. The manufacturing of pipes requires that materials be extracted, transported and processed, which generates environmental discharges and consumes non-renewable energy resources. System components must be disposed of at the end of their service life. These activities, along with others, consume material and energy resources and generate green house gas (GHG), air pollution and solid waste.

Life cycle assessment (LCA) is one method that is widely used to incorporate the environmental impact and sustainability into WSS design. A process based LCA method analyses the environmental impact of a product over the entire period of its life cycle, including extraction, manufacturing, use, and disposal (United Nations Environmental Programme, 2000).

This method of using the LCA in assessing the environmental impacts has been documented in literature:

- Dennison et al. (1999) have implemented LCA to compare the environmental impact of various materials used for different pipes.
- Stokes and Horvath (2006) used this method to assess environmental impacts of WDS alternatives designed to address water shortages.
- Ghimire and Barkdoll (2007) have suggested applying eco-efficiency analysis to system optimisation.
- Dandy et al. (2006) developed an optimisation programme that incorporates sustainability objectives, whole-life-cycle costs, energy use, green house gas emissions, and resource consumption.
- Filion et al. (2004) used EIO-LCA to quantify energy expenditures in the fabrication stages.
- Lundie et al. (2004; 2005) have used the LCA to compare the overall environmental impact of different system alternatives over a planning period, for the purpose of decision making.

6.2 Environmental Assessment of Waterborne sewage Networks

6.2.1 Life-cycle Assessment

When it comes to the evaluation of a WSS, the three life stages should be considered i.e. the fabrication, use and disposal. Filion (2004) noted that the environmental impact of the fabrication of pipes can be equal to that of the energy required for operating the pumps. Therefore, it is important to remember that the material resources extracted and energy required for manufacturing the components such as pipes and pumps also contribute to the environmental impact of the system. The environmental impact in the disposal stage is not always as easily quantifiable as in the two pre-stages, but if data is available it should also be considered.

6.2.2 Comparison of Alternatives

For ease of use and comparison purposes it was decided to use environmental impact as a function of the unit length of pipe. This allows for easy comparison and model setup, as the cost of the pipeline is already a function of the unit length of pipe. This measurable unit has the advantage of assuring that the choice of diameter for the pipe section is directly related to the choice concerning the two opposing objectives, namely minimising of initial investment and environmental impact. From these the environmental evaluation of the different alternatives can be assessed.

6.2.3 Aggregation of Environmental Measures

According to Herstein (2009), there are a number of environmental measures that can be used to assess the impact of a given system design on the environment, such as toxic releases, global warming potential, and non-renewable resource use. Considering a number of different measures makes decision making more complex, since one alternative, while ranking high with respect to one measure, might be outranked by other alternatives with respect to other measures. Therefore, an environmental impact index that combines the total number of measures into a single index is the optimal platform that will allow for a best-fit solution to be achieved. However, the aggregation of environmental impacts into a single parameter does not guarantee that all environmental impacts will be minimised. For instance, an index that values high sustainability will not necessarily be associated with low global warming potential.

6.3 Environmental Impact Index

6.3.1 Introduction and Characteristics

The purpose of an environmental impact index is to quantify the environmental depletion (e.g., use of non-renewable energy resources and unsustainable use of renewable resources) and environmental discharges (e.g., discharges to water bodies, air pollutants) together with the impact those discharges have on basic human health and the surrounding ecological system. Unfortunately this information is not easily accurately determined.

Measures such as the ecological footprint analysis (Monfreda et al., 2004), wherein products and practises are assessed in terms of the bio-productive area that would be required in order to absorb the resulting fossil fuel emissions, or to regenerate utilised renewable resources already exist. Although this method is easily applied to WSS, it considers only one component of environmental pollution; it does not consider measures such as the toxic releases to land, air and water bodies.

The environmental impact index model used in this thesis aggregates measures of resources consumption (non-renewable energy use), environmental discharge (air pollutants, toxic releases to air, land and water), and environmental impacts (ecological fossil fuel footprint) that was developed by the Carnegie Mellon University Green Design Institute (Economic Input-output Life Cycle Assessment (EIO-LCA) Model, 2008). Table 6.1 displays all environmental measures and impact categories that are based on, and evaluated by means of, the EIO-LCA model (Hendrickson et al., 1998). In the table these environmental measures are grouped into four major environmental categories, i.e. air pollution, non-renewable energy depletion, fossil-fuel footprint and toxic releases. The table also indicates the units to be used for each measure.

Table 6.1 Environmental categories and measures

Environmental Category	Examples of Environmental Measures	Type	Unit/m
Air pollution	Sulphur dioxide	discharge	kg
	Carbon monoxide	discharge	kg
	Nitrogen oxides	discharge	kg
	Volatile organic compounds	discharge	kg
	Lead	discharge	kg
	Particulate matter	discharge	kg
Non-renewable energy depletion	Coal	consumption	MJ
	Natural gas	consumption	MJ
	Liquefied natural gas	consumption	MJ
	Liquefied petroleum gas	consumption	MJ
	Motor gasoline	consumption	MJ
	Distillate	consumption	MJ
	Kerosene	consumption	MJ
	Jet fuel	consumption	MJ
	Residual	consumption	MJ
Fossil-fuel footprint	Ecological footprint (volumetric)	impact	metres squared of bio-productive land
Toxic releases	Total air releases	discharge	g
	Water releases	discharge	g
	Land releases	discharge	g
	Underground releases	discharge	g
	Total transfers	discharge	g

*All measures listed other than Ecological Footprint can be obtained directly from the Carnegie Mellon Green Design Institute's online EIO-LCA tool (Carnegie, 2008).

It is noted that in Table 6.1 there is only one environmental impact measure, namely ecological footprint. This measure is based on either carbon dioxide (CO_2) equivalents of green house gas omitted or global warming potential. The fossil-fuel footprint is measured in terms of the area (m²) of bio-productive forest needed to sequestrate the total amount of CO_2 produced in the production of pipes and the electricity used to operate the pumps. The ecological footprint is calculated by using the equation developed by Monfreda et al. (2004), with global warming potential taken from the Carnegie Mellon Green Design Institute's online EIO-LCA tool (accessed September 2010).

$$EF = \frac{GWP \times (1 - fraction\ absorbed\ by\ ocean) \times (10\ 000 m^2)}{(period) \times (sequestration\ rate)} \qquad (6\text{-}1)$$

where EF = ecological footprint
GWP = global warming potential (tons CO_2)
Fraction absorbed by ocean = 0.308 (EPA, 2005)
Period = time used for analysis of GWP (yrs)
Sequestration rate = 3.47(tons CO_2/10 000m^2/yr) (EPA, 2005)

6.3.2 Index Development

Loucks and Gladwell (1999) have presented a method to integrate measures of vulnerability, resilience, and reliability into a single index to evaluate the overall sustainability of a water resource system. A similar method has been used by Saling et al. (2002) in the eco-efficiency method to normalise values of energy consumption for the purpose of comparing alternatives.

The environmental impact index presented is summarised by the findings of Herstein (2009) that combined the evaluation methods of Loucks and Gladwell (1999) and Saling et al. (2002), and evaluation is performed in the three steps outlined below.

6.3.2.1 Evaluate Measure Indices

The EIO-LCA model is used to quantify the discharge, consumption and impact levels of the environmental measures indicated in Table 6.1. The maximum value of each environmental measure, computed across all the design alternatives, is noted. The discharge, consumption and impact levels of all the environmental measures in Table 6.1 are computed for each design alternative, and are then divided by their maximum values to create an index that communicates the level of the environmental measure relative to its maximum level, i.e.:

$$Measure\ Index = \frac{value\ of\ measure\ for\ WSS\ alternative}{maximum\ value\ of\ measure\ for\ all\ WSS\ alternatives} \quad (6\text{-}2)$$

6.3.2.2 Average Measure Indices by Category

Once index values have been computed for all the environmental measures, they are averaged within each environmental category in order to compute the average index value for each environmental category:

$$Category\ Index = \frac{\sum_{i=1}^{n} Measure\ Index_i}{n} \quad (6\text{-}3)$$

where $Category\ Index$ = Environmental Category Index

n = number of environmental measures in an environmental category

$Measure\ Index_n$ = Measure index of the ith measure in an environmental category

Measure indices within single categories are averaged together, to ensure that categories with multiple measures (i.e. air pollution, non-renewable energy depletion, and toxic releases) are given equal weighting to the category with only a single measure (i.e. fossil-fuel footprint). In the next step additional weights are to be applied to the environmental category indices to reflect their relative priority to the stakeholders.

6.3.2.3 Evaluate Overall Environmental Impact Index

An overall environmental impact index can be calculated by weighting the environmental category index values as follows:

$$EI = \frac{\sum_{j=1}^{m}\left(W_j\right) \times \left(Category\ Index_j\right)}{m} \qquad (6\text{-}4)$$

where *EI* = environmental impact index for a WSS alternative

m = number of environmental category indices

W_j = stakeholder weight for category *j*

Category Index = value for category *j*

The environmental impact index is found by averaging the four environmental category indices, using a weight of 1 for each category. The use of unequal category weights signifies that the stakeholders attribute more importance to certain environmental categories than to others. This allows stakeholders to relay their policy priorities through the weighting of category indices.

Weighting is not applied to individual environmental measures because of the difficulty in prioritising a large number of environmental measures. In addition, the unequal number of environmental measures in each environmental category further complicates the assignment of weight to individual measures (Esty et al., 2005).

6.4 Chapter Summary

The environmental impact index evaluates the environmental consequences of the expansion and operation of a WSS in relation to resource consumption, environmental discharges, and environmental impacts associated with pipe fabrication and electricity cost for pumping of sewage. The index can be used to rank the environmental impact of a network alternative relative to other network alternatives in waterborne sewage system design. The environmental impact index can then be incorporated into a multi-objective optimisation to balance effective cost and minimisation of environmental impact.

CHAPTER 7

SANITOWN CASE STUDY

7.1 Introduction

As was discussed in the knowledge review, the Sanitown model is a generic hypothetical sewer system model for separate sewer systems. This model was based on the same principles used in the development of the hypothetical water system model known as Anytown. The Sanitown model is used as a benchmark for sewer optimisation.

The information, parameters and layout as described by De Klerk et al. (2010) are set up to test the models developed in this thesis. The multi-objective NSGA-II by Deb et al. (2002) was implemented to solve the Sanitown expansion problem. The objectives were to minimise capital cost for new pipes, the annual cost of operation, maintenance and rehabilitation of existing pipes and pumpstations, and to minimise the environmental impacts by evaluating the EI index. The case study considered the environmental impacts linked to the manufacture of new pipes and electricity production, the annual amount of electricity used for pumping, the annual maintenance cost, the rehabilitation cost for the upgrade of existing pipelines, and also the cost of the new pipes and pumpstations.

7.2 Growth in Sanitown

Although Sanitown is a hypothetical model, some growth has been occurring. De Klerk et al. (2010) have stipulated that nodal points E1 through E14 denote the existing scenario and F1 through F5 denote inputs that will accommodate future development. Also stipulated is that waste water treatment plant 1 (WWTP1) can only receive 1200 k*l*/day and this means that once F1 to F5 is operational, a pumpstation will be added onto drainage basin 2 (DB2) (see Figure 7-1 for positioning). The need to upgrade some of the existing gravity pipes will be investigated, together with the installation of new gravity pipes, and installation of new rising mains.

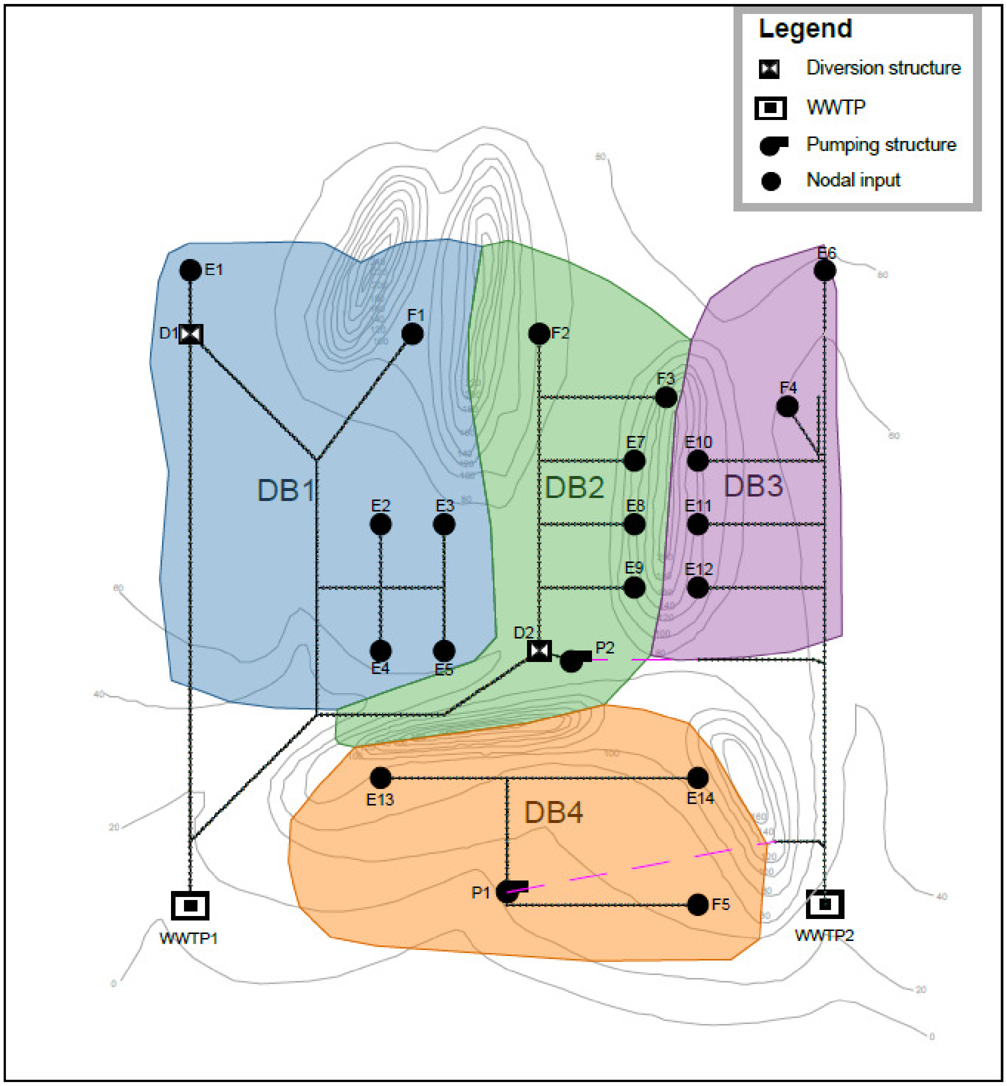

Figure 7-1 Sanitown future scenario (De Klerk & Jacobs, 2010)

The optimisation of these additions forms the basis for testing the application and robustness of the models developed in Chapters 4, 5 and 6.

7.3 Model Population

7.3.1 Solution Chromosome Layout

The optimisation add-in for Microsoft Excel, GANetXL, developed by the implementation code of Bicik et al. (2007) was used to solve NSGA-II in this case study. The Sanitown solutions were coded in 14–gene chromosomes presented in Figure 7-2. The decision variables, options and amount of options are indicated in Table 7.1.

Figure 7-2 Chromosome coding of Sanitown

Table 7.1 Chromosome decision variables

Decision Variable	No. of options	Options
New Gravitational Pipe section	6	6 available pipe diameters
New Rising Main Pipe section	5	5 available pipe diameters
Rehabilitate pipe section	7	None, 6 available pipe diameters

7.3.2 Pipe Costs and Consequent Environmental Impact

Pipe costs were determined by using the equations presented in Chapter 4. To get an accurate estimate for the cost per meter for the construction of the pipe segments it was again assumed that the 5% of the pipeline will be constructed under road conditions, 25% under reserve areas and the remainder in POS. The price includes the excavation, the preparation of the trench bottom, backfilling and reinstatement of top surfaces to their prior condition. The unit cost for commercially available pipe diameters is indicated in Table 7.2.

The environmental measures of pipe fabrication are assessed with the EIO-LCA model produced by the Carnegie Mellon University's Green Design Institute (2008). The pipe cost is input into the model under the industry sector "Plastic Pipe and Pipe Fitting Manufacturing". For reasons of simplicity this thesis considers only those environmental impacts linked to the fabrication of pipes and, in the next section, the lifetime operation of the pumps in the system. Environmental impacts linked to the disposal stages are not incorporated, due to lack of data.

The model of Carnegie Mellon University's Green Design Institute allows for the cost of the system only in 2002 US Dollars. To adjust 2009 Rand values to 2002 Rand values, equation 7-1 implemented, with the known 2009 Rand value. (The model developed in Chapter 4 use 2009 Rand values as baseline indicators). The values obtained were then divided by 6.10948, as this was the average Dollar/Rand exchange rate for 2002 (ABSA Stock Brokers Pty, 2010) to determine the 2002 Dollar value.

$$(2002 Dollars) = \frac{\left((2009 Rands) \times \frac{(2002\ Index\ value)}{(2009\ Index\ value)}\right)}{6.10948} \tag{7-1}$$

It was decided to derive the environmental impact of \$20 million worth of pipe production for each of the alternatives, to keep accuracy high and to simplify the conversion process. The environmental measures were then each divided by $20 million to obtain a unit fraction (environmental measure per 2002 Dollar) for the production of pipes. Each pipe diameter cost was then multiplied by this resulting fraction to determine the actual corresponding environmental measure value for that pipe diameter. This provided each diameter pipe with an environmental measure per meter length.

In Table 7.2 the rising mains environmental impact index is related only to the fabrication of the pipes. Unlike the gravity pipelines, the rising mains also have an impact on the operation cost, in that the diameter of the pipe is related to the energy required for pumping, hence the operation's embodied environmental impact. This relationship is considered later in the chapter.

Table 7.2 Capital cost and fabrication: environmental impact index

Nom. Diameter	Inside Diameter	Unit Cost (R/m)	EI
Gravity Pipes			
110	104	R 444.80	0.337
160	151	R 548.15	0.416
200	188	R 647.05	0.491
250	235	R 786.30	0.597
315	297	R 1 060.60	0.805
355	334	R 1 221.85	0.927
Rising Mains			
90	80	R 266.85	0.202
110	100	R 295.30	0.224
125	113	R 336.70	0.255
140	127	R 376.40	0.286
160	145	R 428.15	0.325

7.3.3 Operation Costs and Consequent Environmental Impact

The brake horsepower over a 24 hour period (of which 18 hours is considered pumping time and the remainder standby time) was integrated to calculate the daily pumping rate and multiplied by 365.25 days/year to determine the annual energy use. Since future electricity pricing is fairly unsure at the time of writing of this thesis, it was decided to consider the annual pumping energy use, as opposed to the energy use during the lifetime of the system. Table 7.3 gives annual pumping energy use (kW.hr/year) and the embodied environmental impact index.

Table 7.3 Annual pumping energy and environmental impact index

Nom. Diameter	Inside Diameter	Headloss [m]	Δz *[m]*	P *[kW]*	Annual pumping energy use *[kWh/yr]*	EI Operation Cost
90	80	85.730	5.00	12.9131	84897.38	0.927
110	100	28.270	5.00	4.7351	31131.06	0.340
125	113	15.406	5.00	2.9042	19093.89	0.209
140	127	8.628	5.00	1.9396	12751.96	0.139
160	145	4.471	5.00	1.3480	8862.50	0.097

The pipe cost is input into the model of the Carnegie Mellon University's Green Design Institute under the industry sector "Electric Power Generation Transmission and Distribution" to compute the discharge, consumption and impact levels of each environmental measure for each alternative. The same procedure as described in the previous section was implemented to adjust and obtain the corresponding 2002 Dollar values to be implemented in the model.

Here the environmental impact index considered only the impact of the electricity supply.

7.3.4 Combining EI of Pipe Manufacturing and Energy Use

Due to the direct impact the choice of the pipe diameter of a rising main has on the operation cost of the pumpstation, it also has a direct impact on the environmental impact, due to electricity production. This, and the environmental impact associated with the pipe manufacturing process, needs to be combined to the correct weight that each impact carries.

For the purpose of this thesis it was decided to take a 30 year life-cycle as a function of the present value of resources needed for construction of the system and operation of the pumpstation. These processes were described in Chapter 5 (see also Appendix D). Tables 7.4 and 7.5 show these costs, with their corresponding greenhouse gas and toxic releases and energy depletion:

Table 7.4 Initial investment and embodied environmental impact

Nom. Diameter	Inside Diameter	Pipe cost (length = 1540m, 2009 Rands)	Pipe cost (length = 1540m, 2002 Dollars)	Green-house Gases (ton CO_2)	Energy (TJ)	Toxic Releases (kg)
90	80	R 412 745.18	$44 467.09	62.92	1.05	12.52
110	100	R 549 018.70	$59 148.51	83.70	1.40	16.65
125	113	R 653 766.58	$70 433.52	99.66	1.67	19.83
140	127	R 760 693.93	$81 953.33	115.96	1.94	23.07
160	145	R 906 654.06	$97 678.34	138.21	2.31	27.50

Table 7.5 Thirty year operation cost and embodied environmental impact

Nom. Diameter	Inside Diameter	30 Yr running cost (PV, 2009 Rands)	30 Yr running cost (PV, 2002 Dollars	Green-house Gases (ton CO_2)	Energy (TJ)	Toxic Releases (kg)
90	80	R 1 155 551.46	$124 493.29	1164.01	13.88	23.72
110	100	R 423 731.92	$45 650.74	426.83	5.09	8.70
125	113	R 259 894.01	$27 999.67	261.80	3.12	5.33
140	127	R 173 568.34	$18 699.38	174.84	2.08	3.56
160	145	R 120 624.14	$12 995.44	121.51	1.45	2.48

Combining the values of each environmental measure (Table 7.6) then yields the overall environmental index for each alternative. These index values are then input in the model for the different rising main pipe diameters and the gravity pipes.

Table 7.6 Environmental index for gravity and rising main alternatives

Nom. Diameter	Inside Diameter	Green-house Gases (ton CO_2)	Energy (TJ)	Toxic Releases (kg)	EI Green-house Gases	EI Energy	EI Toxic Releases	**EI**
Gravity pipes								
110	104	238.55	4.00	47.46	0.19	0.27	0.36	**0.26**
160	151	293.97	4.92	58.48	0.24	0.33	0.45	**0.31**
200	188	347.01	5.81	69.03	0.28	0.39	0.53	**0.37**
250	235	421.69	7.06	83.89	0.34	0.47	0.64	**0.45**
315	297	568.80	9.53	113.16	0.46	0.64	0.87	**0.61**
355	334	655.28	10.98	130.36	0.53	0.73	1.00	**0.70**
Rising mains								
90	80	1226.93	14.93	36.23	1.00	1.00	0.28	**0.70**
110	100	510.53	6.49	25.35	0.42	0.43	0.19	**0.32**
125	113	361.46	4.79	25.16	0.29	0.32	0.19	**0.25**
140	127	290.80	4.03	26.63	0.24	0.27	0.20	**0.22**
160	145	259.72	3.76	29.97	0.21	0.25	0.23	**0.21**

To ensure that the environmental impact of each pipe section bears the correct weight, for example that a 1m 110mm diameter rising main does not impose the same EI as a 1000m 90mm gravity pipe, the EI of each alternative is multiplied by the length of that particular pipe segment. The total of all the EI indices, multiplied by their length, is then divided by the sum of the length of all the pipe sections, in order to obtain an EI index for the system that represents the correct environmental impact of each pipe section.

7.3.5 Cost of New Pumpstation, and Maintenance and Rehabilitation

The cost of the new pumpstation was calculated by using equation 4-11 and was found to be:

$$\text{Cost} = 91169 * 8.58^{0.5444} = R\ 293{,}730.00$$

The cost of pumpstation P2 in the Sanitown model, with the growth indicated by De Klerk et al. (2010), is easily obtained due to the fact that the model developed considers the amount of water to be pumped, in this case 8.58*l/s,* which is the same irrespective of diameter pipes chosen.

The cost of routine maintenance and rehabilitation was considered at 4% of the installation cost (capital cost) of the system, per year (the minimum as stipulated by the CIDB, 2007), and to be added after the choice of pipes for the system has been made.

7.3.6 Performance Constraints

The performance constraint that was implemented into the model was the minimum velocity of 0.75 *m/s* to allow self cleansing (CSIR, 2000). In instances where pipes failed to meet this criterion a penalty was applied, in the form of increased cost for that specific pipe segment. This forced the model to find an alternative within the specified performance constraints.

7.4 Results and Pareto-optimal Front

The Pareto-optimal front obtained in the multi-objective optimisation of capital cost, environmental impact index, and annual pumping energy is indicated in Figures 7-3 to 7-5. Figure 7-3 indicates that capital cost (initial investment) and EI index have an inverse relationship, with the same relationship found between capital cost and annual pumping energy in Figure 7-4. These relationships are not well defined at low and high values of capital cost and annual pumping energy, where the EI index remains fairly constant.

Figure 7-5 indicates that there is also an inverse relationship between capital cost and annual pumping energy use. This is a well-known result in WDS systems with small pipe diameters (with low capital costs), which have a higher annual pumping energy use due to frictional losses, while large-diameter systems (with high capital costs) have a lower annual pumping energy use. An interesting development was that the NSGA-II found far fewer chromosomes on the Pareto-optimal front. This is due to the fact that the annual pumping energy use is influenced only by parameters of gene *x6* (rising main pipe section). The other genes in the chromosome are unrelated to pumping energy.

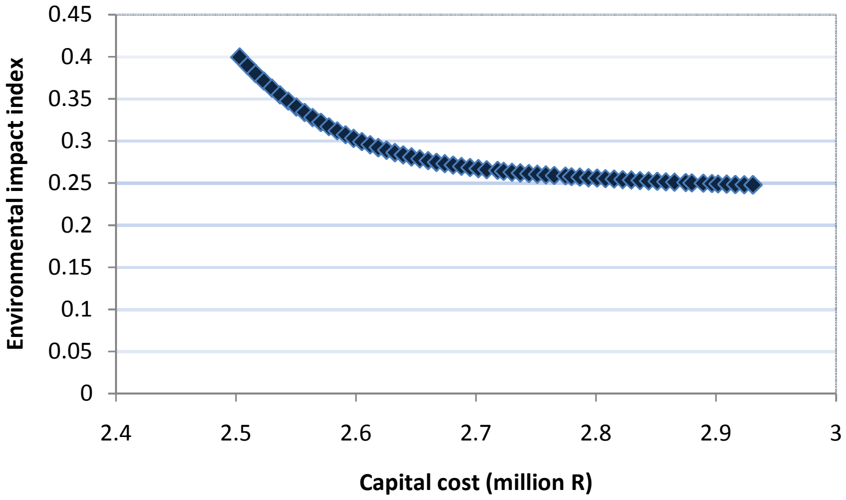

Figure 7-3 Pareto-optimal front for capital cost versus environmental impact index

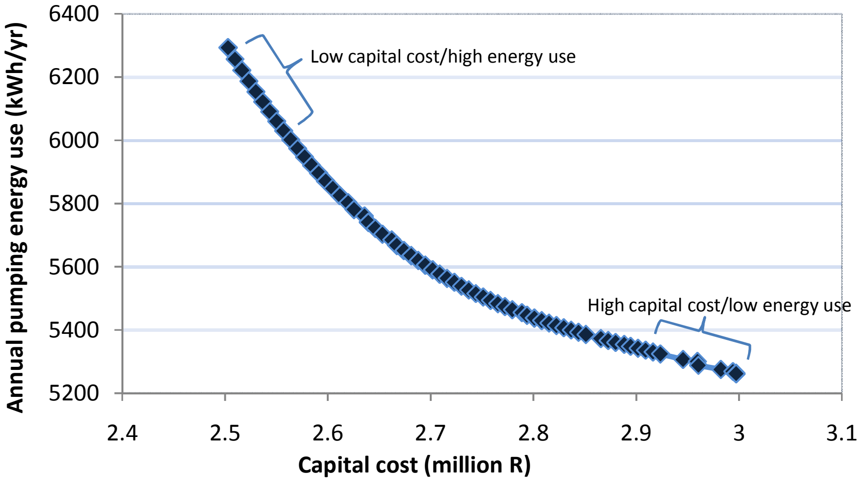

Figure 7-4 Pareto-optimal front for capital cost versus annual pumping energy use

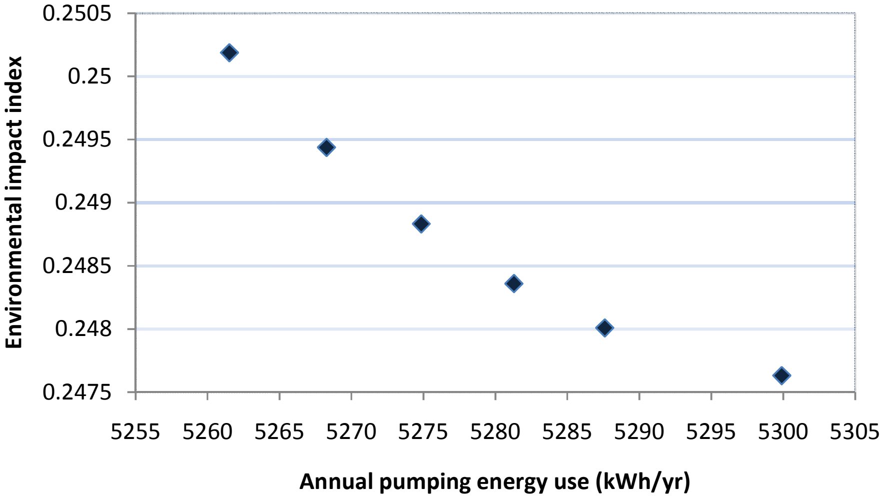

Figure 7-5 Pareto-optimal front for annual pumping energy use versus environmental impact index

The inverse relationship between capital cost and EI index was, however, not found when a 20-year design horizon was investigated. The influence that the operation of the pumpstation, and consequent EI index, exerts is too low to influence the overall EI index of the model, which is not the case in a 30-year design horizon. This is due to the completely linear relationship that exists between capital cost and EI index in gravity pipelines. The Carnegie Mellon Green Design Institute's online EIO-LCA model considers the investment cost as a method of comparing alternatives; an increase in capital cost therefore means an increase in environmental impact index. The fact that the environmental impact in rising mains scenario contains two factors (environmental impact due to pipe manufacturing and environmental impact due to electricity production for pumping) that need to be considered, is the reason for the inverse relationship between these two opposing objectives.

7.5 Hypothetical Scenarios

Two hypothetical scenarios were chosen to be further investigated and broken down to enable comparison of the consequent solutions for the Sanitown problem.

This section aims to further explain the inverse relationships between the three objectives. To detail this explanation, the environmental impacts of two solutions at the opposite ends of the Pareto fronts in Figure 7-4 were investigated:

- Low capital cost/high energy use
- High capital cost/low energy use

The capital cost, annual energy use for pumping, and environmental impact index for the two abovementioned solutions are compared in Table 7.7. The "High capital cost/low energy use" solution has a lower annual use of energy for pumping and EI index than the "Low capital cost/high energy use" solution.

Table 7.7 Objective breakdown for solutions on opposite ends of Pareto front

Objective		Low capital cost/high energy use	High capital cost/low energy use
Capital Cost	New pipes	R 2,502,989.08	R 2,996,901.73
	Pumpstation	R 293,730.00	R 293,730.00
Operation Cost	Annual use of energy for pumping (kWh/yr)	6292.27	5261.52
Environmental impact	Index	0.3542	0.2502

The proportional contribution of the pipe manufacture and the lifetime use of energy for pumping to the EI index for the two solutions is indicated in Figure 7-6 and 7-7. Note that for the "Low capital cost/high energy use" solution the lifetime energy use dominates the majority of the environmental indices when compared to pipe manufacture. Although the proportional distribution for the solution "High capital cost/low energy use" is more equal, Table 7.8 supplies the actual values for electricity generation and pipe production. Tables 7.4 and 7.5 give the value of environmental measures for a certain amount of money spent. The results in these tables suggest that electricity generation for pumping has a significantly higher environmental measure value than that of pipe manufacturing, given that a similar amount of capital is required. Thus the inverse relationship between capital cost and EI index, and capital cost and annual pumping energy, can be explained by:

1. The dominance of lifetime energy use in the EI index
2. The higher environmental measure values and impacts linked to those of electricity generation relative to pipe manufacturing.

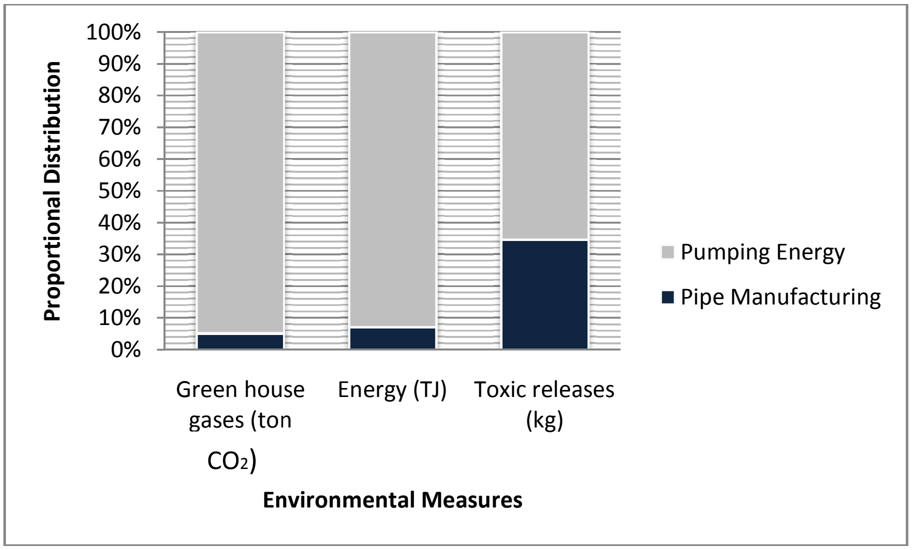

Figure 7-6 Proportional distribution of pipe manufacturing and pumping energy for solution: “Low capital cost/high energy use”

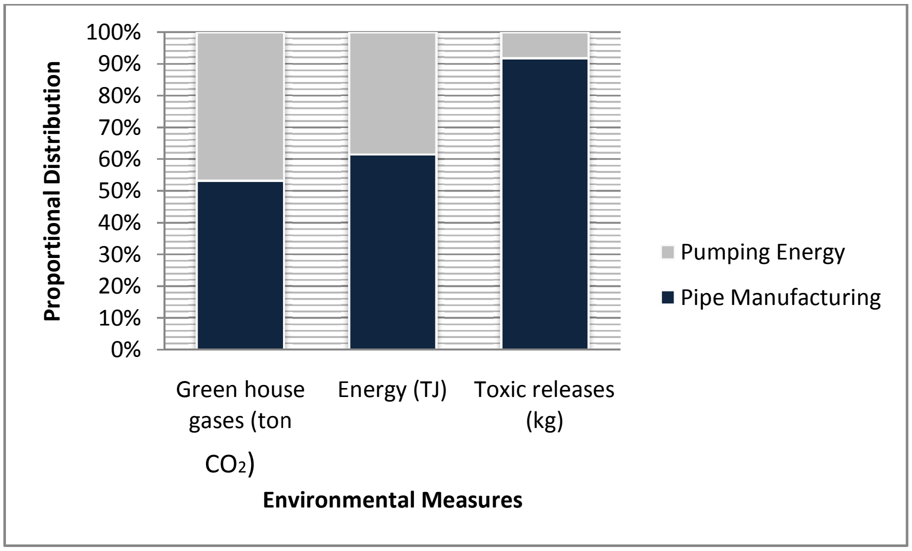

Figure 7-7 Proportional distribution of pipe manufacturing and pumping energy for solution: “High capital cost/low energy use”

Table 7.8 Summation of environmental measures for given solutions

Solution		Green house gases (ton CO_2)	Energy (TJ)	Toxic releases (kg)
Low capital cost/high energy use	Pipe manufacturing	62.92	1.05	12.52
	Pumping Energy	1164.01	13.88	23.72
High capital cost/low energy use	Pipe manufacturing	138.21	2.31	27.5
	Pumping Energy	121.51	1.45	2.48

The dominance of pumping energy and its higher environmental impacts means that increasing capital cost of pipes will decrease annual pumping energy use and the EI index, while increasing annual pumping energy use will increase the EI index.

CHAPTER 8

CONCLUSIONS

8.1 Summary

Municipalities are dealing with ageing waterborne sewage infrastructure. The complexity of WSS expansion decisions, combined with limited infrastructure funding, has encouraged engineers and municipal officials to generate expansion solutions that balance cost and performance objectives. This ensures that there will be a need for better optimisation approaches that are concerned with meeting a diverse set of objectives. In addition, municipalities are starting to recognise the importance of environmental impacts, due to national and international pressure. A WSS expansion optimisation model that considers system cost and operation performance, along with environmental impacts, has been presented in the thesis.

This thesis has made research contributions that begin to address the need to balance cost, operation cost, and environmental concerns in WSS expansion optimisation. This was achieved firstly, with the development of an entirely new sewer construction cost model. The item costs for previous projects across South Africa were collected, from both consultants and actual tender documents, and the typical costs for certain conditions were determined. Numerous factors were taken into consideration to develop a unit cost value. A model was developed to predict the unit value of the various sewer elements, including the gravity pipes, rising mains and pump stations. Although the model was used in the overall optimisation of the expansion of WSS, the cost functions presented in this thesis are used for practical application and cost estimation for sewer networks by consultants and municipal officials (for budgetary purposes). Together with the development of the model, a method to keep the model up-to-date was also outlined.

The other objectives were incorporated by adjusting industry acceptable and standardised models. The EI index is a comparative index that reflects the value of a number of environmental impact measures derived from the fabrication of pipes and the production of electricity to operate the pumping station. In this model the users also have the option to add a weight index to those environmental measures that they may feel are more representative of their priorities.

8.2 Key Findings

This thesis has presented a new approach that incorporates the multi-objectives of WSS optimisation, which have not been found in previous literature. The non-dominated sorting genetic algorithm (NSGA-II) proposed by Deb et al. (2002) was used to minimise capital costs, annual pumping energy use, and the EI index in the Sanitown problem. It was found that an inverse relationship exists between the opposing objectives. Pumping energy use was found to influence the EI index, pumping energy cost also considerably influences the overall expenditure over the whole design life of the system.

The multi-objective non-dominated sorting genetic algorithm-II-based framework was applied to the Sanitown system expansion problem to illustrate the ability of the method to choose solutions from a large solution space that best balance the capital cost, energy use, and environmental impact objectives. The results presented the optimal expansion options for Sanitown. The consideration of multiple environmental impact measures, through the use of the EI index in the multi-objective optimisation approach, can assist decision makers in choosing a preferred solution on the Pareto front. In post-optimisation decision making, the EI index of promising solutions can be dismembered into their component categories to examine specific policy issues or impacts that might be of greater interest to a particular stakeholder.

The findings and models developed enable decision makers in waterborne sewage utilities to compare expansion solutions on the basis of their combined impacts, reflecting the priorities through the most optimal solution.

8.3 Future Research

It will be valuable to understand the sensitivity of the weighting coefficients and develop standardised category indices which can also be implemented as constraints within the model. This will allow users a more user friendly output of data and a better reference to the best fitting solution. The understanding of clear and more complex methods for sewer maintenance and rehabilitation budgeting, that can be mathematically described by means of comparative analysis, can result in developing a more complete and thorough analysis of an entire system expansion problem.

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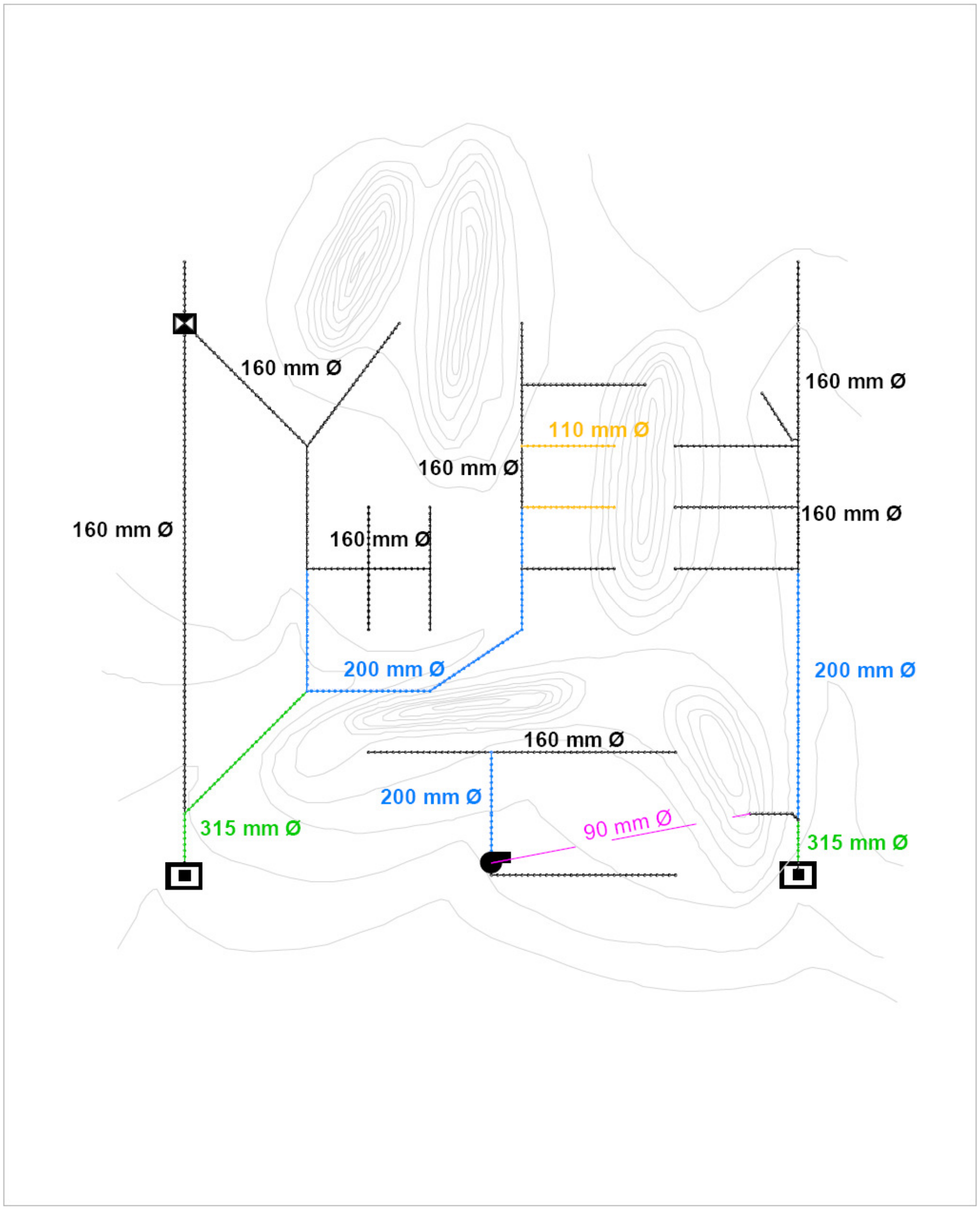
APPENDIX A

PIPE SIZES OF SANITOWN


160 mm Ø
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APPENDIX B

THE SOUTH AFRICAN TENDERING PROCESS

THE SOUTH AFRICAN TENDERING PROCESS

B.1 Introduction

A tender is an offer to perform a certain obligation, together with actual performance or evidence of present ability to perform the aforementioned obligation.

Construction refers to the process that comprises of the building of infrastructure. This requires the interactions of various bodies with different types and levels of expertise. The job of managing the overall project and supervising is normally the responsibility of the project manager.

The system of tendering, contracting and executing of contracts is the driving force behind a free enterprise system. The motive for these systems is profit generation. The successful execution of a project relies on effective planning. Those involved with the planning and design of the infrastructure must consider the following:

- Environmental impact
- Scheduling
- Budgeting
- Site safety
- Availability of materials
- Logistics
- Delays
- Inconvenience to the public
- Preparation of tender documents
- Legal aspects

Each type of construction project requires a unique team to plan, design, construct and maintain the project. However, there are several elements that are common to any project:

- Design,
- Financial, and
- Legal Considerations

The following sections are a breakdown of the processes, the different contracts, and which processes are suited to a specific project.

B.2 The Tendering System

B.2.1 Introduction to the Tendering System

Du Toit (2008) states that most, if not all, major companies maintain a formal tendering system, which is structured to suit and be compatible with the business needs and command structure of that specific company and particularly, how the powers to bind the company in contract have been delegated down the power hierarchy of the company.

In terms of company policy, each employer of contractors has a tendering or procurement system by which goods or services are procured in the market place. For the company to attain maximum profit for its shareholders, it needs to obtain maximum profit for each rand invested.

Having this objective (profit) in mind, the company should implement a formal system for invitation, evaluation and acceptance of tenders.

B.2.2 Invitation to Tender

An invitation to tender is an invitation to interested parties to submit offers based on certain pre-defined parameters, as set out in the tender documents that accompany the invitation. This can be conveyed by various means, such as press notices or by contacting the possible contractors directly.

The essential principle of a competitive tendering process is that the same information about the project is made available to all tenderers. Therefore it is necessary that any changes in the closing date, the time, and additional information should be conveyed to all tenderers to whom the documents are issued. Only then are they able to compete fairly with each other under identical terms and conditions.

B.2.3 Tender Document

B.2.3.1 General

Tender documents should be prepared using the latest versions of the forms which are applicable to the particular works in respect of which the tender is being invited. Special conditions and specifications should be clearly stipulated in any tender, along with their accompanying bill of quantities and prices.

B.2.3.2 Recommended Order

It is recommended by du Toit that tender documents for the construction of civil and commercial infrastructure should be bound together in the following recommended order:

- A Schedule of Tender Documents
- A Notice of Tenders
- A Tender Form
- A Site Inspection Certificate

- A Statement of Works successfully carried out by the tenderer
- A Schedule of Plant and Equipment
- Documents relating to the tenderer's procedural compliance with the Occupational Health and Safety Act (Act No. 85 of 1993) and Regulations
- The contract form with the General Conditions of Contract, with addendum if applicable
- Standard Specifications which are relevant
- Special Conditions and Specifications
- Bill of Quantities and Prices
- Schedule of Drawings
- Drawings
- Policy of Insurance

B.2.3.3 Special Provisions

B.2.3.3.1 Schedule of Quantities

Provisions should also be made in the schedule of quantities and prices for the schedule of day work and plant hire.

B.2.3.3.2 Occupational Health and Safety

A special provision dealing with the procedural requirements of the Occupational Health and Safety Act (Act No. 85 of 1993) and Regulations should be included as a general condition for all engineering and building contracts where the health and safety of the employees and other persons on the site are at risk. Such provisions will require of the constructor to submit a Safety Plan with his tender.

B.2.4 Tender Rules

B.2.4.1 Introduction

It is impossible for any tender committee to function without rules or regulations, although the rules and regulations have to comply with certain reasonable parameters, such as:

- The rule must be necessary, i.e. there must be a good reason for it;
- It must make commercial sense;
- It must not be counter-productive or hamper production;
- It must not exclude the good judgement of an engineer, architect or project manager.

However, good rules cannot be a substitute for competence. It is the duty of the executive of the organisation to ensure that its contracts are managed and administered by professional persons who have the qualifications and experience necessary for the job.

B.2.4.2 Notice to Tenderers

Tender documents can be made available to a closed, pre-qualified list of contractors, through the discretion of the project manager. Some tenders are also advertised by means of open advertisement in the press.

Tender documents are prepared at the cost of the employer, and often include intellectual property of significant value. The issue and return of these documents should therefore be properly controlled. It is a standard practise to require a non-refundable deposit from all prospective tenderers upon the issue of the tenders. The purpose of this deposit is to discourage all but the qualified tenderers.

The notice to the tenderers should also determine the dates at which site inspections will take place.

B.2.4.3 Tender Period

The tender period is there to allow ample time for the prospective tenderers to:

1. Study the tender document;
2. Examine the site;
3. Investigate the possibilities of arranging for materials, labour and plant;
4. Complete their tender.

The time and date when the tenders will close should be shown in the press notices and the notices to the tenderers.

B.2.4.4 General Conditions of Contract

There are a number of standard General Conditions of Contract documents used in the construction industry today, most common is:

- New Engineering Contract (NEC)
- FIDIC
- General Conditions of Contract (GCC 2004)
- General Conditions of Contract (E5)
- JBCC document in building contracts

B.2.4.5 Special Conditions of Contract

The Special Conditions of Contract (project specifications) are the terms and provisions applicable to a specific project. It contains information that is particular to the local circumstances, specific disciplines and types of work and services to be provided.

These specifications normally include clauses on the:

- Scope of work
- Business name
- Completion of work
- Penalties for late completion
- Material to be supplied by the employer
- Advance payments
- Contract price adjustment factor
- Insurance of the work against perils

B.2.4.6 Acceptance of the Tender

The acceptance of a tender concludes the contract between the employer and the contractor. The managing director may conclude the contract by notifying the tenderer of his acceptance of the tender. A copy of the executive officer’s written mandate to conclude the contract should accompany the letter of notification of the acceptance of the successful tender.

However, before the concluding of the contract, the executive officer should satisfy himself firstly, that there is still a need for the work to be provided, and secondly, that the financial provision for the project is adequate.

B.2.5 Characteristics of a good Tendering System

For a tendering system to be acceptable and in compliance with general standards, it must have the following characteristics:

- It must be fair and equal
- Tenderers must all receive the same information
- It must be creditable
- It must be free of corruption

- It must be effective and efficient
- It must reflect high ethical standards
- Tender documents must be professionally prepared

If the system does not comply with these basic characteristics, it has very limited prospects of being able to produce a successful project.

B.3 Legal

B.3.1 Definition of a Contract

"A contract is an engagement between two or more parties which is made with the intention that an obligation or obligations be created."

The above is the most widely accepted definition of the term "contract" by legal authorities. A contract in itself is not an obligation, but it intends that one or more obligations should flow from it.

Engineering and building type contracts create two or more obligations. This creates two or more rights, i.e. that each party has the obligation to deliver and the right to receive.

A contract is a juristic fact. A juristic fact has legal consequences. The legal consequences of valid contract are that the law will enforce the terms thereof.

B.3.2 Parties in a Contract

B.3.2.1 Introduction

In terms of South African Law, three different legal entities are permitted by law to participate in the business exchange, i.e. to do business by entering into contracts in South Africa. These are:

- A Natural Person (including partnerships and trusts)
- The State
- A Juristic Person (i.e. a registered company or an Closed Corporation)

B.3.2.2 Contracts with Natural Persons

Any natural person is legally competent to do business in his own name by entering into contracts, subject to a number of provisions:

- He/she must be more than 18 years old (in terms of the new Child Act of 2008)
- He/she must be solvent

Trusts and partnerships are not a juristic person. In the case of partnerships, the partners are bound jointly as natural persons entering into a contract. For trusts the trustees act in their capacity for the trust, but the trustees cannot be held liable in their personal capacity for the obligations of the Trust created by a contract.

B.3.2.3 Contracts with the State

The South African State is governed by a democratically elected Government seated at three different levels:

- Central Government
- Provincial Governments

- Local or Municipal Governments

The powers of the State to enter into or execute a contract by which the State is legally bound are defined in the Constitution of the Republic of South Africa (Act No. 2000 of 1993).

B.3.2.4 Contracts with Juristic Persons

All companies and Closed Corporations are juristic persons. The fact is that the majority of business contracts (for the scope of this report) are concluded between or with businesses. It is required by law that a registered company states the nature of their business, along with their financial structure, in order to identify it do any person doing business with that company. All these particulars are registered with the Registrar of Companies in the Statutes of the company.

There are numerous documents on commercial law. Larger companies usually hire professionals or have in-house professionals specifically to handle such matters.

B.3.3 Requirements of a Valid Contract

The basis of a valid contract is the mutual consensus between the parties comprises an agreement to perform by the giving or the delivery of, or either making or doing of something, or not making or doing something, together with the serious intent to be legally bound by the terms of the contract. In other words there must be an "*animus contrahendi*" (an intention to contract) between the parties.

Therefore the entities must adhere to the following to be able to conclude a contract:

- The parties must have legal capacity to enter into a contract.
- The contract must be allowed by law.

- The agreed performances must, objectively, be possible.
- The legally prescribed formalities must be complied with.
- The obligations of the parties in respect of what must be made, done, or delivered must be certain or ascertainable.

Civil engineering contracts are largely uncertain, in respect of both of what is to be done, made, or delivered by the contractor, and what the employer has to pay (See section B.3.4 and section B.3.5).

B.3.4 Engineering and Building Contracts

It is important that the full scope of the contractor’s obligations should be determined, e.g. by drawings, instructions, etc. The contract should also stipulate how the amounts to be paid by the employer will be ascertained, e.g. by measurement and payment for unit quantities measured at pre-agreed unit rates or prices.

Building and engineering contracts are grouped under three categories:

- *Lump-sum Contracts without a Bill of Quantities* – typical for smaller building contracts
- *Lump-sum Contracts with a Bill of Quantities* – e.g. building contracts, electrical contracts, etc.
- *Schedule of Quantities and Prices* – typical for civil engineering contracts, also known as ad-measurement contracts.

B.3.5 Characteristics of Engineering and Building Contracts

The following sections (section B.3.5.1, B.3.5.2 and B.3.5.3) are primarily extracts from T. du Toit's (2008) Project Management and the Law.

B.3.5.1 Lump-sum Contracts without a Bill of Quantities

Lump-sum Contracts without a Bill of Quantities are used when the entire project can be accurately priced, or where the contract includes the design of the structure or installation.

Typical characteristics and requirements of Lump-sum Contracts without a Bill of Quantities are as follows:

- A general performance specification is available.
- The contractor is responsible for the construction and commissioning of the complete project.
- The tenderer is required to offer an all-inclusive price.
- There is no breakdown of the lump sum price at any stage.
- The tendered price, if accepted, becomes the contract price for all that is indispensible to completion of the specified work.
- There is no measurement of whether the specified work done has been done.
- Variations are allowed only in respect of additional work ordered by the employer.

B.3.5.2 Lump-sum Contracts with Bill of Quantities

Lump-sum Contracts with Bills of Quantities are used when a specification and detailed drawings are available, and when it is possible for the employer to accurately assess the detailed make-up of the work covered by the contract.

Typical characteristics and requirements of Lump-sum Contracts with Bills of Quantities are as follows:

- The employer's quantity surveyor breaks down the architectural work for each constituent activity in considerable detail.
- The tenderer quotes a lump-sum price despite the bill of quantities.
- The tendered price, if accepted, becomes the contract price for the amount of work fixed by measurement.

The functions of the Bill of Quantities are the following:

- It determines the exact measure of work to be undertaken and enables the tenderer to calculate the lump-sum price.
- It indicates the make-up of the tender price.
- It does not form part of the contract for architectural work, although this is bound to the contract documents.
- It is used for determining new rates and remuneration for additional work and extras.

B.3.5.3 Schedule of Quantities and Prices

A schedule of quantities and prices is a type of contract that is used typically for civil engineering works which do not lend themselves to precise estimation of quantities due to the many unknown variables.

Typical characteristics and requirements of a schedule of quantities and prices are as follows:

- Drawings and designs are available and supplied by the employer.
- The contract specifies that all quantities are estimates and may be more or less than stated.
- The rates of the schedule of quantities are adjustable at the request of either the employer or the contractor if it is found that the actual measured

quantities differ from the schedule of quantities by more than a permitted percentage, usually 15-20%.

- Tender prices are fixed per unit of construction process in the schedule of quantities and prices, and these are totalled to produce an approximate tender price.
- The approximate tender price, when accepted, becomes the estimate contract value with fixed rates and prices.

The functions of the schedule of quantities and prices are the following:

- It is a provisional measure of the quantity of work to be done.
- It indicates the prices and rates for the construction processes and the approximate total contract value.
- It forms part of the contract and has legal consequences.
- It is used as the basis for payment for the quantity of work done and to determine the actual contract price.
- It is the basis for determining new rates and prices in respect of extras and variations.

B.3.6 Contracts for Letting and Hiring Services

Contracts for the letting and hiring of services, e.g. consulting services, plant hire, labour team hire, etc. are contracts with measurement on a time basis.

Typical characteristics of these types of contracts are:

- Services and items or goods are provided on a time measurement basis.
- The consultant or plant hire contractor exercises direct supervision and control over his own performance or the performance of the plant provided.
- The employer’s supervision and control are indirect.

B.4 Procurement of Construction Projects

B.4.1 Procurement Overview

Construction Procurement describes the merging of activities undertaken by the client to obtain the infrastructure. There are many different types of procurement, however the three most common types are:

- Traditional (Design-Bid-Build)
- Design and Build
- Management Contracting

For the purpose of this report a review of only the traditional (Design-Bid-Build) method will be undertaken (described in full in the next section), as this method incorporates all the major sequential phases of construction procurement.

B.4.2 Design-Bid-Build Procurement Process

B.4.2.1 Introduction

Design-Bid-Build is a project delivery method for which a client contracts with separate bodies to complete the design and construction of a civil or building project. This is the method most commonly used and it is well established.

The client employs a consultant (architect or engineer) who acts as the project coordinator. The consultant then prepares construction drawings and specifications, tenders the works, and manages the project on behalf of the client, from inception to completion.

There are three main sequential phases for the Design-Bid-Build delivery method:

a) The Design Phase
b) The Tender (Bid) Phase
c) The Construction Phase

B.4.2.2 Design Phase

In this phase the client employs a consultant to design and produce tender documents on which various general contractors will, in turn, bid and some of whom will ultimately be employed to construct the project.

The consultant will work with the owner to identify the owner's needs, develop a written programme documenting those needs and then produce a conceptual or schematic design. This early design is then developed, and the consultant can, if necessary, bring in other professionals to assist with and complete the documents (drawings and specifications).

These documents are then coordinated and put out for tender to various general contractors.

B.4.2.3 Tender Phase

The bidding for tenders can either be "open", in which any qualified bidder may participate, or "select", in which a limited number of pre-selected contractors are invited to bid.

The various general contractors who are bidding on the project obtain copies of the tender documents, and then put them out to multiple subcontractors for bids on sub-components of the project. From these elements the contractor compiles a complete tender price for submission by the closing date and time.

Once tenders have been submitted, the consultant typically reviews the tenders, seeks any clarifications required of the tenderers, ensures that all documentation is in order, and advises the owner as to the ranking of the tenders. If the tenders are acceptable to the owner, the owner and consultant discuss the suitability of various tenderers and their proposals.

The client and the consultant then award the contract to the successful tenderer, which initiates the construction phase.

B.4.2.4 Building Phase

After the project has been awarded, the complete construction documents are issued for construction. The necessary approvals (such as the building permit, environmental consent, health and safety certificates, etc.) must be sought from all jurisdictional authorities in order for the construction process to begin.

The contractor provides work by using his own workforce, but it is not uncommon for the contractor to use sub-contractors to perform or complete specific components of the project.

The consultant acts as the owner's agent to review the progress of the work and to issue site instructions, also to change orders or other documentation necessary to the construction process.

APPENDIX C

ESKOM ELECTRICITY RATES AND ANNUAL COST CALCULATION

Published rates with price increase

Ruraflex *[local authorities]*

		Active energy charge [c/kWh]												**Network access charges** [R/kVA/m]	
Transmission zone	**Voltage**	**High demand season** [Jun - Aug]						**Low demand season** [Sep - May]							
		Peak	*VAT incl*	**Standard**	*VAT incl*	**Off Peak**	*VAT incl*	**Peak**	*VAT incl*	**Standard**	*VAT incl*	**Off Peak**	*VAT incl*		*VAT incl*
≤ 300km	< 500V	**190.66**	*217.35*	**48.85**	*55.69*	**25.69**	*29.29*	**52.48**	*59.83*	**31.78**	*36.23*	**21.95**	*25.02*	**R 6.68**	*R 7.62*
	≥ 500V & ≤ 22kV	**181.84**	*207.30*	**46.64**	*53.17*	**24.55**	*27.99*	**50.11**	*57.13*	**30.36**	*34.61*	**20.99**	*23.93*	**R 6.14**	*R 7.00*
> 300km and ≤ 600km	< 500V	**191.88**	*218.74*	**49.16**	*56.04*	**25.84**	*29.46*	**52.83**	*60.23*	**31.97**	*36.45*	**22.08**	*25.17*	**R 6.70**	*R 7.64*
	≥ 500V & ≤ 22kV	**183.03**	*208.65*	**46.93**	*53.50*	**24.70**	*28.16*	**50.43**	*57.49*	**30.56**	*34.84*	**21.12**	*24.08*	**R 6.16**	*R 7.02*
> 600km and ≤ 900km	< 500V	**193.10**	*220.13*	**49.46**	*56.38*	**26.00**	*29.64*	**53.15**	*60.59*	**32.18**	*36.69*	**22.22**	*25.33*	**R 6.75**	*R 7.70*
	≥ 500V & ≤ 22kV	**184.22**	*210.01*	**47.22**	*53.83*	**24.86**	*28.34*	**50.75**	*57.86*	**30.75**	*35.06*	**21.26**	*24.24*	**R 6.19**	*R 7.06*
> 900km	< 500V	**194.33**	*221.54*	**49.77**	*56.74*	**26.16**	*29.82*	**53.48**	*60.97*	**32.37**	*36.90*	**22.35**	*25.48*	**R 6.77**	*R 7.72*
	≥ 500V & ≤ 22kV	**185.42**	*211.38*	**47.53**	*54.18*	**25.00**	*28.50*	**51.07**	*58.22*	**30.94**	*35.27*	**21.38**	*24.37*	**R 6.20**	*R 7.07*

Environmental levy [c/kWh]		**Reactive energy charge** [c/kvarh]			
All Seasons		**High Season**		**Low Season**	
	VAT incl		*VAT incl*		*VAT incl*
1.97	*2.25*	**3.17**	*3.61*	**0.00**	*0.00*

	Service charge [R/Account/day]		**Administration charge** [R/POD/day]	
Monthly utilised capacity		*VAT incl*		*VAT incl*
≤ 100 kVA	**R 6.48**	*R 7.39*	**R 1.86**	*R 2.12*
> 100 kVA & ≤ 500 kVA	**R 22.12**	*R 25.22*	**R 10.25**	*R 11.69*
> 500 kVA & ≤ 1 MVA	**R 68.06**	*R 77.59*	**R 15.72**	*R 17.92*
> 1 MVA	**R 68.06**	*R 77.59*	**R 29.21**	*R 33.30*
Key customers	**R 1 333.79**	*R 1 520.52*	**R 29.21**	*R 33.30*

APPENDIX D

OPERATION COST WEIGHT EXAMPLE

Operation Cost Weight Example

The author deemed it necessary to indicate the weight the operation cost can have on the decision for a WSS.

If we take pumpstation P2 in the Sanitown model, De Klerk et al. (2010) have stipulated that at the stage where only nodal points E7 to E9 (See Figure 2-3) are operational the pumps need to transfer sewage water at 5 *l/s.* If nodal points F2 and F3 are also to become operational there will be an increase in the volume to be pumped. Table D.1 gives the calculation on the increase in volume that will need to be pumped:

Table D.1 Pumpstation P2 inputs

Node	Land use	Units	k*l/unit/day*	k*l/day*
E7	Residential: Medium Income	200	0.78	156
E8	Industrial	150	2.988	448.2
E9	Large	1	500	500
			Total	**1104.2**
F2	Flats	200	0.492	98.4
F3	Residential: Medium Income	100	0.78	78
			Total	**176.4**

$$\%\ volume\ increase = \frac{176.4}{0.5 \times 1104.2} \times 100$$

This means that when nodal points F2 and F3 are also operational there will be a flow increase of 31.95 % to the pumpstation; therefore the design engineer needs to accommodate this future scenario by adding an additional capacity to the pumpstation (only half of the initial flow is to be considered, due to the diversion structure D2).

Therefore the flow that needs to be allowed for will be:

$$1.3 \times 1.3195 \times 5 = 8.58\ l/s$$

The 1.3 represents a safety factor and the 5 the *l/s* value as stipulated by De Klerk et al. (2010) under the initial conditions.

From equation 4-11 the cost of the pumpstation (including the cost of the structure, the pump/s and the pipe works) will roughly conform to:

$$\text{Cost} = 91169 * 8.58^{0.5444} = R\ 293{,}730.00$$

As was described in section 5.2.1, the electricity cost was calculated according to the rates supplied by Eskom (see Appendix B) for the number of kW used in one hour. The per day value was then calculated by assuming that the pumps operate 16 hours a day, of which 6 hours is at peak rate, 6 hours at standard rate, and 6 hours in off-peak rate (if possible the design engineer should try and design the pumpstation at such a manner that the pumping needs can predominately be met during off-peak hours). The daily values were then converted (Table D.2) to the values for a specific month with its specific rate, as the rate for the different months in the year vary seasonally, and then multiplied by the number of days in that month. The monthly totals were then added together to find an annual cost for electricity (with 2009 being the base year).

Table D.2 Annual pumping cost per kW (per hour)

Month	Days	Cost per Day *[c/kW/day]*	Environmental levy *[c/kW/day]*	Service charge *[R/Account/ day]*	Cost per Month *[R/kW]*
Jan	31	726.48	40.5	R 7.39	R 466.85
Feb	28.25	726.48	40.5	R 7.39	R 425.44
Mar	31	726.48	40.5	R 7.39	R 466.85
Apr	30	726.48	40.5	R 7.39	R 451.79
May	31	726.48	40.5	R 7.39	R 466.85
Jun	30	1813.98	40.5	R 7.39	R 778.04
Jul	31	1813.98	40.5	R 7.39	R 803.98
Aug	31	1813.98	40.5	R 7.39	R 803.98
Sep	30	726.48	40.5	R 7.39	R 451.79
Oct	31	726.48	40.5	R 7.39	R 466.85
Nov	30	726.48	40.5	R 7.39	R 451.79
Dec	31	726.48	40.5	R 7.39	R 466.85
			Total for 1 year per kW:		R 6 501.09

Now, knowing the cost of the pumpstation and electricity cost per year per kW, the pumping power is calculated per hour, using the brake horsepower equation. The Darcy-Weisbach equation is applied to calculate the major headloss values for each hydraulically sound pipe diameter:

Darcy-Weisbach equation:

$$h_f = \lambda \times \frac{L}{D} \times \frac{V^2}{2g}$$

where h_f = the head loss due to friction

L = the length of the pipe

D = the hydraulic diameter of the pipe (for a pipe of circular section, this equals the internal diameter of the pipe)

V = the average velocity of the fluid flow, equal to the volumetric flow rate per unit cross-sectional wetted area

g = the local acceleration due to gravity

λ = a dimensionless coefficient called the Darcy friction factor

The Darcy friction factor was calculated by using the Moody formula:

$$\lambda = 0.0055 \times \left[1 + \left(\frac{20000 \times k_s}{D} + \frac{10^6}{Re}\right)^{\frac{1}{3}}\right]$$

where k_s = the friction factor

Re = Reynolds number

Table D.3 shows the headloss calculations for five pipe diameters that were found to be hydraulically suitable, the friction factor that was chosen for uPVC Class20 pipe was 0.06 as found by Chadwick et al. (2004). The pipe length was calculated to be 1540m.

Table D.3 Headloss calculation

Nom. Diameter	Inside Diameter	Flow speed *[m/s]*	Reynolds ($x10^6$)	Turbulent	Darcy friction factor *f*	Headloss *[m]*
90	80	1.707	0.1208	yes	0.02999	85.730
110	100	1.092	0.0967	yes	0.03018	28.270
125	113	0.856	0.0856	yes	0.03030	15.406
140	127	0.677	0.0761	yes	0.03043	8.628
160	145	0.520	0.0667	yes	0.03060	4.471

Therefore the total primary headloss is calculated by:

$$H = \Delta z + h_f$$

where Δz = height difference between inlet and outlet (m)

Taking into account that the minor losses will be similar for each diameter of pipes identified, and will be covered by a 10% safety margin, the brake horsepower per hour can be calculated by Equation 5-1. From here the total annual cost can be calculated. Now, given a 30 year design period, at a discounted rate of 6%, the total running cost of the pumpstation can be calculated:

$$(P/A, i\%, N) = \frac{(1+i)^N - 1}{i(1+i)^N}$$

That means:

$$PV = Running\ cost\ for\ first\ year\ \times (\frac{(1+0.06)^{30}-1}{0.06(1+0.06)^{30}})$$

where PV = Present Value (2009 Rands)

N = time in years

i = discount rate (6%)

Table D.4 gives a summation of the calculations for the different selected pipe diameters.

Table D.4 Pumpstation P2 thirty year running cost

Nom. Diameter *[mm]*	Inside Diameter *[mm]*	Headloss *[m]*	Δz *[m]*	P *[kW]*	Annual running cost	30 Yr running cost (PV)
90	80	85.73	5.00	12.9132	R 83 949.56	R 1 155 551.46
110	100	28.27	5.00	4.7352	R 30 783.66	R 423 731.92
125	113	15.41	5.00	2.9043	R 18 881.02	R 259 894.01
140	127	8.63	5.00	1.9396	R 12 609.55	R 173 568.34
160	145	4.47	5.00	1.3480	R 8 763.21	R 120 624.14

Table D.5 gives a summary of the three costs. The cost of the pipes for the different diameters was estimated using the model developed in Chapter 4, with the assumption that 5% of the construction of the pipeline will be underneath roads, 25% in reserve areas and the remainder in public open spaces.

Table D.5 Cost consideration for different diameter pipes for pumpstation P2

Nom. Diameter *[mm]*	Inside Diameter *[mm]*	Pumpstation Construction cost	30 Yr running cost (PV)	Pipe cost (length = 1540m)
90	80	R 293 730.00	R 1 155 551.46	R 412 745.18
110	100	R 293 730.00	R 423 731.92	R 549 018.70
125	113	R 293 730.00	R 259 894.01	R 653 766.58
140	127	R 293 730.00	R 173 568.34	R 760 693.93
160	145	R 293 730.00	R 120 624.14	R 906 654.06

It was found that the running cost can have an significant influence on the consideration of pipes, if the objective is to minimise overall capital investment. Figure D-1 indicates the three diferent costs involved for each diameter and the impact each carries in the overall cost of a pumpstation.

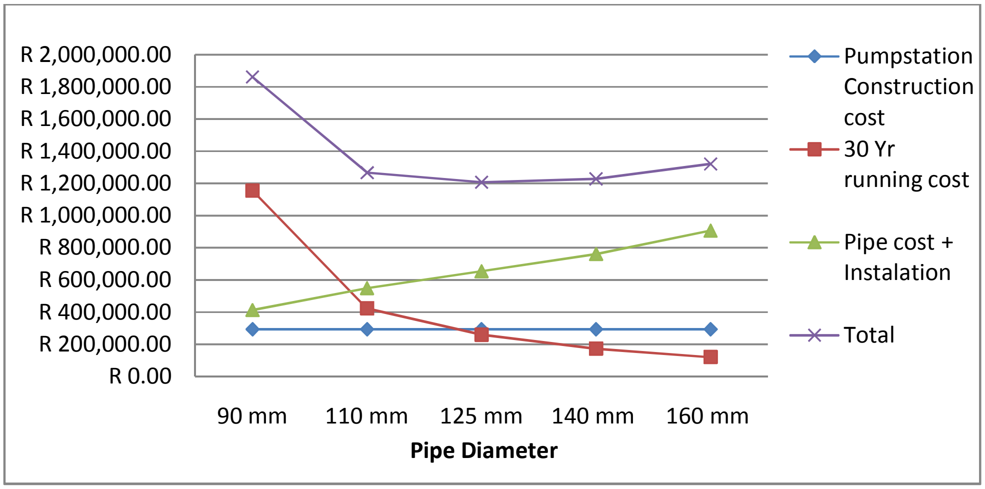

Figure D-1 Cost consideration of different diameter pipes for pumpstation P2

However, the National Energy Regulator of South Africa (NERSA) has announced that it will allow Eskom a percentage price increase of 24.8% on the average standard tariff from 1 April 2010, followed by another average increase of 25.8 % from 1 April 2011 and a further price increase of 25.9 % from 1 April 2012 (NERSA Media Release, 2010). This will have a significant impact on the running cost of the pumpstation, and will put the onus even more on effective operational design.

APPENDIX E

ENVIRONMENTAL INDEX BREAKDOWN – CAPITAL COST

($20 million US Dollars (2002) worth of pipe production)

Greenhouse gases

	Sector Total	t CO2e CO2 Fossil	t CO2e CO2 Process	t CO2e CH4	t CO2e N2O	t CO2e HFC/PFCs	t CO2e
	Total for all sectors	28300	23700	1290	2160	761	440
221100	Power generation and supply	8300	8180	0	22.5	50.8	52.6
325211	Plastics material and resin manufacturing	4350	4350	0	0	0	0
325110	Petrochemical manufacturing	3160	2650	365	151	0	0
325190	Other basic organic chemical manufacturing	3020	2710	0	0	310	0
211000	Oil and gas extraction	2200	620	403	1180	0	0
324110	Petroleum refineries	1580	1570	0	4.89	0	0
484000	Truck transportation	444	444	0	0	0	0
325310	Fertilizer Manufacturing	413	102	138	0	172	0
486000	Pipeline transportation	407	186	0.51	220	0	0
331110	Iron and steel mills	376	142	232	2.29	0	0

Energy

	Sector	Total Energy, TJ
	Total for all sectors	474
221100	Power generation and supply	101
325211	Plastics material and resin manufacturing	100
325190	Other basic organic chemical manufacturing	69.2
325110	Petrochemical manufacturing	58.3
326122	Plastics Pipe and Pipe Fitting Manufacturing	32
324110	Petroleum refineries	26.4
211000	Oil and gas extraction	13.2
484000	Truck transportation	6.02
482000	Rail transportation	5.2
486000	Pipeline transportation	4.87

Toxic releases

	Sector	Carcinogens Mg C_2H_3Cl eq	Non-carcinogens Mg C_2H_3Cl eq	Respiratory inorganics kg PM2.5 eq	Ozone Dep kg CFC-11 eq	Respiratory organics kg C_2H_4 eq	Aquatic ecotoxicity Gg TEG water	Terrestrial ecotoxicity Gg TEG soil	Terrestrial acid/nutri kg SO_2 eq	Aquatic acidif kg SO_2 eq	Aquatic eutro kg PO_4 P-lim
	Total for all sectors	5630	57800	142	117	6730	15600	12700	17400	6950	0.302
2122A0	Gold, silver and other metal ore mining	5070	52800	0.307	0	0.012	492	1690	37.8	10.9	0
326122	Plastics Pipe and Pipe Fitting Manufacturing	152	306	82	68.3	4810	38	21.3	10100	3120	0
221100	Power generation and supply	148	1580	0.739	0	0.163	613	518	91	960	0
212230	Copper, nickel, lead and zinc mining	109	1720	0.005	0	0.068	12100	8600	0.619	0.666	0
331411	Primary smelting and refining of copper	86.9	943	0	0	0.005	1770	895	0.021	0.232	0
562000	Waste management and remediation services	14.4	141	0	0.002	0.047	145	232	0.021	0.239	0.273
325190	Other basic organic chemical manufacturing	12	10.5	22.2	19.3	711	35.1	29.6	2740	1060	0
325220	Artificial and synthetic fibres and filaments manufacturing	5.19	56.8	0.148	3.94	16.1	27	36.9	18.2	45.3	0
325188	All other basic inorganic chemical manufacturing	4.19	104	1.8	3.45	1.72	28.3	94.3	221	75.8	0.018
212100	Coal mining	4.05	44.2	0.134	0	0	16.5	20.4	16.5	5.7	0

APPENDIX F

ENVIRONMENTAL INDEX BREAKDOWN – OPERATION COST

($20 million US Dollars (2002) worth of electricity generation)

Greenhouse gases

	Sector Total	t CO2e CO2 Fossil	t CO2e CO2 Process	t CO2e CH4	t CO2e N2O	t CO2e HFC/PFCs	t CO2e
	Total for all sectors	187000	178000	626	6910	1130	1150
221100	Power generation and supply	176000	174000	0	478	1080	1120
212100	Coal mining	4590	518	0	4070	0	0
211000	Oil and gas extraction	2580	726	473	1380	0	0
486000	Pipeline transportation	1340	614	1.68	727	0	0
482000	Rail transportation	519	519	0	0	0	0
324110	Petroleum refineries	397	396	0	1.23	0	0
484000	Truck transportation	183	183	0	0	0	0
230301	Nonresidential maintenance and repair	175	175	0	0	0	0
331110	Iron and steel mills	151	56.9	92.9	0.918	0	0
221200	Natural gas distribution	146	13.2	0	133	0	0

Energy

	Sector	Total Energy,TJ
	Total for all sectors	2230
221100	Power generation and supply	2150
486000	Pipeline transportation	16.1
211000	Oil and gas extraction	15.4
212100	Coal mining	10.6
482000	Rail transportation	7.69
324110	Petroleum refineries	6.65
230301	Nonresidential maintenance and repair	2.74
484000	Truck transportation	2.48
331110	Iron and steel mills	1.75
322130	Paperboard Mills	1.09

Toxic releases

	Sector	Carcinogens Mg C2H3Cl eq	Non-carcinogens Mg C2H3Cl eq	Respiratory inorganics kg PM2.5 eq	Ozone Dep kg CFC-11 eq	Respiratory organics kg C2H4 eq	Aquatic ecotoxicity Gg TEG water	Terrestrial ecotoxicity Gg TEG soil	Terrestrial acid/nutri kg SO2 eq	Aquatic acidif kg SO2 eq	Aquatic eutro kg PO4 P-lim
	Total for all sectors	3810	40500	21.3	0.873	65.3	15700	13300	2620	20700	0.16
221100	Power generation and supply	3150	33600	15.7	0	3.46	13000	11000	1930	20400	0
2122A0	Gold, silver and other metal ore mining	537	5590	0.033	0	0.001	52.1	179	4.01	1.16	0
212100	Coal mining	66.5	725	2.2	0	0	271	334	271	93.5	0
331411	Primary smelting and refining of copper	25.1	272	0	0	0.002	510	258	0.006	0.067	0
212230	Copper, nickel, lead and zinc mining	15.6	247	0	0	0.01	1740	1230	0.089	0.096	0
562000	Waste management and remediation services	8.28	80.9	0	0.001	0.027	83.4	134	0.012	0.137	0.157
324110	Petroleum refineries	0.881	0.143	0.823	0.038	18.5	0.652	0.734	101	37.9	0
331110	Iron and steel mills	0.57	5.47	0.078	0	0.308	12.4	44.8	9.63	3.98	0
331420	Copper rolling, drawing, extruding and alloying	0.537	6.01	0.029	0	0.042	6.32	2.6	3.51	1.31	0
333611	Turbine and turbine generator set units manufacturing	0.463	0.02	0.001	0	0.06	0.051	0.024	0.15	0.042	0