Management model to optimise the use of reverse osmosis brine to backwash ultra-filtration systems at Medupi power station

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Dissertation submitted in fulfilment of the requirements for the degree *Master* in Engineering at the Potchefstroom Campus of the North-West University

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May 2014

Acknowledgements

I would like to thank my mentor Professor Harry Wichers for his guidance and continuous support and encouragement during this study.

I would like to thank Marleen Theunissen with the assistance on all aspects of language, editing and referencing.

I would also like to thank my wife, Annelie and my kids, Anri and Ruan for their encouragement, support and the sacrifice they made, allowing me to complete this study.

Finally, I would like to thank our Heavenly Father for the ability and strength to complete this dissertation.

Abstract

According to the Department of Water Affairs (DWAF, 2004 p.15), South Africa's water resources are scarce and extremely limited and much of this precious resource is utilised and consumed in our industries. Treatment and re-use of effluent generated is, in some cases, preferred over use of alternate water resources (Du Plessis, 2008 p.3).

The volume of effluent generated in treatment processes like ultra-filtration (UF) and reverse osmosis (RO) units is determined by the feed water quality, with high water loss through effluent generation at poor feed water quality. Current UF and RO applications require an increased UF production capacity due to the use of UF filtrate for periodic backwashing of the UF membrane units. This results in loss of water and decreases overall recovery.

The need therefore exists to increase the overall recovery of product water from the raw water stream by reducing the amount of effluent generated. This would be possible to achieve by using RO brine to backwash the UF unit.

The study was conducted to provide a modelling tool, assisting management to optimise the use of RO brine as backwash water on the UF system at the Medupi power station. The secondary objective of this study was the development of a modelling tool that can be used for other projects, new or existing, as a measure and indication of the usability of RO brine as backwash water on UF systems.

By successfully applying this newly developed model, the viability of utilising the RO brine as backwash water for the UF was investigated. This modification would lead to utilizing smaller UF units than previously envisioned, which in turn leads to reducing capital cost with 11.07% and operating expenditure with 9.98% at the Medupi power station. This also has a positive environmental impact by reducing the amount of raw water used monthly by 10.34% (108 000 m^3/month).

Keywords:

ultra-filtration (UF), reverse osmosis (RO), membranes, backwashing, RO brine, modelling tool, Medupi power station.

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List of abbreviations

µS/cm – Micro siemens per centimetre
AWWA – American Water Works Association
BATNEEC – Best available technology not entailing excessive costs
BPEO – Best Practical Environmental Option
CA – Cellulose Acetate
CEB – Chemically Enhanced Backwash
CIP – Clean In Place
CIX – Conventional Ion Exchange
CSIR – Council for Scientific and Industrial Research
DWAF – Department of Water Affairs
EPA – Environmental Protection Agency
GDP – Gross Domestic Product
ISO – International Organization of Standardizations
l/h – litres per hour
l/kWh – litres per kilowatt-hour
LCC – Life Cycle Cost
LSI – Langelier Saturation Index
mg/l – milligram per litre
NSW – New South Wales
PAN – polyacrylonitrile
PBIX – Packed Bed Ion Exchange
PESU/PES – Polyethersulphone
PP – Polypropylene
PS – Polysulfone
PVDF – Polyvinylidene fluoride
RO - Reverse Osmosis
SDI – Silt Density Index
SI – Sustainability Index
TDS - Total Dissolved Solids
TMP – Trans-membrane Pressure
UF – Ultra Filtration
USGS – United States Geological Survey
WBS – Work Breakdown Structure
WISA – Water Institute of South Africa
ZLED - Zero Liquid Effluent Discharge

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Equation 1: $A_T = \frac{Q_N}{F_N}$

Equation 2: $M_T = \frac{A_T}{A_M}$

Equation 3: $P_T = \frac{M_T}{4}$

Equation 4: $S_T = \frac{M_T}{40}$

Equation 5: $Q_{FD} = F_G \times A_T$

Equation 6: $R_C = \left[1 - \left(\frac{B_V}{Q_N}\right)\right] \times 100$

Equation 7: $A_{S=}\frac{A_T}{S_T}$

Equation 8: $Q_{BW} = F_{BW} \times A_S$

Equation 9: $Q_{SH} = \frac{(D_{SH} \times Q_{CEB})}{SH_{CN}}$

Equation 10: $Q_{CL} = \frac{(D_{CL} \times Q_{CEB})}{CL_{CN}}$

Equation 11: $Q_S = \frac{(D_S \times Q_{CEB})}{S_{CN}}$

Equation 12: $CEB_C = \frac{24\ hours}{CEB_F}$

Equation 13: $SH_C = \left(\frac{Q_{SH}}{3600\ seconds}\right) \times CEB_T \times CEB_C \times S_T$

Equation 14: $CL_C = \left(\frac{Q_{CL}}{3600\ seconds}\right) \times CEB_T \times CEB_C \times S_T$

Equation 15: $S_C = \left(\frac{Q_{SH}}{3600\ seconds}\right) \times CEB_T \times CEB_C \times S_T$

Equation 16: $LSI = pH_W - pH_S$

Equation 17: $pH_S = (9.3 + A + B) - (C + D)$

Equation 18: $A = \frac{(\log_{10}[TDS] - 1)}{10}$

Equation 19: $B = -13.12 \times \log_{10}(°C + 273) + 34.55$

Equation 20: $C = \log_{10}[Ca^{2+}\ as\ CaCO_3] - 0.4$

Equation 21: $D = \log_{10}[alkalinity\ as\ CaCO_3]$

Equation 22: $C_F = \frac{1}{(1 - R_{RO})}$

1. Introduction

1.1 Background

According to the Department of Water Affairs (DWAF, 2004 p.15), South Africa's water resources are scarce and extremely limited and much of this precious resource is consumed in industry. South Africa is a dry country with an average rainfall of 450 mm per annum while the average yearly rainfall globally is 860 mm (CSIR, 2010 p.4). The water consumption is divided amongst industry by the use of each sector.

Water is a re-usable resource and not a renewable resource and should, as such, be re-used within industry to the extent practicable to reduce the consumption from existing reservoirs.

Water that is used in a non-consumptive manner becomes available for direct recycling and re-use or is returned to the water source after treatment, thereby becoming available for re-use. Treatment and re-use of effluent generated is in some cases preferred over the use of alternative water resources.

The re-use of water is an important part of South Africa's water strategy. According to Buylwa Sonjica, ex-minister of environmental affairs: "Our challenge here is not so much to invent as it is to alter the way we think and act on how we use our water. We don't have the luxury of choice and time unfortunately — we must act now and do that decisively." (Parliamentary Monitory Group, 2009). The utilisation of our water resources and the limited supplies means that sustainable use will require far more efficient utilisation by all sectors (CSIR, 2010 p.6).

The power generation sector consumes 2% of the available water (DWAF, n.d.). Eskom supplies up to 95% of South Africa's power requirements (Pather, 2004 p.659). The coal fired power station Medupi, currently being built in Lephalale in South Africa's Limpopo province, will be Eskom's first super critical boilers, operating at 24 MPa and 565°C (Galt, 2009 cited in Power Plant Chemistry, p.620). Super critical boilers require ultra-pure water for the efficient operation. The Medupi power station's water treatment plant uses membrane technology to produce ultra-pure water for the efficient operation of their super-critical boilers.

Membrane systems are used in industry for the purification of water. The water treatment system at Medupi Power Station utilises ultra-filtration (UF) and reverse osmosis (RO) technology as part of the process stream to purify the water. It is common in industry to use UF and RO in combination for water treatment. The UF is used as pre-treatment and the RO as final treatment.

1.1.1 Membrane technology

The term filtration refers to the removal of particulates from a feed stream by size exclusion (Byrne, 2002 p.3). The particulates are too big to pass through the filter pores. Membrane filtration is a term used to describe the removal of particulates from a feed stream utilising a membrane based process (Pearce, 2007 p.24). This membrane process can be an UF process, removing particulates from water and; RO process, removing dissolved solids from water; or both in series.

A questionnaire was sent to four of the most prominent UF membrane suppliers in South Africa on the use of UF units (Membrane questionnaire, 2011 p.1). This revealed that 48% to 95% of the UF membrane units sold are utilised as pre-treatment for RO units.

The UF membrane used on the Medupi Power Station is made out of hollow fibre capillaries, 0.8 mm inside diameter (Norit, 2010). The UF membrane is made of the material polyethersulphone (PESU). According to dr. Christian Maletzko (2009 p.22), Engineering Plastics BASF, PESU membranes combine high removal efficiency, due to a fine pore-size rating and narrow pore size distribution, with excellent permeability.

Operation of the UF system will be inside-out, meaning the feed water enters the capillaries on the inside. The filtrate goes through the capillary wall and the particulates are retained on the inside. A backwash procedure is performed, typically every 20 minutes. This entails water entering the membrane from the filtrate side and exits on the feed side, washing away the particulates retained on the inside. This is known as a hydraulic clean. The UF system also uses chemicals combined with a short soak period to clean off matter which does not get removed by backwashing.

The main objective of the UF system is to remove particulate matter from the water, as pre-treatment to a RO system. The removal rating of UF membranes is denoted as ‘absolute’. This means that the membrane will retain any particulate matter in the feed stream which exceeds the pore size of the membrane. The membrane pore size ranges from approximately 0.001 – 0.002 µm (Pearce, 2007 p.25). The membrane also removes bacteria and some viruses from water. The specific membrane for the Medupi plant claims a Log 4 virus removal and a log 6 bacteria removal (Norit, 2010).

Although UF technology is good at removing contaminants from water it does have a downside in the form of a waste stream. By requiring a hydraulic clean or ‘backwash’, as it is commonly known, a waste stream is generated. Depending on the raw water quality this waste stream can be up to 15% of the inlet flow. The UF system sizing requires additional capacity to provide for the volume requirement of the backwash as well as the down time during the membrane backwash activity.

RO technology is used to remove dissolved solids from water. The dissolved solids can be salts or organics such as sugar or dissolved oils (Byrne, 2002 p.1). The removal mechanism of RO systems is different to the removal mechanism of filtration. Physical holes do not exist in the RO membrane. It is more likely that water molecules diffuse between the structures of the membrane polymer by bonding through segments of the polymers' structure (Byrne, 2002 p.3). The dissolved salts and organics are retained on the concentrate side of the membranes.

The feed stream entering the membrane is separated into the clean water stream, also called the permeate stream and a second stream, known as the concentrate stream or brine stream. As the water passes across the membrane surface the water permeates the membrane. The water molecules permeating the membrane leave behind the solids, thereby creating a concentration of salts in the brine side. The permeate stream for the RO system is used in the process while the brine stream is discarded to waste. The brine stream typically accounts for 20 – 25% of the feed stream.

The volume of effluent generated in treatment processes like UF and RO units is determined by the feed water quality, with high water loss through effluent generation at poor feed water quality. Current UF applications require an increased production capacity due to the use of filtrate for periodic backwashing of the membrane units. This results in loss of water and lower overall recoveries. The need exists to increase overall recovery of clean product water from the raw water stream by reducing the amount of effluent generated.

The overall recovery can be improved by using RO brine to backwash the UF unit continuously or periodically. The focus of this research was to develop a modelling tool to assist management in deciding whether to re-use RO brine for backwashing purposes in industrial processes where UF system is followed by a RO system such as in the Medupi power plant, where electricity is generated by supercritical boilers (Galt, 2009 cited in Power Plant Chemistry, p.620).

The utilisation of the RO brine as backwash water reduces the amount of raw water consumed by increasing the amount of water re-used. The re-use of the RO brine improves the overall plant system recovery of water. By using the RO brine as backwash water for the UF system the capacity can be reduced. The reduction in capacity of a UF system reduces the amount of capital required for the project. The development of the modelling tool to optimise the use of RO brine as backwash water for a UF system assists management in making the best decision in terms of the overall plant life cycle cost (LCC).

1.1.2 Usability of RO brine water as UF backwash water

Current UF systems utilise filtrate (UF product water) for backwashing the membranes. UF system capacities are increased to produce additional water to cater for this purpose. This ultimately increases the water usage and waste generation. The idea of utilising the RO brine as backwash water to UF systems is not very well documented. The questionnaire that was sent to four prominent suppliers of UF membranes in South Africa revealed that the concept of utilising the RO brine as UF backwash water was not widely known or used in industry, apart from pilot tests to test performance and usability. These pilot tests are still in progress and no practical data is available. Theoretical data and assumptions have been used in the development of the modelling tool, which can be verified or updated later when results become available. Investigating the use of RO brine as backwash water is extremely important in reducing waste generation.

The water balance across the UF system at Medupi Power Station indicates that 85% of the feed water to the unit is recovered as filtrate, which is used in the next process stream, and 15% is utilised in backwashing. This volume constitutes the effluent generated and is not re-used. The RO system operates at a recovery rate of 80%, i.e. 20% of the feed stream to the RO unit is released as an effluent (brine) stream and is not re-used. The feed water to the UF and RO system is from the Mokolo dam.

1.1.3 Management model to optimise the use of RO brine as backwash water on UF system

Part of the modelling process includes using the calculated RO brine water quality in terms of total dissolved solids (TDS), to calculate the scale forming effect of the water. On an existing site, water analysis can confirm the RO brine quality without the need for calculations and simulations. The scale forming potential of the water was subsequently calculated using the Langelier saturation index (LSI) method. The prediction of scaling on membrane systems is a field of study which justifies research on a master’s degree level by itself. For the purpose of this study, only the LSI indicator was used for predicting the scaling tendencies of the water.

The system was modelled for two scenarios. Case 1 was for the current system utilising filtrate as backwash water. This was the original design for the UF system at the Medupi Power Station as well as being the industry norm. The system was designed for 85% recovery, catering for the backwash volume and downtime requirements. Data from the membrane supplier was used to estimate the membrane life, taking into account the feed water and backwash water quality, number of hydraulic cleans and the estimated number of chemically enhanced backwashes. This was input data into the life cycle analysis, calculating the membrane replacement cost monthly.

Case 2 was the optimised system utilising RO brine as backwash water to the UF system. As mentioned, this is not the norm for applications using UF and RO systems in a process stream. The RO brine quality was calculated using the concentration factor and the raw water analysis from site. The UF system was designed with the reduced capacity. The chemical consumptions were re-calculated. The membrane life was estimated as discussed above.

The modelling tool was developed to assist management in high level decisions on the water treatment plant by converting the impact and influences to a financial currency value and comparing the two options based on this. The tool can also assist in justification for capital expenditure for certain changes required on the existing system if the improved LCC is provided. **Figure 1:** Cost influencing the LCC indicates the cost to be considered. The exclusion of some cost parameters reduces unnecessary effort from the available workforce. Only cost that changed from the current to the optimised situation was evaluated.

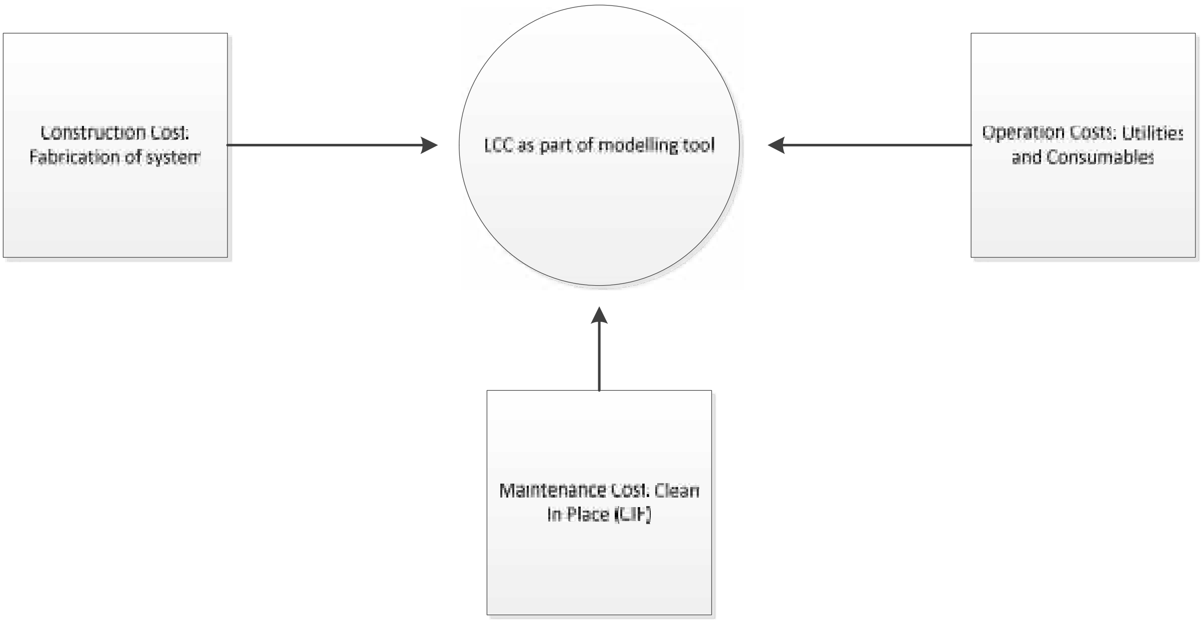


Figure 1: Cost influencing LCC

1.2 Specific objectives of study

The study was conducted to provide a modelling tool, assisting management to optimise the use of RO brine as backwash water on the UF system at the Medupi power station. The modelling tool consists of a technical component where the process and hydraulic calculations are conducted. The utility consumption is calculated and the cost parameters, indicated in **Figure 1:** Cost influencing the LCC, is used in LCC.

The main objective of the study was:

- Present management of the Medupi Power Station with a modelling tool to optimise the use of RO brine as backwash water on the UF system.

The secondary objective of the study was:

- Development of a modelling tool that can be used for other projects, new or existing, as a measure and indication of the usability of RO brine as backwash water on UF systems. This is illustrated in chapter 4 with the case study of Company X.

1.3 Deliverables

The study deliverable is **Figure 10:** Flow Sheet of Optimisation Management Model (Medupi). The flow sheet describes the 8 steps that can be applied by management to reach a final decision on the use of RO brine as backwash water on a UF system.

1.4 Overview of dissertation

The study aimed to produce a modelling tool in the form of a flow sheet (**Figure 10:** Flow sheet of the optimisation management model (Medupi)) which can assist management in the optimisation of the re-use of RO brine to backwash a UF system, based on the financial implications. The modelling tool was developed with the use of recognized reference material such as the international standard for life cycle costing ISO 15686-5 and others. The need to increase the efficiency of current water treatment systems and reducing the amount of fresh water used is expressed by Eskom on their official website. This fact highlight that the need exists to decrease the withdrawing of water from our reservoirs by re-using the water from existing treatment facilities.

2 Literature study

2.1 Introduction – Structure of literature review

The specific objective of the study was to develop a modelling tool to optimise the use of RO brine as backwash water on the UF system at the Medupi power station. The modelling tool can also be used for future projects as a measure and indication of the usability of RO brine as backwash water on UF systems. The literature study was conducted with the specific aim of detailed discussions on the elements of the study, as listed in the title of the document. Topics highlighted from the title are:

- Management model (required for assistance in decision making).
- RO and UF (water treatment technologies).
- Backwash water and re-use (implicating water scarcity).
- Medupi power station (water use in power generation).

After evaluating the literature review the reader will understand the current situation of water usage in the power industry as well as the need to re-use the precious resource. Methodology discussed sheds light on the requirement and need for management in industry, and specifically the power industry as illustrated by this study, to have the required information to make enlightened decisions that benefits the industry as well as the environment. Tools required for this purpose can be specifically developed, as in the case of this study. Utilisation of RO brine as backwash water on a UF system presents financial and environmental benefits, which needs to be placed under the attention of key decision makers.

In conducting the literature review **Figure 2:** Structure of literature review, was followed. The literature review focused on the main topics, as listed above. The literature review supplies high level background information on current water situation, in general and more detailed info on the power generation industry. Following the structure, allowed for a comprehensive study of the required elements.

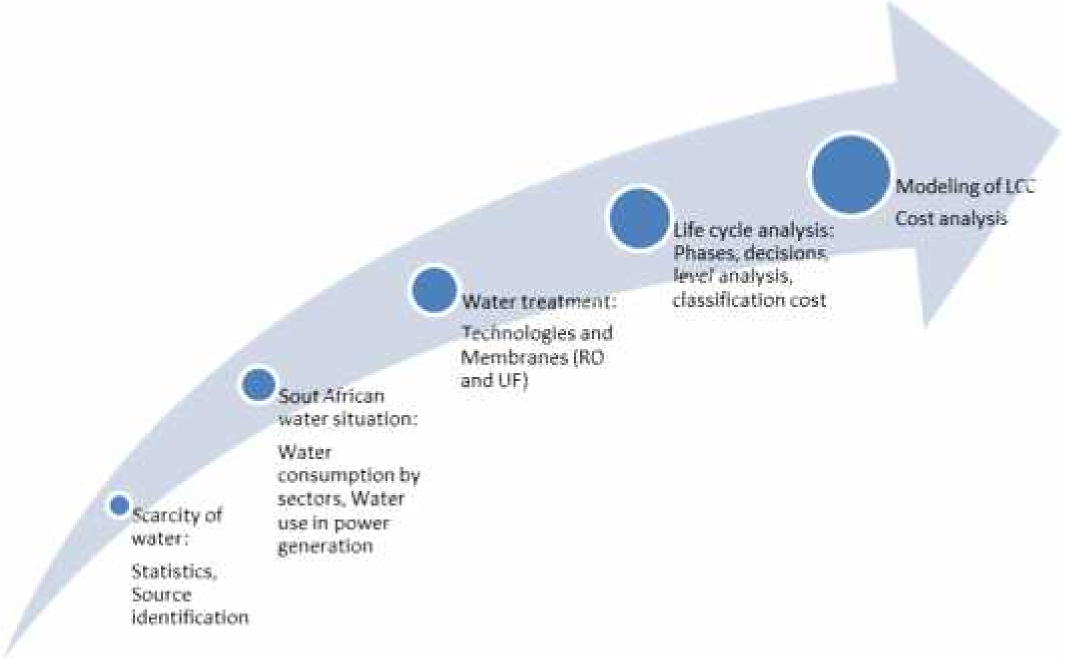


Figure 2: Structure of literature review

2.2 Scarcity of water

The human development report of 2006 states that human security means having protection from unpredictable events that disrupts lives and livelihoods. Few resources have a more critical effect on this security than water. In the hierarchy of human needs water is essential for drinking, health, sanitation and agriculture. Thereafter water is important for industry, power generation, mining operations and tourism (CSIR, 2010 p.4).

Seventy per cent of the earth is covered with water. This fact would tend to indicate that we do not have a problem with water scarcity. Even though the earth is apparently a water planet, 98% of all the water on earth forms part of oceans. This water is not useable for human consumption in its natural state due to the salinity of the water. Salinity of water refers to the amount of dissolved salt that is present in the water. Sea water contains approximately 35,000 mg/l of dissolved salts (Byrne, 2002 p. 116 and Noyes Data Corporation, 1981 p. 11). The amount of dissolved salts present in seawater makes it too salty to use, without extensive treatment called desalination. Fresh water or water not present in oceans also has dissolved salt present. The amount of salts present in fresh water is not enough to give the water a salty taste. Approximately 2 per cent of the water available on earth is referred to as fresh water. Of this 2% of fresh water on earth, 80% constitute the glaciers and ice caps, a total of 1.6% of the planet's water. This leaves only about 0.4 % available fresh water, which is split into 90% as ground water, a total of 0.36% of the planet's water and 10% in rivers and lakes, 0.036% of the planet's water (Eskom, 2013).

2.3 South Africa water situation

It is commonly thought that South Africa is a water rich country. In fact South Africa is a water scarce country. The annual rainfall of 450 mm is far below the global average of 860 mm (CSIR, 2010 p.4). The western and interior part of the country is arid or semi-arid and receives less than 500 mm rainfall per year and 21% of the country receives less than 200 mm per year (DWAF, 1994 cited in Mukheiber, 2005 p.2). South Africa is the 30th driest country in the world (DWAF, 2013 p. 19).

South Africa is dependent on surface water for most of the urban, industrial and irrigation water supplies in the country (CSIR, 2010 p.4) Surface water originates from runoff. The term runoff means precipitation in the form of rain, fog, hail and snow that runs off the land surface and appears in streams (CSIR, 2010 p.6).

The total surface water available in South Africa is 49200 million cubic meters (m^3) per year (DWAF, 2002 p.4). Of this total about 4800 million m^3 per year of water originates from Lesotho and 700 million m^3 of water originates from Swaziland. (DWAF, 2002 p.4).

South Africa shares six river basins with six neighbouring countries. These river basins are Incomati, Limpopo, Maputo, Orange-Senqu, Thukela and Umbeluzi. The countries are Botswana, Lesotho, Mozambique, Namibia, Swaziland and Zimbabwe. (Ashton, Hardwick and Breen, n.d.). Approximately 70% of the South Africa's gross domestic product (GDP) and a similar percentage of the population of the country is supported by 4 of these rivers, namely Incomati, Limpopo, Pongola (Maputo basin), and Orange (Senqu basin) (DWAF, 2002 p.2). According to the CSIR (2010 p.4), after careful calculations, the runoff yield and water use indicate that at national level we have enough water for the immediate future. South Africa has 569 major dams with individual capacity exceeding 1 million m^3 and a total capacity of 32400 million m^3 (CSIR, 2010 p.4). The dams have enough capacity for 70% of the run off.

According to Ashton, Hardwick and Breen (n.d.) the water use patterns of South Africa indicate that the river basins shared with the neighbouring states have reached a point where little additional water is available. Population growth will aggravate the situation. According to the Strategic Overview of the Water Sector in South Africa (DWAF, 2010 p.15) the projected total water requirement in 2025 is estimated to be 17 billion cubic metres per annum (m^3/annum) versus a reliable yield of 15 billion cubic metres per annum (at 98% assurance of supply). This implies additional water resources will need to be developed to provide for increased domestic water requirements. All indications are that although the immediate future is catered for, the long term future needs planning and participation to reduce the amount of water consumed. Additionally we need to ensure that the current available sources of water are not polluted.

2.3.1 The water use by sectors

The use of the water resources is indicated by sectors. The main water use sectors according to the Water for Development and Growth Framework (DWAF, n.d.) are the following:

- Rural requirements. This mainly constitutes domestic use and stock watering in rural areas.
- Urban requirements. This constitutes all water used in urban areas such as domestic, industrial and offices.
- Mining and bulk users, with the latter essentially representing large industrial users outside urban areas.
- Power generation.
- Irrigation for agricultural production;
- Afforestation, as a formally declared stream flow reduction activity.
- Transfers of water out of a particular area, which constitutes a requirement for water from that area.

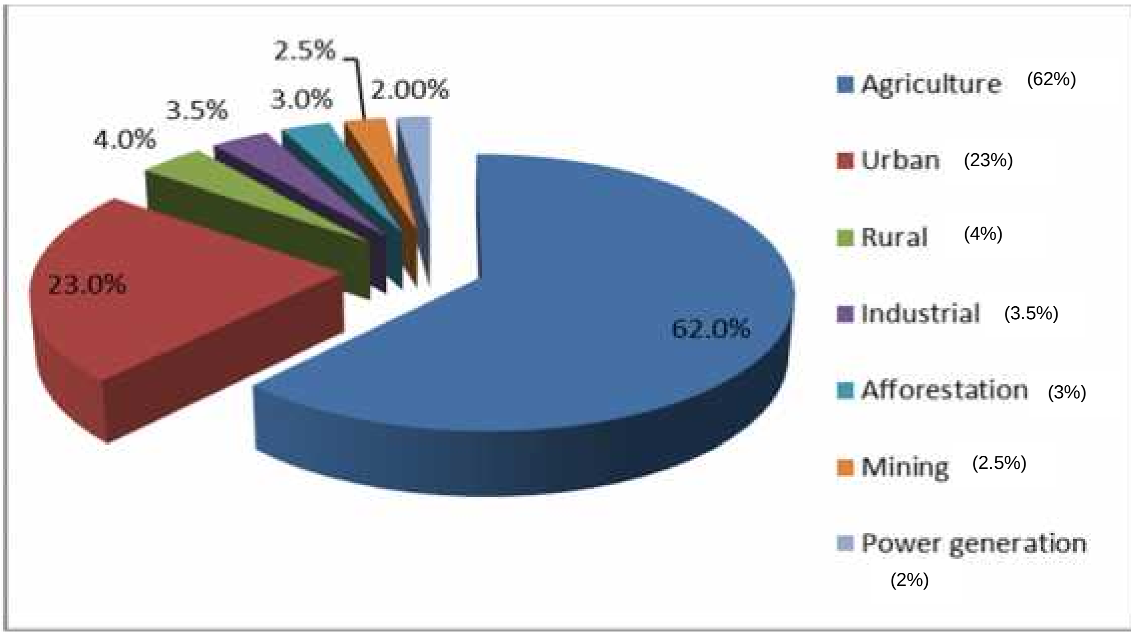


Figure 3: Water use by sector

2.3.2 Water use in power generation

Power generation requires a significant amount of water to operate the required technologies. Water purification is used to supply water for (Naidoo, 2003 p.26):

- Potable water,

- Demineralised water for the steam cycle in generating electricity,
- Cooling,
- Sluicing of ash,
- Drainage and sewage.

South Africa is very rich in coal resources and for this reason we rely on coal fired power stations. Eskom, a wholly state-owned electricity utility, is one of the top 13 utilities in the world in terms of generating capacity (Galt, 2009 cited in Power Plant Chemistry, p.620).

The current Eskom fleet consists of 24 power stations with a nominal capacity of 40585 megawatts (Pather, 2004 p.659). This will change in the near future with the addition of the Medupi and Kusile power stations. Eskom supplies approximately 95% of South Africa's energy requirements and more than half of the electricity used on the African continent (Pather, 2004 p.659). Of the total amount used in South Africa approximately 93% is generated by coal fired power stations (Galt, 2009 cited in Power Plant Chemistry, p.620). Coal fired power stations have always been constructed close to the coal sources. This allows for short transport distances from the coal reserve to the power stations. Unfortunately the coal is not always situated close to a suitable water source. Water is pumped long distances or alternative sources with poorer quality is used.

Eskom is the single biggest water consumer in South Africa by consuming approximately 1,5% of the consumed water the country (Eskom, 2013 and Pather, 2004 p.659). Over the last two decades Eskom have introduced a number of innovative technologies to reduce the amount of water consumed. These technologies include dry cooling, both direct and indirect cooling, desalination of polluted mine water, and technical improvements in current treatment plants (Pather, 2004 p.659).

Eskom adopted the Zero Liquid Effluent Discharge policy (ZLED) during 1987 (Pather, 2004 p.663). The ZLED policy states that all reasonable measure will be taken to prevent pollution of water resources through the establishment of a hierarchy of water based on quality (Pather, 2004 p.663). The water is extensively re-used by cascading the water from a higher to a lower quality (Pather, 2004p.663). According to the ZLED policy, ZLED is also achieved by incorporating processes into the water treatment chain that aim to produce relative low volumes of effluent. If the water cannot be re-used it needs to be treated to a quality which can be re-used. Crystallisation facilities will be incorporated once the salt load of the re-used water becomes excessive.

Part of Eskom's innovative water management strategy is to ensure the sustainable use of water resources. The specific water consumption is a key indicator for the organisations water management drive, for the individual power stations as well as for the entire company (Pather, 2004 p.663). It refers to a direct relationship between the amount of water consumed and the electricity produced. The unit is litres/kilowatt-hour (l/kWh). The specific water consumption forms part of the sustainability index (SI), which was introduced in 1996 (Pather, 2004 p.663).

The sustainability index was introduced to ensure the long term sustainability of Eskom's business in the areas of technical, financial, social and environmental issues (Pather, 2004 p.663). The use of this index allows management to monitor water use, identifying problem areas. Eskom have shown a decrease in specific water consumption from 2.85l/kWh in 1980 to 1.35l/kWh in 2009 (Pather, 2004 p.663).

Eskom recognises the fact that water is a scarce and important resource in South Africa. According to the website Eskom will endeavour in the next few years to increase the water usage efficiency. Eskom aims to bring down the specific water consumption indicator from 1.35 l/kWh in 2011 to 0.99 l/kWh in 2030 through innovative measures (Eskom, 2013). As an intermediate goal, Eskom aims to reduce the specific water consumption from 1.35 l/kWh in 2011 to 1.21 l/kWh in 2015/16 (Eskom, 2013).

In 2011 Eskom consumed 327 billion litres of water to generate approximately 44000 MW of electricity. The business as usual scenario predicts that power generation in South Africa will require 530 billion litres of water in 2030. If Eskom is successful in improvements through efficiency and re-use the value could be reduced to 270 billion litres of water in the year 2030 (Eskom, 2013). In 2011 Eskom embarked on a search for expertise and systems for integrated water and waste management (open innovation pilot). According to an open innovation pilot brochure from the Eskom website one of the goals of the challenge was to minimize the quantity of fresh water necessary to operate the industrial process.

The need exist for industry to reduce the fresh water intake on the water treatment systems and specific for this study on one of the Eskom power stations. The specific objective of the study was to present management on the Medupi Power station with a modelling tool to optimise the use of RO brine as backwash water on the UF system. This will lead to the reduction of waste stream on current water treatment plants. The outcome of the study is a modelling tool that can assist management in re-using RO brine, thus reducing the amount of fresh water required for the system and thereby satisfying the need that exist according to the innovation pilot from Eskom.

2.4 Water treatment process technology

Since the dawn of civilization communities have located near water sources. The simple reason for this is that life does not exist without water. Water is a re-usable resources and not a renewable resource. Water cannot always be used in the quality it is presented or available in, which led to various water treatment technologies being developed. The technology required for treating water depends on the original state or quality of the water as well as the required quality for the intended use of the water. Typical water treatment works that would provide water for use to communities would consist of different technologies than those required for water use in power generation. The feed source of water is usually from rivers and lakes, which will constitute water gathered and stored from run-off. This is termed surface water. The other alternative would be water in underground aquifers and boreholes, termed ground water. Typical water treatment works will consist of the following treatment steps:

- Coagulation and flocculation
- Sedimentation
- Filtration
- Dis-infection

Turbidity in water is a measure of the muddiness of water which is caused by suspended matter (USGS, 2004 p.1). According to the EPA (2000 p.1), turbidity refers to the cloudiness of water. They continue to say that turbidity has no health effects, but can interfere with disinfection and provide a medium for microbial growth.

The accepted unit for turbidity is nephelometric turbidity units (USGS, 2004 p.1). The suspended solids concentration in water is caused by colloidal particles (Anon, n.d.). Particles in water can be in suspension or they can settle out. The stability of the suspension is a result of the electrostatic forces of repulsion between particles (Degremont, 1973 p.25). Colloidal particles are almost always negatively charged in natural waters (Degremont, 1973 p.25). In order for the particles to agglomerate and form bigger particles to settle, the repulsion forces needs to be neutralised. This is achieved by dosing with chemicals to neutralise the electrostatic forces of the particles, allowing the particles to agglomerate and settle. Coagulation is the addition of a chemical to destabilise the electrostatic forces between particles, thus neutralising them and allowing agglomeration of particles.

When the particles have grown, by agglomeration, into larger particles they will start to settle out of suspension (EPA, 2004). When agglomeration of the particles has reached a point where the particles will settle, sedimentation takes place. Sedimentation operates on the density difference between the suspended particle and the suspending fluid (Sutherland, 2008 p.3). The forces of gravity works on the density difference and cause the particles to settle. Settlement area and particle size play a role in the sedimentation process. A larger particle with the same density as a smaller particle will settle faster (Sutherland, 2008 p.3). Sedimentation has been part of the human existence since people started gathering water in containers (AWWA, 1990 p.367). Without realizing it, water that was stored in a container and left undisturbed improved in quality due to sedimentation (AWWA, 1990 p.367). The sedimentation process, although in existence for a long time, did not evolve much before the need for water increased during the industrial age (AWWA, 1990 p.368).

According to Perry's Chemical Engineering Handbook, sedimentation is the removal of suspended solids particles from a water stream by gravity. Settling can be divided into 2 sections (Green and Perry, 2008 p.19 - 44):

- Clarification
- Thickening

Clarifiers are commonly used in water treatment, in potable water production and waste water treatment. The main function of clarification is to remove the relatively small quantities of suspended matter from a feed stream, producing a clear stream (Green and Perry, 2008 p.19 - 44). The main function of thickening is to increase the concentration of a large amount of suspended solids in a feed stream (Green and Perry, 2008 p.19 – 44). One of the factors influencing the sedimentation process is surface area. The clarifiers and thickeners require large construction footprints to provide this large surface area. This increases the cost of sedimentation.

When the feed water stream exits the sedimentation step, it enters the filtration step.
"Filtration is a process that consists of passing a solid-liquid mixture through a porous material (filter) which retains the solids and allows the liquids (filtrate) to pass through" (Degremont, 1973 p.45). When the suspended solids in the feed stream have a particle dimension equal to or larger than the effective pore size of the filtering media, the suspended matter will be retained on the surface of the media. This process of filtration is known as surface filtration (Degremont, 1973 p.45). When the suspended solids are retained within the pores of the media, the filtration process is known as depth filtration (Degremont, 1973 p.44). The most commonly used filtration step in potable water treatment plants is sand filters. Sand filters uses depth filtration as the process of operation and it can remove suspended solids as well as turbidity from a water stream. It uses sand as the filter medium. One of the main disadvantages of media-filtration is the inconsistency in the performance of the system (Teng, Hawlader and Malek, 2003 p.52).

After the feed stream has been clarified and filtered the water requires disinfection. Disinfection is a process designed with the primary function of reducing the pathogenic microorganisms in a water stream (AWWA, 1990 p.877).The main disinfection processes used are (Degremont, 1973 p.229):

- Chlorine and its derivatives,
- Ozone,
- Ultra-violet rays,
- Silver and bromine

After disinfection the water is pumped to reservoirs, where it is ready for distribution to the user points. Water treatment technology is improving and evolving into better, safer and more efficient technologies. This is also true with membrane technology.

2.4.1 Membrane technology

Membrane filtration is a term used to describe the removal of particulates from a feed stream utilising a membrane based process (Pearce 2007, p.24). This membrane process can be designed to remove particulates from water or it can be designed to remove dissolved solids from water. When the removal rating for suspended matter requires a value of less than 1 µm, it is termed UF (Green and Perry, 2008 p.19 - 44). When the requirement is to remove dissolved solids from water it will be RO or nano filtration (NF).

The development of a support structure, to strengthen the membrane material, was one of the driving forces to commercialise membranes. This made membranes more durable. UF membranes were first developed for process applications such as protein separation in the biotechnology industry (Pearce, 2007 p.26).

2.4.1.1 Ultrafiltration

The first large scale UF installation for municipal use was completed in 1988 (Pearce, 2007 p.27). The differences in the conventional use of sand or media filtration and the use of UF are in the filtration process. Conventional media filtration, sand or anthracite, or a combination of media, has a nominal removal rating of approximately 100µm -150 µm. According to the filtration handbook page 22, a nominal rating for a filter is an indication of the performance of the filter, determined by the filter manufacturer, expressed in percentage retention of a specified contaminant of a given size.

The nominal rating value states the particle size above which the filter will be most efficient (Lenntech, 1998 - 2013). This means that a certain percentage of the particles in the water, with the assigned removal rating, will be removed i.e. 90% of 10 µm particles (Lenntech, 1998 - 2013). This also means that 10% of the specified particle size of 10 µm can pass through the filter unit.

Although a media filter using sand can have a removal rating of 100µm -150 µm it is possible for the filter system to achieve much better removal ratings. This is due to the process called depth filtration. The particles move through the media and removal takes place due to the high difficulty of passing through the structures of the media. Sand filtration is a depth filtration process.

UF removes particles based on the size of particles exceeding the size of the pores on the surface of the filter. UF units are classified as an absolute rated filtration system. With any filtration equipment there is a point of classification above which no particle of the rated size can pass through. This point is called the particle size cut-off point. The cut-off point refers to the largest particle, usually by measuring the diameter, which can pass through the filter (Sutherland, 2008 p.21).

When the pore size of the filter is exact and consistent the cut-off point can be called absolute rated (Sutherland, 2008 p.21). The absolute rating of a filter can also refer to the absolute size of the particle which will be removed by the filter (Lenntech, 1998 - 2013). Theoretically, no particles larger than the absolute rating of the filter should pass through.

UF is a surface filtration process. According to Dr. Christian Maletzko from BASF SE in Germany, one of the main drivers for selection of membrane filtration in the municipal application is the ability of the membrane to provide a continuous disinfection barrier. The removal of viruses requires a membrane with a pores size of less than 20 nm and a narrow pore size distribution (Maletzko, 2009 p.22). The Norit XIGA membranes used for the Medupi power station have a nominal pore size of 10 nm and a maximum pore size of 20-25 nm (Norit, 2006 p.4).

The UF membrane used on the Medupi power station is made out of hollow fibre capillaries, 0.8 mm inside diameter (Norit, 2010). UF capillaries consist of a protection layer, support layer and a separation layer (Maletzko, 2009 p.22). The separating layer can be seen in **Figure 4:** Cross section of module fibre.

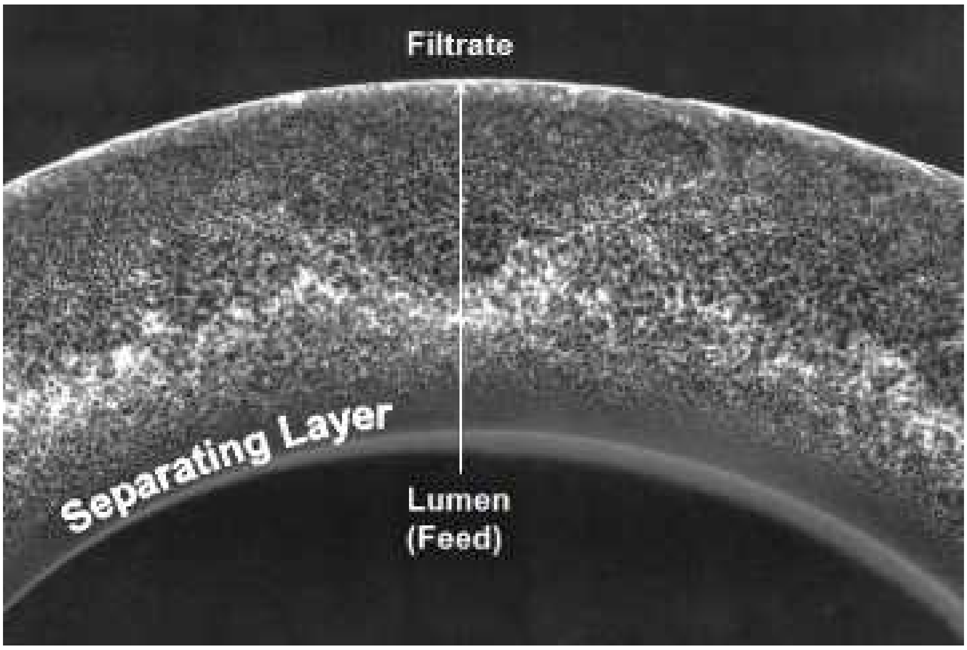


Figure 4: Cross section of module fibre

The pore size on the inside of the hollow fibre membrane is much smaller than on the outside of the membrane. This feature reduces the possibility for foulants being lodged within the pore structure (Byrne, 2002 p.228). The larger pore size support layer reduces the restriction of water to permeate through the hollow fibre membrane, thus reducing the pressure drop across the membrane (Byrne, 1995 p.228). The final result is higher permeate flux rates and lower feed pressures.

As the filtration process continues and suspended solids accumulate on the separation layer, also called the skin layer (Byrne, 2002 p.228), higher feed pressure will be required for the process. This leads to increased pressure drop across the hollow fibre membrane. The pressure required to move the water from the feed side to the permeate side in a dead end UF filtration system is called the trans-membrane pressure (TMP) (Lenntech, 1998 - 2013). In order for the membrane to be operated effectively the separation layer needs to be strong enough to withstand the operating conditions and high TMP's.

Incorrect operating conditions can lead to fibre breakage. This is when the hollow fibre capillaries break off from the module potting material and the integrity of the module is compromised. The construction of the capillaries of a UF module is carefully considered to reduce the amount of capillary breakages. A standard in situ test using air is conducted to test the integrity of installed modules. These tests are also performed when the modules are removed from the system. Special equipment is required for conducting the test in the workshop environment, while very little additional equipment is required to conduct the test in-situ.

The principle of an air integrity test is based on the fact that a wetted UF module will pass very little air by diffusion, while a broken fibre will pass a substantial amount of air. The test takes on various formats. Some systems include automatic air integrity tests that will pressurise the system and check for any pressure decay, due to air escaping from broken fibres. Other test can be by visual inspection by removing the top connector of the module and checking for any air bubbling out of the area where the broken fibre is located. UF module construction needs to allow for air integrity testing to be conducted as well as the repair of any broken fibres (Maletzko, 2009 p.22). Repairing a broken fibre includes plugging the hole with a steel pin.

During normal operation of a UF system periodic cleaning operations are conducted to recover the membrane flux and return the operating parameters to the normal level. This includes backwashing, chemical enhanced backwashing (CEB) and air scouring of the membrane. The air scouring process introduces air into the flushing stream to increase the turbulence created and improve the efficiency of the cleaning step.

The backwashing step is used to remove accumulated contaminants from the membrane surface (Anon, n.d. p.9). During the backwash procedure the direction of the flow through the hollow fibre capillaries is reversed. The force and direction of flow removes the accumulated solids from the membrane surface and wash them to drain (Anon, n.d. p.9). This process is conducted on a frequent basis, which is different from application to application. The time between backwash operations could range from 15-60 minutes a duration of only a few seconds (Anon, n.d. p.9).

The UF system also uses chemicals combined with a short soak period to clean off matter which does not get removed by backwashing. Some systems use chlorine during the backwash step to assist in removing solids from the membrane surface, provide pathogen inactivation, and biofouling control (Anon, n.d. p.9). Other chemicals like acid and caustic is also used to improve the efficiency of the backwash procedure (Anon, n.d. p.9).

Material selection is vital to the application, life span and durability of the UF module. According to an article by Graeme Pearce on membrane selection, the membrane making process should control the surface characteristics and the supporting substructures of the membrane during production. This means the material and fabrication process should promote a smooth surface finish with a very narrow pore size distribution while maintaining a very solid supporting layer of the final product.

Polymers used in the production of UF membranes should have very good mechanical properties by providing burst and collapse strength with reasonable flexibility (Pearce, 2007 p.35). Flexibility is very important for applications where air scouring will be used as part of the daily or weekly cleaning regime. Very rigid material fibres will tend to break from the air scouring process.

Another important aspect of a membrane polymer is that it needs a good chemical resistance, tolerance to a wide pH range and high chlorine concentration tolerance (Pearce, 2007 p.35). This will allow rigorous cleaning regimes to be applied where the application requires it.

2.4.1.2 UF membrane material of construction

Various materials have been used in the construction of UF membranes. These materials include cellulose acetate (CA), polyvinylidene fluoride (PVDF), polyacrylonitrile (PAN), polypropylene (PP), polysulfone (PS), polyethersulphone (PESU/PES) and other polymers (Anon, n.d. p.4). The range of materials spans from hydrophilic polymers such as CA, to hydrophobic polymers such as PP. The material polymer of PVDF, PAN, PS and PESU is hydrophobic, but can be altered to moderately hydrophilic membranes with the additions of additives to the polymer process (Pearce, 2007 p.35).

Some advantages of CA membranes are (Pearce, 2007 p.36):

- Good permeability and rejection characteristics of the membrane and
- Good chlorine tolerance

The disadvantage of CA as membrane material is that it is susceptible to hydrolysis and it has limited pH variation resistance (Pearce, 2007 p.35).

Other materials like PESU, PVDF, PS, and PAN have the advantage that the polymer properties can be modified with polymer blend through additives and these materials provide good membrane strength and permeability (Pearce, 2007 p.35).

It must be noted that PVDF material, apart from the fact that it can be altered to be more hydrophilic material, it is not commonly done due to the hydrophilic additives leading to macrovoid formation (Pearce, 2007 p.35). PVDF material is regarded as having the best flexibility while PESU is regarded as the best polymer for blending and provides the membranes with the best UF rating (Pearce, 2007 p.35).

Some of the disadvantages of PP material are (Pearce, 2007 p.35):

- Limited blend capacity
- Susceptibility to oxidation

The membranes supplied in the early days of membrane filtration were mostly made of CA, PS, and PP, but the current market typically uses PESU and PVDF (Pearce, 2007 p.35). PVDF and PESU membranes are known as the two polymer classes with the best strength characteristics (Maletzko, 2009 p.24). The UF membranes used at Medupi power station is made of the material polyethersulphone (PESU). According to DR. Christian Maletzko (2009 p.22), Engineering plastics BASF, PESU membranes combine high removal efficiency, due to a fine pore-size rating and narrow pore size distribution, with excellent permeability.

2.4.1.3 UF modes of operation

UF systems can operate in 2 configurations. One of the configurations is inside out hollow-fibre configuration, which means the feed water enters the capillaries on the inside (Anon, n.d. p.6). The filtrate goes through the capillary and the particulates are retained on the inside. The filtrate stream exits the hollow fibre on the outside.

When a backwash procedure is required the flow direction will be reversed. This entails water entering the membrane from the filtrate side and exits on the feed side, washing away the particulates retained on the inside. The other UF system configuration is the outside in hollow-fibre configuration which means the feed water enters the capillaries on the outside of the hollow fibre capillaries (Anon, n.d. p.6). The filtrate goes through the capillary and the particulates are retained on the outside. The filtrate stream exits the hollow fibre capillary from the inside.

The UF system is also operated in 2 operational modes. The first mode is called the deposition mode and refers to a system that operates with only one feed stream and one filtrate stream (Anon, n.d. p.7). This mode of operation is commonly known as dead-end filtration. In the deposition mode the accumulated solids are retained and kept on the membrane surface by the hydraulic forces acting on them from the water passing through the membrane (Anon, n.d. p.7). The second operational mode is called the suspension mode. In this operational mode a scouring force using water or air is applied parallel to the membrane surface during the production of the filtrate in a continuous or intermittent manner (Anon, n.d. p.7). This mode is commonly called the cross-flow mode. The main objective of operating in the suspension mode is to minimize the accumulation of suspended matter on the surface on the membrane, thus reducing the possibility of fouling (Anon, n.d. p.7).

The main objective of the UF system is to remove particulate matter from the water, as pre-treatment to a RO system. The membrane also removes bacteria and some viruses from water. The specific membrane for the Medupi plant claims a Log 4 virus removal and a log 6 bacteria removal (Norit, 2010).

UF technology is considered to be an excellent technology for removing contaminants from a water source. The downside to UF technology is the waste stream generated. By requiring a hydraulic clean, or backwash as commonly known, a waste stream is generated. Depending on the raw water quality this waste stream can be up to 15% of the feed flow. The UF system sizing requires additional capacity to provide for the volume requirement of the backwash as well as the down time during the membrane backwash activity.

2.4.1.4 Reverse osmosis

Reverse osmosis technology is used to remove dissolved solids from water. The dissolved solids can be (Byrne, 2002 p.1):

- Salts;
- Organics, such as sugar
- Dissolved oils.

The removal mechanism of RO systems is different to the removal mechanism of filtration. Physical holes do not exist in the RO membrane. It is more likely that water molecules diffuse between the structures of the membrane polymer by bonding through segments of the polymers' structure (Byrne, 2002 p.3). The dissolved salts and organics are retained on the concentrate side of the membranes.

RO is a process of separation where the feed stream entering the membrane is separated into a clean water stream, also called the permeate stream and another stream known as the concentrate stream. The concentrate stream is also called the brine stream. As the water passes across the membrane surface the water permeates the membrane.

The water molecules permeating the membrane leave behind the solids. This results in a concentration of salts in the brine side. The permeate stream for the RO system is used in the process while the brine stream is discarded to waste. The brine stream typically accounts for 20 – 25% of the feed stream.

2.5 Life cycle costing (LCC)

The specific objective of this study was to present management of the Medupi Power station with a modelling tool to optimise the use of RO brine as backwash water on the UF system. Recognized reference material such as the international standard for life cycle costing ISO 15686-5 was used extensively in the formulation of the input steps for the completion of the LCC as part of the modelling tool.

According to ISO 15686-5 (2008, p.viii) "*Life-cycle costing is relevant at portfolio/estate management, constructed asset and facility management levels, primarily to inform decision making and for comparing alternatives*". Furthermore ISO 15663-2 defines LCC as "*the process of evaluating the difference between the life cycle costs of two or more alternative options*".

The LCC should cover a defined list of cost over the physical, economic or functional life of the asset, over a defined period of time (ISO 15686-5, 2008 p.5). **Figure 5:** Whole life costing and LCC elements below illustrates the costs that should be included in LCC and the wider cost that should be referred to as whole life costs (WLC).

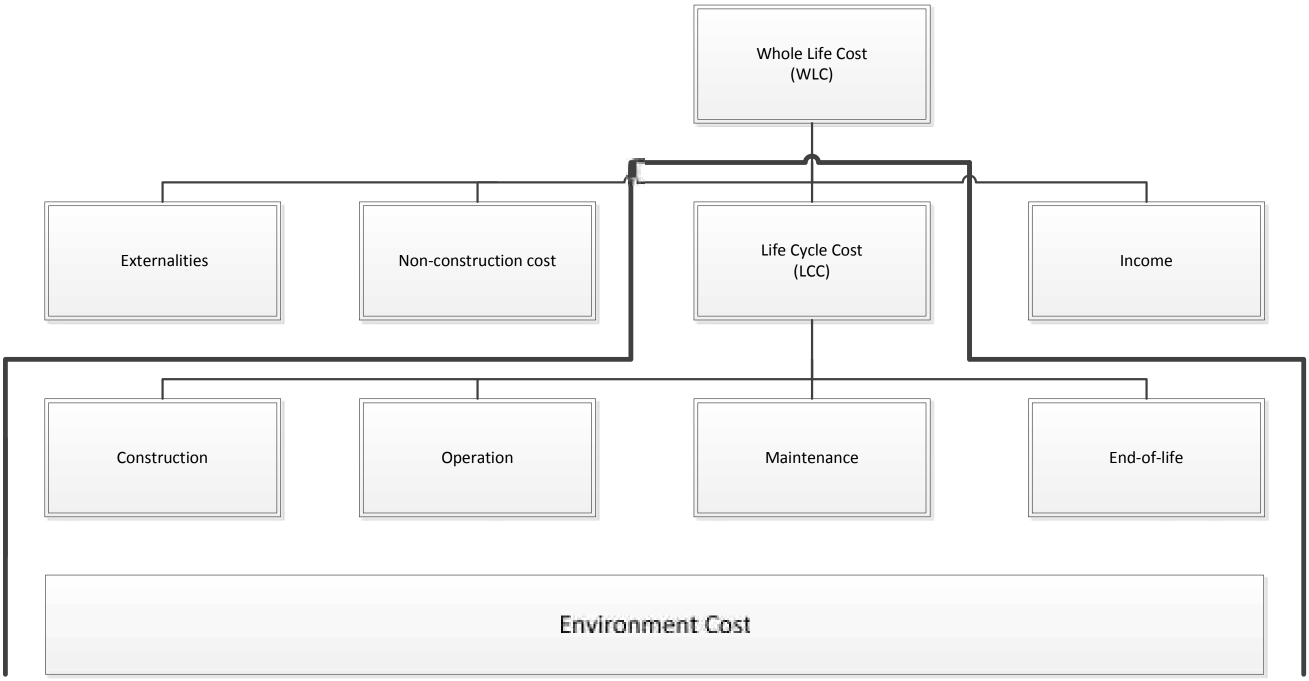


Figure 5: Whole life costing and LCC elements

From **Figure 5:** Whole life costing and LCC elements the following four phases or elements of the LCC are identified:

- Construction phase

- Operation phase
- Maintenance phase
- End-of life phase

Other publications differ slightly in the definition and scope of the LCC phases. According to Systems engineering and analysis, fourth edition (Blanchard and Fabrycky, 2006), the four phases include:

- Design and development cost
- Construction and production cost
- Operation and maintenance cost
- Retirement and material cost

2.5.1 Phases of the LCC

The construction phase is also referred to as the project investment and planning phase (ISO 15686-5, 2008 p.8) or the acquisition phase (Schuman and Brent, 2007). During the acquisition phase the emphasis is on implementing a technology within the boundary limits of an approved budget and time frame and conformance to technical specifications (Schuman and Brent, 2007). According to Schuman and Brent, the acquisition phase consists of conceptual design, preliminary design, detailed design and construction.

The operation phase is where the system is operating to the design parameters and requirements. Operationally the system will achieve the deliverables as per the design.

The maintenance phase will commence simultaneously with the operational phase. During this stage the system will require maintenance, both planned and unplanned. The operational and maintenance phases are usually the longest phases in the LCC (ISO 15686-5, 2008 p.8). According to the ISO 15686-5 the LCC should include documentation of the reliability plans, maintenance plans and estimates for major repairs or replacement on the systems. For the water treatment system in the study these would include the costs for replacing the membranes. This is deemed to be a major replacement and forms a significant part of the operational and maintenance cost.

2.5.2 Decisions influence by LCC

The LCC influence the decision making by management by supplying comparative results on different scenarios with relevant cost included. The LCC assist with the following decisions (ISO

15686-5, 2008 p.10):

- Evaluation of different investment scenarios. This is during the investment planning stage.
- Choices between alternative designs for the entire facility or part of the facility. For this study the LCC provides alternatives and comparisons on part of the design. This is referred to as detailed element level.
- Choices between alternative components with the same functionality and acceptable performance. This is referred to as detailed component level.
- Estimate of future cost for budgetary purposes for the evaluation of the acceptability of an option on the basis of cost.

2.5.3 Different levels of analysis

Different levels of analysis of the LCC include:

- Strategic level
- Systems level
- Detail level

The strategic level of the system includes the evaluation of several strategic options in the acquisition of an asset. Some of the activities of the strategic level include (ISO 15686-5, 2008 p.12):

- Definition of the performance and functional requirements. This can be in the form of a user requirement specification developed for the detail planning.
- Design life and period of analysis for asset and LCC.
- Priorities and requirements on return on investment.
- Preliminary design and LCC assumptions.
- Consideration of whole life cycle cost (WLC).

During the strategic level of the system, assumptions are made, which must be noted for future reference. Technical assumptions must be made to assist with the completion of the activity LCC. These assumptions will be refined as the process progress to detailed design.

The next level is the system and detailed level. During this level the LCC is incorporated into design appraisals (ISO 15686-5, 2008 p.12). The planning and design phase offers the biggest opportunity to influence the post – construction cost. **Figure 6:** Scope of influence: LCC saving over time indicates the decline in potential for improvement over time. As the project moves through the phases, the potential for improvement is reduced.

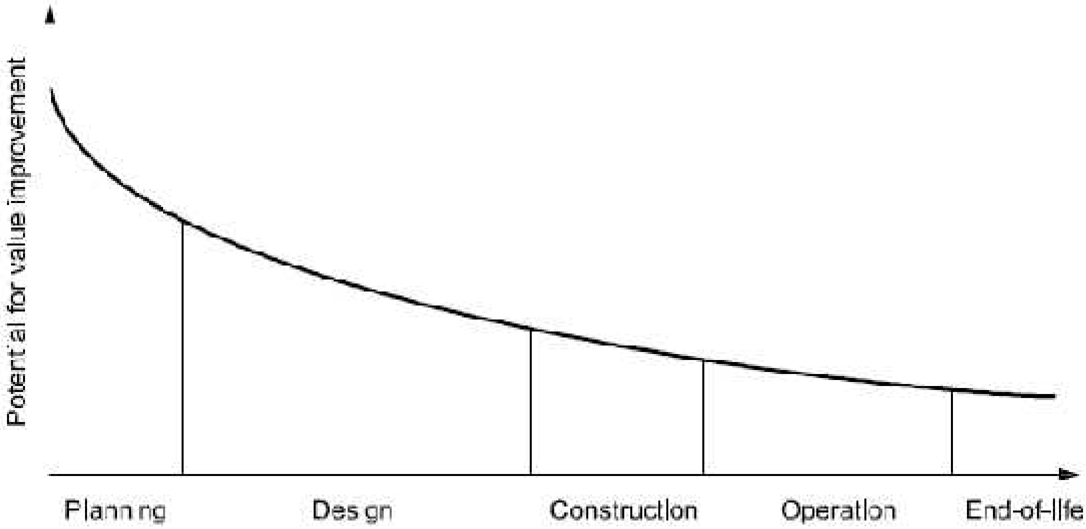


Figure 6: Scope of influence: LCC saving over time (ISO 15686-5:2008 p.12)

According to ISO 15686-5, up to 80% of the operation and maintenance cost can be influenced in the first 20% of the design process. This point is also illustrated by studying the cost of activities. From **Figure 7:** Activities affecting LCC it is illustrated that the initial phases of the life-cycle account for the bulk of the cost. As illustrated approximately 60% of the projected life cycle cost is committed by the system planning function and conceptual design stage. Management must have the correct information, timeously, during the planning and design phase to influence cost in later phases.

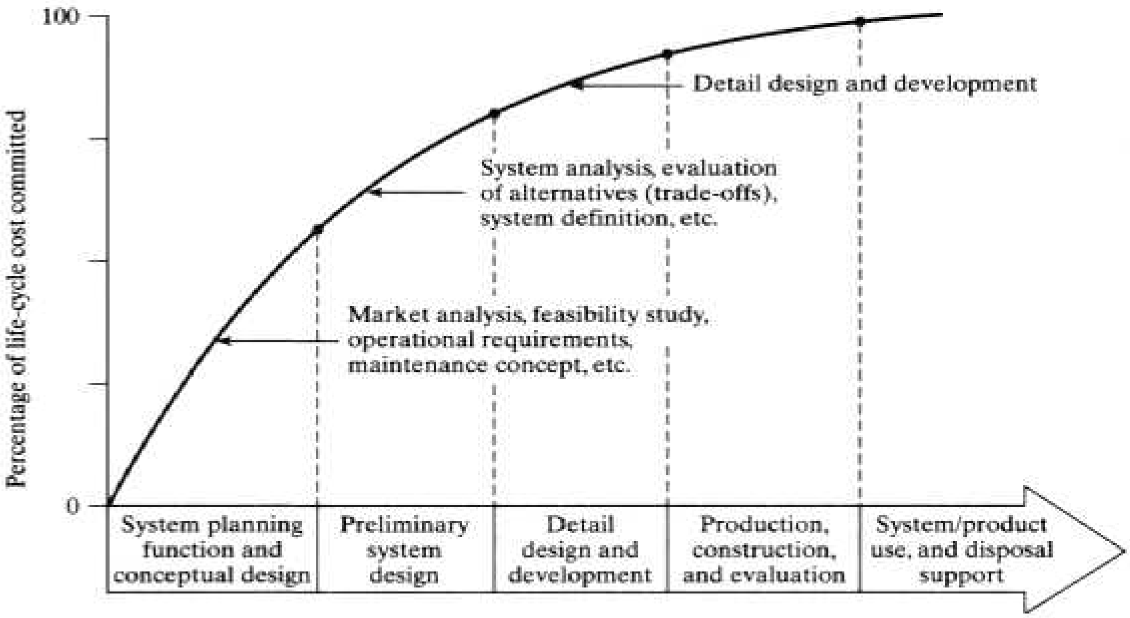
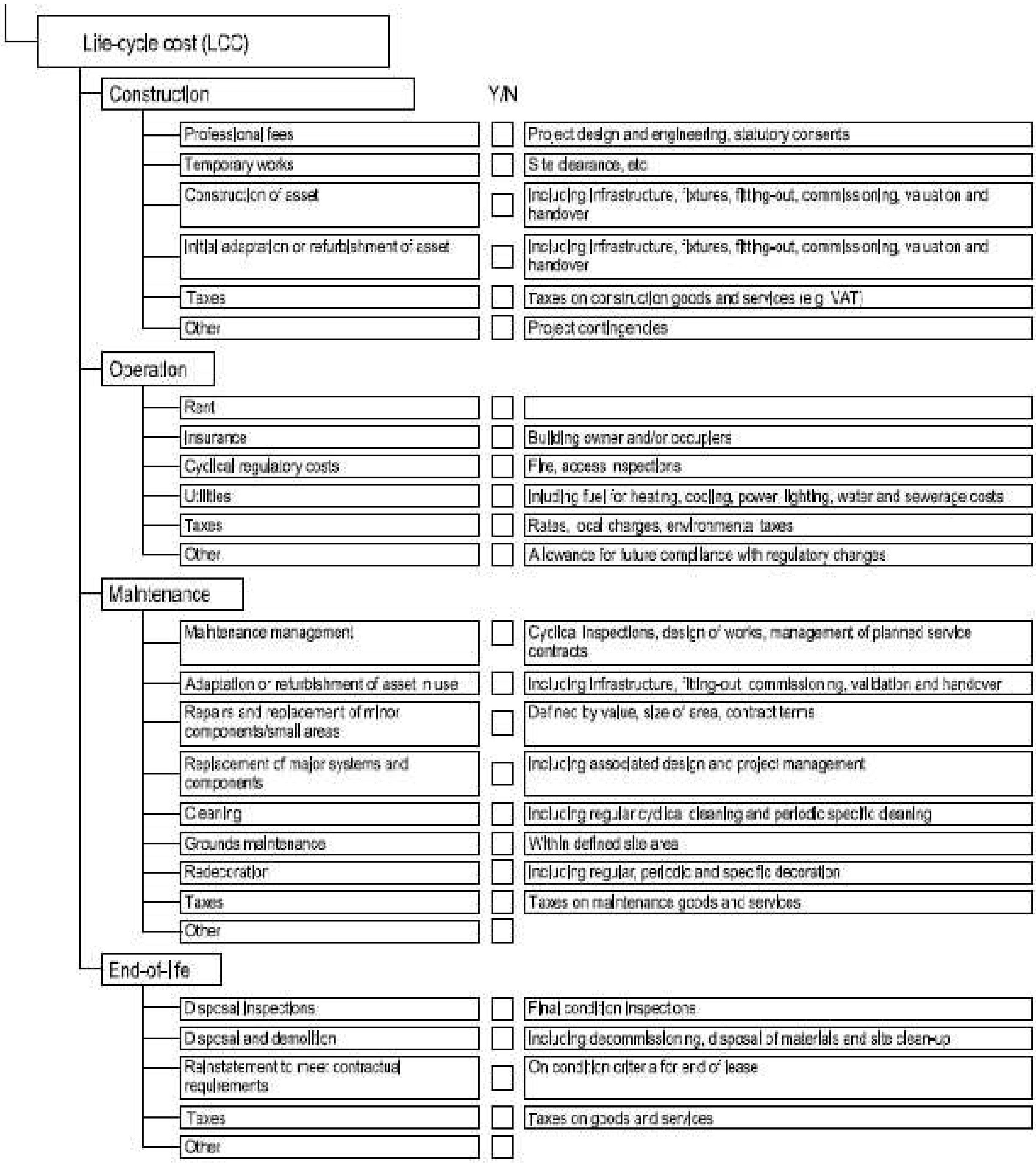


Figure 7: Activities affecting LCC (ISO 15686-5:2008 p.)

2.5.4 Classification of costs

The classification of costs is required to define the scope of the LCC. **Figure 8:** Typical classification of costs indicates a list of typical cost as outlined in the specification ISO 15686-5:2008. The list below is non-exhaustive and is only for generic purposes. Each LCC must have a list of defined costs as per the specific project or activity.



Life-cycle cost (LCC)

	Y/N	
Construction		
Professional fees	☐	Project design and engineering, statutory consents
Temporary works	☐	Site clearance, etc
Construction of asset	☐	Including infrastructure, fixtures, fitting-out, commissioning, valuation and handover
Initial adaptation or refurbishment of asset	☐	Including infrastructure, fixtures, fitting-out, commissioning, valuation and handover
Taxes	☐	Taxes on construction goods and services (e.g. VAT)
Other	☐	Project contingencies
Operation		
Rent	☐	
Insurance	☐	Building owner and/or occupiers
Cyclical regulatory costs	☐	Fire, access inspections
Utilities	☐	Including fuel for heating, cooling, power, lighting, water and sewerage costs
Taxes	☐	Rates, local charges, environmental taxes
Other	☐	Allowance for future compliance with regulatory changes
Maintenance		
Maintenance management	☐	Cyclical inspections, design of works, management of planned service contracts
Adaptation or refurbishment of asset in use	☐	Including infrastructure, fitting-out, commissioning, validation and handover
Repairs and replacement of minor components/small areas	☐	Defined by value, size of area, contract terms
Replacement of major systems and components	☐	Including associated design and project management
Cleaning	☐	Including regular cyclical cleaning and periodic specific cleaning
Grounds maintenance	☐	Within defined site area
Redecoration	☐	Including regular, periodic and specific decoration
Taxes	☐	Taxes on maintenance goods and services
Other	☐	
End-of-life		
Disposal inspections	☐	Final condition inspections
Disposal and demolition	☐	Including decommissioning, disposal of materials and site clean-up
Reinstatement to meet contractual requirements	☐	On condition criteria for end of lease
Taxes	☐	Taxes on goods and services
Other	☐	

Figure 8: Typical classification of costs (ISO 15686-5:2008 p.)

For the purpose of the study the following cost components will be evaluated and incorporated into the management model:

- Construction cost – Fabrication of system including component costs, testing and commissioning of system
- Operation of system – Utilities and consumable costs of system
- Maintenance costs – Cleaning of system

2.6 Modelling life cycle costs

The LCC is an accounting structure containing terms and factors which enable the estimation of a system component and equipment cost (NSW Treasury, 2004 p.4).

According to TAM01-10 (NSW Treasury, 2004 p.4), a LCC model should:

- Represents the characteristics of the system being analysed and the intended use. It should also identify and consider maintenance concepts and limitations and constraints.
- Be comprehensive and include relevant factors.
- Be easy to understand and use for decision making.
- Provide independent evaluation of LCC elements.

2.6.1 Methods of analysing cost data

There are different methods in analysing costs data.

2.6.1.1 Engineering cost method

This is method is also known as the activity based costing (ABC). This method is used where a detailed and very accurate capital and operational cost data is required. It involves the direct estimation of costs for each activity or cost element by examining the system component by component (NSW Treasury, 2004 p.5). This requires full cost visibility and traceability of all costs back to the activities or components (Blanchard and Fabrycky, 2006 p.595). The deliverable from the engineering cost procedure is a very accurate and detailed cost estimation which can assist management in decision making.

2.6.1.2 Analogous cost method

The analogous cost method is a method utilizing historical data from components for the cost estimation in terms of analogous size, technology, use patterns, and operational characteristics (NSW Treasury, 2004 p.5). The results from the analogous method provide the same level of detail as the engineering cost method (NSW Treasury, 2004 p.5).

2.6.1.3 Parametric – Based Costing

This is the most general approach for cost estimation and is applied to system components with very little or known historical data (Blanchard and Fabrycky, 2006 p.594). These cost estimates are basically rules of thumb (Blanchard and Fabrycky, 2006 p.594).

2.7 Conclusion of literature review

The literature review discussed the elements of study as detailed in the title of the dissertation with the aim of creating understanding of the following:

- Scarcity of water, in our country.
- Current situation of water consumption in different sectors including the power industry as well as the need to re-use the precious resource.
- Water treatment technologies.
- Life cycle analysis.
- The requirement and need for management in industry, to have the required information to make enlightened decisions that benefits the industry as well as the environment.

3 Empirical Review

3.1 Structure of empirical review

The specific objective of the study was to present the management team of the Medupi Power station with a modelling tool to optimise the use of the brine from the RO systems as backwash water on the UF system. The modelling tool consists of a technical component where the process parameters are evaluated and a cost component where the LCC will be completed. The modelling tool can be used for new systems, still in design phase and existing systems. As can be seen from **Figure 6**: Scope of influence: LCC saving over time (ISO 15686-5:2008 p.12), the potential for improvement of the LCC deteriorates with time and thus, the most beneficial application of the modelling tool will be at the planning stage of a project.

This chapter discuss the basic technical description as well as technical calculation on the design and sizing of the UF system used on the Medupi power station. The following operational parameters are discussed:

- Basic operation of UF system
- Backwash requirement of UF system
- CIP of UF system
- Chemical consumption of UF system
- CEB of UF system
- Scaling calculation

Figure 10: Flow sheet of the optimisation management model (Medupi), illustrates how the modelling tool should be completed step by step.

Before the modelling tool can benefit any project or potential project, the management team of the project or site is required to identify and commit that the need exist to optimise or improve the current situation. This is where, in a business environment, leadership is required and a good realization technique can be implemented. **Figure 9:** Process flow of need identification to modelling tool implementation illustrates the flow of proceedings from the realization technique, need identification to the implementation of the modelling tool.

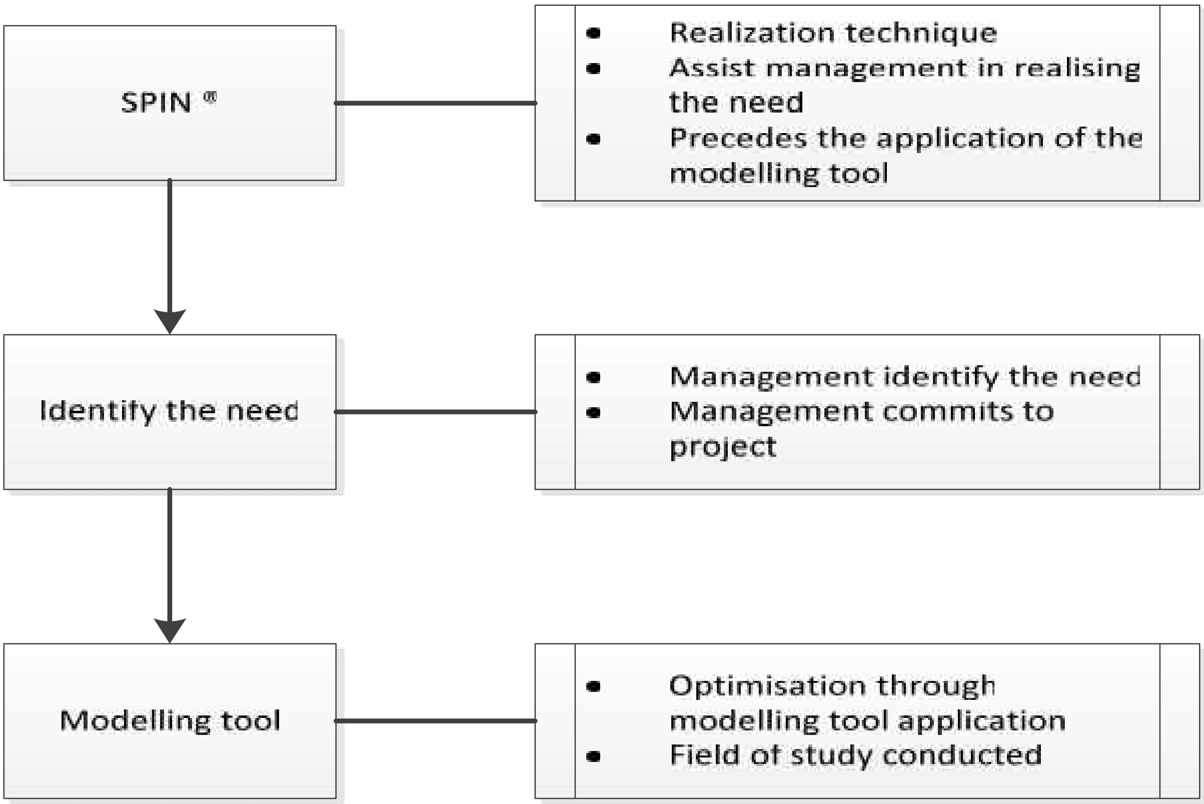


Figure 9: Process flow of need identification to modelling tool implementation

During the planning stage of a new constructed asset, like a power station, decision makers will be faced with the daunting task of deciding on technologies for the future operation. These decision makers will be management staff of the company or project. The need and requirement of the project must be clearly defined. **Figure 10:** Flow Sheet of the Optimisation Management Model (Medupi), assist in supplying the correct and relevant information to management for informed decision making. Before the model can be used the need must be clearly defined.

This is the point where principles, found in the book by Neil Rackham called Spin selling can be applied. Neil Rackham and his company developed a Model called The Spin® Model to assist young sales professionals to achieve higher sales volumes. The model assist the seller in asking different questions, which leads the customer to realise the implied needs, which with further questioning can be changed into an explicit need. **Appendix 4:** The Spin® Model flow sheet illustrates the procedure. The relevance of the Spin Model is illustrated with **Appendix 3:** Presentation slides, which was used with customers in assisting in highlighting the explicit needs. It can be also illustrated in the following way:

Management at Medupi power station can be approached and can be asked the following situational questions, which form part of the Spin® Model:

- How much water will be wasted in the form of brine reject from the RO unit?

This is a situational question, which is enquiring about the existing customer situation. These questions clearly define the current situation. This could be for a new project or it could be for an existing site.

This will lead to problem questions being asked:

- What will be done with the waste water?

Problem questions are questions about what problems or difficulties the customer face or will face, with the current situation. These questions lead the customer to the realization of these challenges. Management will see the implied need, in this case that the amount of waste water is a problem.

At this stage implication questions will be asked like:

- What effect will this waste water have on costs?
- What effect will the waste water have on the environment?

Implication questions are questions that built up the seriousness of the challenge. These questions are followed by Need-payoff questions like:

- What will be the benefit in re-using the waste water?

This leads management to realize the explicit need, which is a clear statement from management on what they want and desire. At this point in time managements' realization on the need is where the starting point will be according to **Figure 10:** Flow sheet of the optimisation management model (Medupi) step 1.

Realization for the Medupi management team is that the following need and requirement exist:

- Reduce the intake of raw water
- Reduce waste discharge
- Increase water re-use

After the need have been identified by management, a process is started to address the need. Step 2 of the flow sheet is the identification of how to address the need. This includes identifying the area of improvement.

Step 3 is the technical evaluation step. This step defines the process parameters and is the final step in identifying the area of potential optimisation.

Step 4 includes all the technical calculations required to define the current and the optimised situation. This is where the engineers will assist in supplying correct engineering data as input parameters to the LCC.

Step 5 includes the identification of the cost parameters which will be included in the LCC. The reason for this step is that there is a requirement to clearly define only costs that will change from the current to the optimised situation. If the cost parameter does not have a significant difference in the 2 studied situations then there is no need to include it in the LCC.

Step 6 includes the LCC completed for the current situation as well as the optimised situation.

Step 7 includes the comparison of the LCC. This is the step where the output of results from the modelling tool will become available.

Step 8 is the final decision by management based on the current and relevant information. For the purpose of this dissertation step 8 will be the findings and results as well as the discussion of the results.

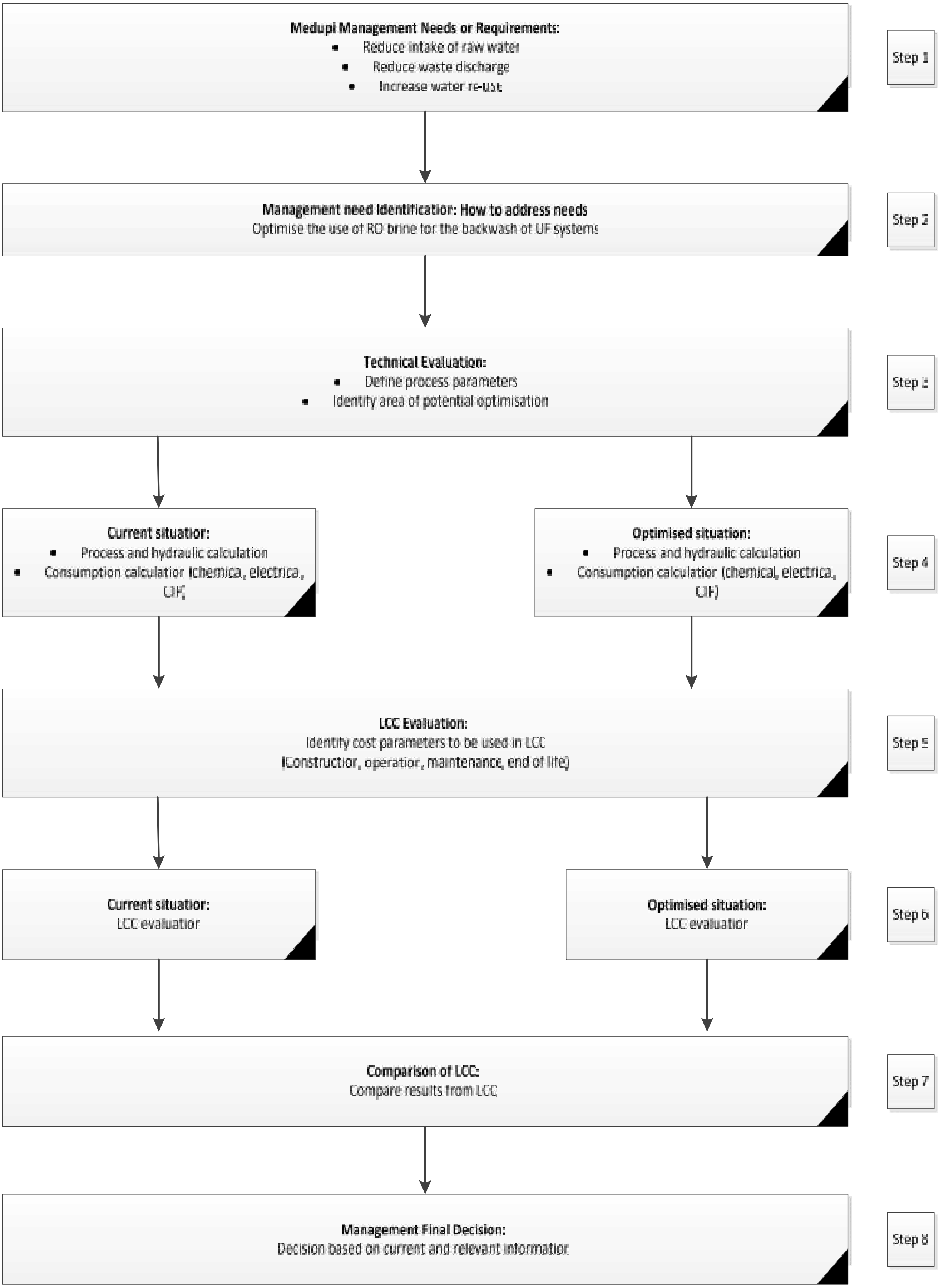


Figure 10: Flow Sheet of Optimisation Management Model (Medupi)

3.2 Technical description – Basic operation of UF system

This relevance of this section is to familiarise the reader with the basic operation and technical calculations required on UF systems. This section includes:

- Technical description of UF systems
- Backwash requirement of UF systems
- Clean in place (CIP) requirement of UF systems
- Chemical consumption of UF systems
- Scaling calculation

3.2.1 Basic UF operational calculations

Hydraulic design of a UF system is based on flow per time unit per available filter area, known as flux rate. The flux rate is expressed in l/h/m^2. The industry norm is to express the flux rate as lmh. The surface area refers to the total surface area of the UF membrane capillaries and is made available by the membrane supplier.

UF membrane suppliers have tested the membranes in different conditions and recommend design flux rates for each application. Calculation to determine the surface area required for the UF system is:

$$Surface\ area\ (A_T) = \frac{net\ production\ flow\ rate\ (Q_N)}{net\ flux\ rate\ (F_N)}$$

Equation 1: $$A_T = \frac{Q_N}{F_N}$$

With:

- A_T in m^2
- Q_N in in litres / hour (l/h)
- F_N in litres per hour per area (l/h/m^2)

When the surface area is known the number of membranes can be selected by the following formula:

$$Number\ of\ membranes\ (M_T) = \frac{Surface\ area\ (A_T)}{Surface\ area\ of\ membrane\ (A_M)}$$

Equation 2: $$M_T = \frac{A_T}{A_M}$$

With:

- M_T as a quantity
- A_T in m^2
- A_M in m^2

After calculating the number of membranes required, the number of pressure vessels required can be calculated. For the selected membrane at the Medupi Power station the total number of membranes per pressure vessel is 4, thus:

$$Number\ of\ pressure\ vessels\ (P_T) = \frac{Number\ of\ membranes\ (M_T)}{4}$$

Equation 3: $$P_T = \frac{M_T}{4}$$

With:

- P_T as a quantity
- M_T as a quantity

UF systems, normally, is skid based, meaning that the pressure vessels is mounted on a steel frame forming a skid. When the UF system caters for a high net production flow rate it is possible to have more than one skid of pressure vessels. According to the supplier of the Medupi membranes the maximum number of pressure vessels which can be installed on one skid is 40.

The number of skids is calculated in the following way:

$$Number\ of\ skids\ (S_T) = \frac{Number\ of\ pressure\ vessels\ (M_T)}{40}$$

Equation 4: $$S_T = \frac{M_T}{40}$$

With:

- S_T as a quantity
- M_T as a quantity

The UF feed flow is calculated in the following way:

$$Feed\ flow\ (Q_{FD}) = Gross\ Flux\ (F_G) \times Surface\ area\ (A_T)$$

Equation 5: $Q_{FD} = F_G \times A_T$

With:

- Q_{FD} in in litres / hour (l/h)
- F_G in litres per hour per area (l/h/m^2)
- A_T in m^2

The recovery on the UF system is calculated in the following manner:

$$Recovery = \left[1 - \left(\frac{Backwash\ volume\ (B_V)}{Net\ production\ flow\ (Q_N)}\right)\right] \times 100$$

Equation 6: $R_C = \left[1 - \left(\frac{B_V}{Q_N}\right)\right] \times 100$

With:

- R_C in percentage
- B_V in litres / hour (l/h)
- Q_N in in litres / hour (l/h)

The UF membrane supplier normally has application software which assists the design engineer with the design of the UF system.

3.2.2 Backwash requirements of a UF system

UF membranes are physical barriers which remove particulate matter from the feed water stream where it accumulates on the inside of the membrane capillaries, as in the case of the Norit membrane. Accumulation of particulate matter on the inside of the capillaries creates a pressure differential across the membrane. When left unattended the accumulation of particulate matter can create an increased differential pressure which can lead to a loss in filtrate production.

To negate the effects of solid accumulation on the membrane, UF systems require a periodic backwash. Backwash operation can be initiated on a differential pressure setting or alternatively on a time basis. The latter is the preferred method to initiate the backwash operation. Backwash operation entails reversing the flow through the UF membrane to remove the accumulated particle matter and flush it to drain. Flow reversal means the water is pumped from the filtrate side through the membrane out to drain. UF systems utilises filtered water to conduct a backwash. The reason for this is that the filtrate side of the membrane is the clean side and if feed water is used the clean side will be contaminated.

Frequency of backwash and the amount of water used is application specific. Typical frequencies include every 20-60 minutes with a usage of water of 10-25%. Water required for the backwash must be produced by the UF system. The recovery on a membrane system is the amount of water available for other process users after the unit's loss was deducted. The loss of water on the UF system is the backwash water required for cleaning.

The recovery is a function of the feed water quality. When the quality of the feed water is very good fewer solids accumulate on the inside of the membrane capillaries. The aim of every system is to have a recovery as high as possible.

Backwash procedure is a periodical procedure which is only conducted on one skid at a time. For the calculation of the backwash flow rate it will be required to calculate the surface area of each skid (A_S). The equation for calculating the surface area of each skid is:

$$Surface\ area\ of\ skid\ (A_S) = \frac{Surface\ area\ (A_T)}{Number\ of\ skids\ (S_T)}$$

Equation 7: $A_S = \frac{A_T}{S_T}$

With:

- A_S in m^2
- A_T in m^2
- S_T as a quantity

Backwash is conducted by a separate pump, called the backwash pump, drawing water from the filtrate tank. Flow rate of the backwash operation is determined by calculation. The supplier of the UF membranes have tested and documented the optimum flux rate to achieve the most efficient removal of accumulated solids. The equation to calculate the backwash flow rate is:

$$Backwash\ Flow\ Rate\ (Q_{BW}) = Backwash\ flux\ (F_{BW}) \times Surface\ area\ of\ skid\ (A_S)$$

Equation 8: $Q_{BW} = F_{BW} \times A_S$

With:

- Q_{BW} in in litres / hour (l/h)

- F_{BW} in litres per hour per area ($l/h/m^2$)
- A_S in m^2

When the backwash procedure is not successful in removing the particulate matter and restoring the differential pressure to original parameters a chemical enhanced backwash (CEB) is required. CEB entails conducting a backwash with chemicals added to the backwash streams. These chemicals enter the membrane and a soak period is initiated. When the soak period is completed the system is backwashed with filtrate water and the contaminants are flushed to drain.

CEB chemicals include acid (sulphuric acid or hydrochloric acid), sodium hydroxide and sodium hypochlorite. During the CEB operation the membrane is soaked with a low pH, using the acid dosing. After the low pH clean the membrane is soaked in a high pH and high chlorine soak using sodium hydroxide and sodium hypochlorite.

CEB chemicals are introduced into the membrane by the backwash pump system. During the introduction of chemicals into the membrane the backwash flux rate is reduced to 50% of the normal backwash flux rate. This means that the CEB backwash flow rate (Q_{CEB}) is 50% of the normal backwash flow rate (Q_{BW}).

The flow rate of the dosing pumps is calculated as follows:

Sodium hydroxide dosing station:

$$Sodium\ hydroxide\ dosing\ flow\ (Q_{SH}) = \frac{(dose\ concentration\ (D_{SH}) \times CEB\ backwash\ flow\ rate\ (Q_{CEB})}{Sodium\ hydroxide\ concentration\ (SH_{CN})}$$

Equation 9:
$$Q_{SH} = \frac{(D_{SH} \times Q_{CEB})}{SH_{CN}}$$

With:

- Q_{SH} in litres /hour (l/h)
- D_{SH} in milligram per litre (mg/l)
- SH_{CN} in milligram per litre (mg/l)
- Q_{CEB} in litres / hour (l/h)

Sodium hypochlorite dosing station:

$$\mathit{Sodium\ hypochlorite\ dosing\ flow}\ (Q_{CL}) = \frac{(\mathit{dose\ concentration}\ (D_{CL}) \times \mathit{CEB\ backwash\ flow\ rate}\ (Q_{CEB})}{\mathit{Sodium\ hopochloride\ concentration}\ (CL_{CN})}$$

Equation 10: $$Q_{CL} = \frac{(D_{CL} \times Q_{CEB})}{CL_{CN}}$$

With:

- Q_{CL} in litres /hour (l/h)
- D_{CL} in milligram per litre (mg/l)
- CL_{CN} in milligram per litre (mg/l)
- Q_{CEB} in litres / hour (l/h)

Sulphuric acid dosing station:

$$\mathit{Sulphuric\ acid\ dosing\ flow}\ (Q_S) = \frac{(\mathit{dose\ concentration}\ (D_S) \times \mathit{CEB\ backwash\ flow\ rate}\ (Q_{CEB})}{\mathit{Sulphuric\ acid\ concentration}\ (S_{CN})}$$

Equation 11: $Q_S = \frac{(D_S \times Q_{CEB})}{S_{CN}}$

With:

- Q_S in litres /hour (l/h)
- D_S in milligram per litre (mg/l)
- S_{CN} in milligram per litre (mg/l)
- Q_{CEB} in litres / hour (l/h)

3.2.3 Clean in place requirements of UF

During normal operation the backwash procedure returns the differential pressure to the original value. If the backwash procedure fails to achieve this then a chemical enhanced backwash is required to return the differential pressure to the original value. When fouling and scaling of the system is severe and a chemical enhanced backwash is not successful to return the differential pressure to the original state, then a clean in place (CIP) is required.

The CIP procedure entails cleaning the UF membrane with different chemical solutions until the system parameters is returned to the original state.

3.2.4 Chemical consumption of UF system

Different chemicals are used on sites that differ in feed water quality. For some applications coagulants are dosed to coagulate the particles into larger particles to assist in the mechanical removal by the membrane. The other chemicals used are for the cleaning of the membrane during operation when conducting a CEB. For the Medupi power station study no coagulant dosing will be required. It can however be considered for other applications and is thus discussed in this section.

The use of coagulation upfront of the membranes enhances filtration, assist in the removal of suspended and dissolved solids and improve overall operation.

For dead-end operation, the coagulation philosophy is to create "pinflocs", i.e flocs of limited size. On the one hand these pinflocs have sufficient size to be retained by the UF membranes and to create a relatively open cake structure on the membrane surface. On the other hand the flocsize required can be limited because solids removal is determined by the size difference between flocs and membrane pores and not depending on gravitational separation." (Norit Technical bulletin, 2005 p.3).

According to the UF membrane supplier Norit the effective coagulant concentration for optimum pinfloc formation is in the range of 0.1 – 3 mg/l as metal (Norit Technical bulletin, 2005 p.4).

During the operation of the UF system the system will be periodically backwashed. When the normal backwash cannot return the membrane to the original operating conditions and fouling is suspected a chemical enhanced backwash is conducted. CEB is conducted in 2 stages: a high pH clean and a low pH clean. Chemicals used with a high pH CEB is sodium hydroxide and sodium hypo chlorite in combination. Chemicals used with a low pH CEB is sulphuric acid or hydrochloric acid.

The consumption of the chemical is a function of the water quality. When conducting a high pH CEB the pH must be > 12. When conducting a low pH CEB the pH must be < 3.

Coagulation chemicals are dosed in the feed stream while the CEB chemicals are dosed in the backwash stream. The amount of chemicals used is a function of the capacity of the UF unit and the quality of the feed water.

3.2.4.1 CEB chemical consumption

Firstly it required to calculate the number of CEB cycles (CEB_C) in 24 hours:

$$CEB_C = \frac{24\ hours}{Frequency\ of\ CEB\ (CEB_F)}$$

Equation 12: $$CEB_C = \frac{24\ hours}{CEB_F}$$

With

- CEB_C in quantity off
- CEB_F in hours

Calculate the chemical consumption for sodium hydroxide:

$$Sodium\ hydroxide\ consumption\ per\ 24\ hours\ (SH_C) = \left(\frac{sodium\ hydroxide\ dosing\ flow\ (Q_{SH})}{3600\ seconds}\right) \times CEB\ dosing\ time\ (CEB_T) \times Number\ of\ CEB\ cycles\ in\ 24\ hours\ (CEB_C) \times number\ of\ skids\ (S_T)$$

Equation 13: $$SH_C = \left(\frac{Q_{SH}}{3600\ seconds}\right) \times\ CEB_T\ \times\ CEB_C\ \times\ S_T$$

Calculate the chemical consumption for sodium hypochlorite:

$$Sodium\ hypochlorite\ consumption\ per\ 24\ hours\ (CL_C) = \left(\frac{sodium\ hypochlorite\ dosing\ flow\ (Q_{CL})}{3600\ seconds}\right) \times CEB\ dosing\ time\ (CEB_T) \times Number\ of\ CEB\ cycles\ in\ 24\ hours\ (CEB_C) \times number\ of\ skids\ (S_T)$$

Equation 14: $$CL_C = \left(\frac{Q_{CL}}{3600\ seconds}\right) \times\ CEB_T\ \times\ CEB_C\ \times\ S_T$$

Calculate the chemical consumption for sulphuric acid:

$$Sulphuric\ acid\ consumption\ per\ 24\ hours\ (S_C) = \left(\frac{Sulphuric\ acid\ dosing\ flow\ (Q_{SH})}{3600\ seconds}\right) \times CEB\ dosing\ time\ (CEB_T) \times number\ of\ CEB\ cycles\ in\ 24\ hours\ (CEB_C) \times number\ of\ skids\ (S_T)$$

Equation 15: $S_C = \left(\frac{Q_{SH}}{3600\ seconds}\right) \times CEB_T \times CEB_C \times S_T$

3.2.5 Scaling

During the operation of RO system water is removed from the feed stream and the reject stream have increased number of salts. This is due to the rejection of salts in the RO membrane. Salt in the water dissolves into the cation and anion components. When the concentration of the salts' cation and associated anion component reach solubility of that salt, crystal formation can occur followed by precipitation (Byrne, 2002 p.157). This precipitation is called scaling on the membranes.

Scaling on the membranes has adverse effects on the membranes. Scaling on a membrane system increases the differential pressure and flow production of the system can reduce. In a RO system the salt rejection can decrease leading to poorer outlet quality. Due to the potential problem of scale formation efforts are made to predict and counter the effect of scale formation.

One of the methods to predict scaling is the use of an index called Langelier saturation index (LSI). This index is used to predict the calcium carbonate ($CaCO_3$) stability of water. It will indicate whether the water will form scale or dissolve scale. This index was developed by Wilfred Langelier in 1936. He developed a method to predict the pH at which water is saturated with calcium carbonate scale. This pH is called the saturation pH (pH_s). The LSI of the water is then expressed as the difference between the water pH (pH_w) and the saturation (pH_s).

Thus:

Equation 16: $LSI = pH_W - pH_S$

pH_s is the pH at saturation in calcite or calcium and is defined as:

Equation 17: $pH_S = (9.3 + A + B) - (C + D)$

Equation 18: $A = \frac{(\log_{10}[TDS] - 1)}{10}$

Equation 19: $B = -13.12 \times \log_{10}(°C + 273) + 34.55$

Equation 20: $C = \log_{10}[Ca^{2+}\ as\ CaCO_3] - 0.4$

Equation 21: $D = \log_{10}[alkalinity\ as\ CaCO_3]$

The values can be interpreted the following way:

LSI value	Influence of LSI
LSI = 0	Water is saturated with $CaCO_3$ but a scale layer is not formed or dissolved.
LSI < 0	Water is under saturated and tends to dissolve solid $CaCO_3$.
LSI > 0	Water is supersaturated with $CaCO_3$ and scale layer tends to precipitate.

Table 1: LSI values and interpretation

LSI is a very good indicator for the formation of calcium carbonate ($CaCO_3$) scale but lacks the ability of predicting the scale formation of calcium sulphate (CaSO4), barium sulphate (BaSO4), strontium sulphate (SrSO4) and silica scale. Formation of these scales is commonly problematic in the treatment of industrial waters. The study we are conducting is with raw water drawn from the Mokolo dam or the crocodile West supply. **Appendix 2:** Design water analysis – Medupi power station indicates the quality of the water used for the design purposes. Prediction of scaling on membrane systems is a field of study which justifies research on a master's degree level by itself. For the purpose of this study, only the LSI indicator will be used for predicting the scaling tendencies of the water used.

3.3 Medupi system description

3.3.1 Background of project – Need and requirement – step 1

The Medupi power station situated 15 km west of the town of Lephalale in the Limpopo province of South Africa is the second largest coal power station in the world and the largest one in Africa. The power station will consist of six super critical units with a generating capacity of 4800 MW (Eskom tender RFP section 3.3.1, p.1). Lephalale is situated in a summer rainfall area, with a semi-arid climate. Rainfall for the Lephalale area ranges from 380 mm to 700 mm with a mean value of 550 mm (Eskom tender RFP section 3.3.1, p.5).

The requirement for pure water is extremely high. At the Medupi power station there will be 2 potential water sources, namely the Crocodile river water source and the Mokolo dam water source. The plant design parameters made provision for the flexibility required to utilise both the abovementioned sources as a feed source. **Appendix 2:** Design water analysis – Medupi power station indicates the design figures, which is based on the averages of the highest values observed during the sampling process.

Options available for the treatment process which was installed at the Medupi power station included, ion–exchange technology, which utilises resins and alternatively membrane based processes (UF/RO).

Table 2 below is, as a rule of thumb, used by Eskom for initial screening for process selection (Galt, 2009 p.626)

TDS value (mg.L^{-1})	Most Appropriate Technology in Accordance with BATNEEC
< 150	PBIX > CIX > RO
150-200	PBIX > RO > CIX
250-350	PBIX = RO > CIX
350-500	RO > PBIX > CIX
>500	RO >> PBIX > CIX

Table 2: Technology selection, initial screening

BATNEEC – Best available technology not entailing excessive costs.

PBIX is packed bed ion exchange, CIX is conventional ion exchange and RO is Reverse osmosis.

In addition to using the above table and the consideration of the raw water quality, the following requirements from Eskom acted as selection drivers to the technology used (Galt, 2009 cited in Power Plant Chemistry, p.621):

1. Compliance with South African statutory requirements as provided in National environmental act, national water act, water service and environmental conservation act.
2. Eskom water management policy.
3. GGM0970 – Guideline for the integrated water and waste water management process.
4. Minimisation of raw water usage.
5. Maximisation of water reclamation, recycling and re-use.
6. Minimisation of the salt water loading in effluent streams.
7. Compliance with applicable Eskom water quality standards.
8. Minimisation and optimisation of the use of chemicals for regeneration, cleaning and neutralisation.
9. Maximised use of automation. Operate with reduced staff members.
10. Application of the BATNEEC principles.
11. Application of best practical environmental option (BPEO) when selecting treatment processes.

Process technology that formed part of the final decision included UF and RO systems. The complete process flow is discussed in the next section. The specific goal of the study was to develop a modelling tool to assist management in decision in optimising the use of RO brine as backwash water on the UF system. As can be seen from the selection drivers point 4, 5 and 6 for the initial system at the Medupi power station is that minimisation of raw water usage and increase in reclamation, recycling and re-use was considered in the final decision. The need exists to reduce the water use by re-use and recycling. This concludes step 1 of the management model flow sheet.

3.3.2 How to address the need – Step 2

Step 2 is addressing the need. **Figure 11:** Block diagram Medupi UF system output requirement indicates the flow requirement for the Medupi power station UF system. As can be seen from the process flow diagram is that the UF requires 195 m^3/h of water to be used during the backwash procedure. This indicates an area of optimisation. Re-use RO brine as backwash water on the UF system.

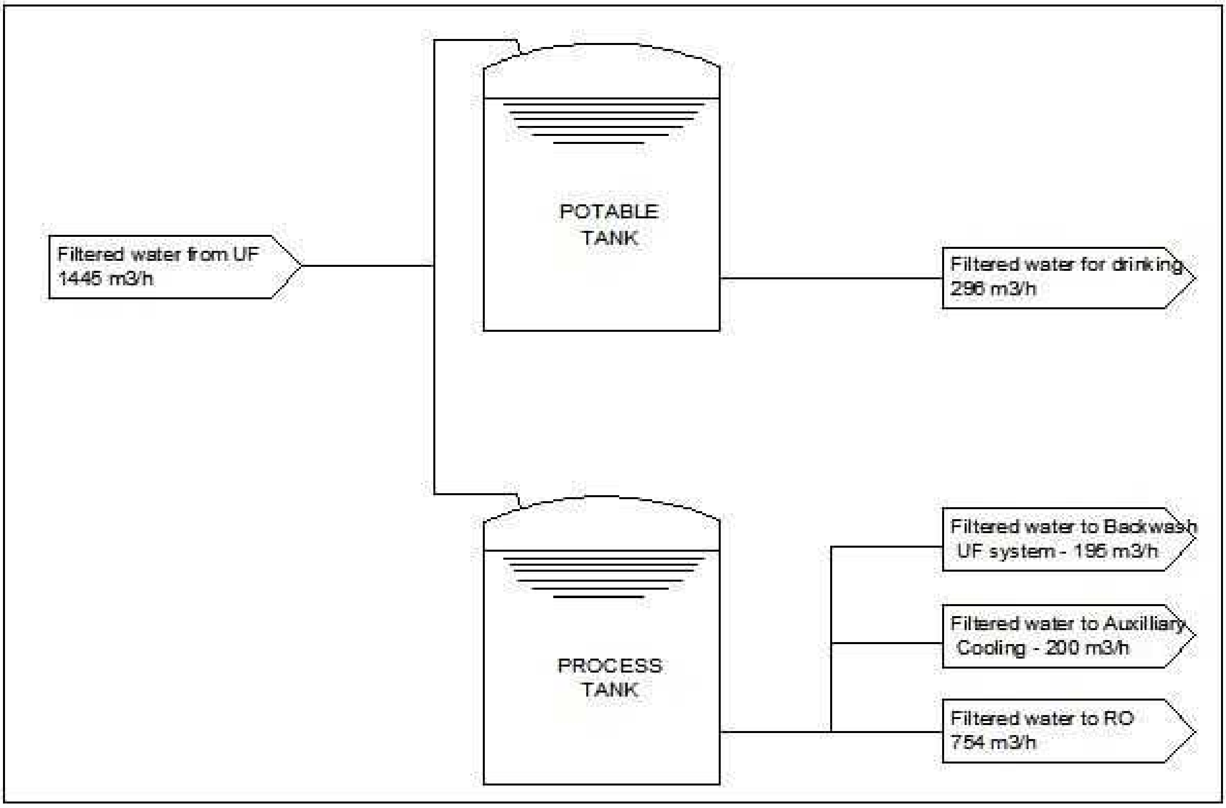


Figure 11: Block diagram Medupi UF system output requirement

3.3.3 Process flow of system – Medupi power station – Step 3

3.3.3.1 Define the process parameters

The final completed water treatment plant at the Medupi power station consists of the following process steps, named in process order:

1. Clarification
2. Ultrafiltration
3. Organic scavenging
4. Reverse Osmosis stage 1
5. Reverse osmosis stage 2
6. Gas transfer membranes (GTM)
7. Continuous de-ionisation (CEDI)

For the purpose of this dissertation two of the above process steps were discussed. The two systems included the UF system and the RO system.

UF units are installed to serve as pre-treatment to the RO units. The main goal of the UF system is to reduce the suspended solids to a level acceptable to the RO system. The system will utilise the hollow fibre capillary membrane with a horizontal configuration. Operation will be inside out and dead end filtration mode.

The system has the following plant configuration and process parameters, as obtained from the Medupi process design documentation and the data from the supplier design criteria:

Design parameter and supplier data – Medupi UF	Value
Required Net flow production (Q_N):	1445 m^3/h
Net flux rate (F_N):	56.4 l/m^2/h
Gross flux (F_G):	70 l/m2/h
Backwash flux rate (F_{BW}):	250 l/m^2/h
Filtration time:	24 minutes before backwash is required
Maximum feed pressure:	3 bar
Frequency chemical enhanced backwash (CEB_F):	17.6 hours
Chemical enhanced backwash dosing time (CEB_T):	60 seconds
Chemical enhanced backwash flow rate (Q_{CEB}):	800 m^3/h
Sodium hydroxide concentration (SH_{CN}):	319 g/l
Sodium hypochlorite concentration (CL_{CN}):	150 g/l
Sulphuric acid concentration (S_{CN}):	1800 g/l
Sodium hydroxide dose concentration (D_{SH}):	610 g/l
Sodium hypochlorite dose concentration(D_{CL}):	200 g/l
Sulphuric acid dose concentration (D_S):	560 g/l
Recovery (R_C):	85-88%
Estimated clean in (CIP) place frequency	Once every 3 months
CIP chemical: Hydrogen peroxide	Approx. 2 litre/skid
CIP chemical: Sodium hypochlorite	Approx. 40 litre/skid
CIP chemical: Hydrochloric acid	Approx. 5 litre/skid

Table 3: Medupi plant configuration and process parameters – Information used from supplier design documents

These parameters were used as design input figures to the design software packages, as well as the validation by hand calculation. Membrane suppliers have design software which assists in the hydraulic designs for the units. They also have guidelines and specifications on the flux rates to be used.

System net flow production is 1445 m^3/h as indicated above. Filtrate water users include the potable tank, where 296 m^3/h of water is consumed as potable supply, as indicated by **Figure 11:** Block diagram Medupi UF system output requirement. Other users include water supply to the auxiliary cooling circuit at a flow rate of 200 m^3/h. The RO unit process requires 754 m^3/h. Finally the UF backwash requires 195 m^3/h.

From the flow values above it is evident that the UF requires an additional 195m^3/h of flow capacity to cater for the backwash requirements. The recovery specified on the RO is 80%. This means that 20% of the feed flow to the RO will be dumped as RO brine, while 80% will be permeate. The RO brine equates to 20% of 754 m3/h which equals 150.8 m^3/h. This value requires additional treatment for re-use at the inlet of the water treatment system, or cost would be incurred to remove this water as waste from the site.

Eskom adopted the Zero Liquid Effluent Discharge policy (ZLED) during 1987 (Pather, 2004 p.663). The ZLED policy states that all reasonable measure will be taken to prevent pollution of water resources through the establishment of a hierarchy of water based on quality (Pather, 2004 p.663). The water is extensively re-used by cascading the water from a higher to a lower quality (Pather, 2004 p.663). ZLED is also achieved by incorporating processes into the water treatment chain that aim to produce relative low volumes of effluent. Utilising the RO brine falls within the parameters of this requirement. The re-use of RO brine is identified as an area of potential optimisation and completes step 3 of **Figure 10:** Flow sheet of the optimisation management model (Medupi).

3.3.3.2 Process description RO system at Medupi power station

The membrane used in the RO system is a poly amide spiral wound membrane. Membrane size is 8 inch diameter with a 40 m^2 surface area. The RO system at the Medupi power station is designed to operate at a recovery of 80%. The recovery refers to the amount of water recovered from the feed stream. This equates to a waste stream of 20%. As mentioned the aim of this study is to optimise the use of this brine stream to backwash the UF system. This will reduce the amount of waste as well as reduce the required size of the UF system. The study only utilised the brine quality figures and brine flow rate from RO stage1. The RO design is not discussed in detail as it does not form part of the study.

Design parameter	Value
Required net production flow / skid	120.64 m^3/h
Net flux rate	21.17 $l/m^2/h$
Recovery	80 %
Feed flow rate / skid	150.8 m^3/h
Reject brine flow rate / skid	30.16 m^3/h
Total number of skids	5
Total number of pressure vessels / skid	22 off
Total number of membranes / skid	154 off
Total net production flow	603.2 m^3/h
Total feed flow rate	754 m^3/h
Total reject flow rate	150.8 m^3/h

Table 4: Summary of RO design parameters - Medupi Power station, from design documents. RO pass 2 reject return was excluded from above calculations.

Appendix 2: Design water analysis – Medupi power station is used for the design values for the input water quality. On this list the design value of the water quality clearly defined. The information comes from initial analysis. Without the parameters from an operational plant, the value for the RO concentrate will have to be calculated. According to Byrne with normal rejection membrane elements, it can be assumed that most of the dissolved salts from the feed water will end up in the concentrate stream (Byrne, 2002 p.67). Based on this assumption the concentration factor is:

$$Concentration\,factor\ (C_F) = \frac{1}{[1 - recovery\ (R_{RO})]}$$

Equation 22: $$C_F = \frac{1}{(1 - R_{RO})}$$

With

- C_F no unit
- R_{RO} as a fraction

Thus the Concentration factor is = $\frac{1}{(1 - 0.8)}$

= 5

This means that the salts in the reject stream will have an approximate concentration of 5 times that in the feed stream.

Thus, brine concentration = TDS from analysis x 5

$$= 595.2 \times 5$$

$$= 2976\, mg/l$$

If the model needs to apply to an operating plant then various test can be conducted on the RO brine to see the applicability of use as UF backwash water. One of the areas that would require additional study is the scaling tendency of the water this will be discussed in the next section. Additional testing that can be done on the RO brine will include:

1. Inorganic testing of dissolved salts (TDS).
2. Turbidity tests.
3. Silt density index (SDI).
4. Trial work on actual operating plants.

Point number 4 will always be favoured as this would allow the engineers to see the exact influence of the RO brine on the UF during the backwash procedure in continuous use.

SDI test is also known as the fouling index (Byrne, 2002 p.24). In industry, it is used as an indicator of RO membrane fouling. The test measures the fouling of a 0.45 µm filter disc by suspended solids. It is a unit less measurement that indicates the ratio between filling a 500 ml volume of water at the initial start-up time and then again after 15 minutes. Typical results would mean the following for RO membrane fouling rate (Byrne, 2002 p.25):

SDI value	Influence of SDI on fouling
< 3	Indicate low membrane fouling
3-5	Indicate normal fouling rate
> 5	Indicate high fouling rate

Table 5: SDI values and interpretation

It is believed by the author of this dissertation that this test would be a valuable indicator in the use of RO brine for the backwash of the UF system, but this would need to be confirmed in conjunction with trial work.

3.3.3.3 LSI calculation of reject water

LSI of the water, as mentioned, indicates the scaling tendency of the water. This is included in the study to ensure that the relevant information is given to management regarding the scaling tendency of the water.

For the reject water quality we will use the water analysis as set out in **Appendix 2:** Design water analysis – Medupi power station.

$$LSI = pH_W - pH_S$$

pH_s is the pH at saturation in calcite or calcium and is defined as

$$pH_S = (9.3 + A + B) - (C + D)$$

$$A = \frac{\log_{10}[TDS] - 1)}{10}$$

$$B = -13.12 \times \log_{10}(°C + 273) + 34.55$$

$$C = \log_{10}[Ca^{2+} \ as \ CaCO_3] - 0.4$$

$$D = \log_{10}[alkalinity \ as \ CaCO_3]$$

$$\begin{aligned} A &= \frac{(\log[TDS] - 1)}{10} \\ &= \frac{(\log[2976] - 1)}{10} \\ &= 0.24736 \end{aligned}$$

$$\begin{aligned} B &= -13.12 \times \log(°C + 273) + 34.55 \\ &= -13.12 \times \log(25 + 273) + 34.55 \\ &= 2.08828 \end{aligned}$$

$$\begin{aligned} C &= \log(Ca^{2+} \ as \ CaCO_3) - 0.4 \\ &= \log(642) - 0.4 \\ &= 2.4075 \end{aligned}$$

$$\begin{aligned} D &= \log[alkalinity \ as \ CaCO_3] \\ &= \log[1252.2] \\ &= 3.09767 \end{aligned}$$

Thus

$$\begin{aligned} pH_S &= (9.3 + A + B) - (C + D) \\ &= (9.3 + 0.24736 + 2.08828) - (2.4075 + 3.09767) \\ &= 6.1304 \end{aligned}$$

Finally

$$\begin{aligned} LSI &= pH_w - pH_S \\ &= 7.08 - 6.1304 \\ &= 0.9496 \end{aligned}$$

From the LSI value it indicates that the water is supersaturated with $CaCO_3$ and scale layer tends to precipitate. As mentioned above the prediction of scaling on membrane systems is a field of study which justifies research on a master’s degree level by itself. As the influence of scaling is only an assumption, the LSI influence table will be adapted as follows:

LSI value	Influence of LSI	Effect on CIP frequency (Assumption)
LSI = 0	Water is saturated with $CaCO_3$ but a scale layer is not formed or dissolved.	No effect.
LSI < 0	Water is under saturated and tends to dissolve solid $CaCO_3$.	No Affect.
LSI > 0	Water is supersaturated with $CaCO_3$ and scale layer tends to precipitate.	15% additional CIP frequency

Table 6: Assumed impact on CIP based on LSI values

Please note that this is only an assumption and research is required to confirm these assumptions. These assumptions are made with the information that the original feed water conforms to drinking water specification and falls within the limit of low brackish water supply. For sea water applications the same assumption will not be considered by the author.

3.3.4 Current situation - Medupi UF system design - step 4

The process and hydraulic calculation of the current system follows in this section. This is the partial fulfilment of step 4 – Current situation.

3.3.4.1 UF hydraulic design – Current situation

The design parameters from **Table 3** (information from supplier) are used for the following calculations. From the mass balance description it is clear that the required net flow production is 1445 m^3/h.

Thus, required membrane surface area (A_T) is:

Equation 1: $A_T = \frac{Q_N}{F_N}$

$$= \frac{1445000}{56.4}$$
$$= 25620.567\ m^2$$

From here we can calculate the number of membranes (M_T):

Equation 2: $M_T = \frac{A_T}{A_M}$

$$= \frac{25620.567}{40}$$
$$= 640.512\ membranes\ \approx 640$$

Each pressure vessels can be loaded with 4 membranes. Thus the number of pressure vessels (P_T) is:

Equation 3: $P_T = \frac{M_T}{4}$

$$= \frac{640}{4}$$
$$= 160\ vessels$$

For an optimised hydraulic design and from the supplier specification the maximum number of pressure vessels per skid is 40, configures in 4 rows of 10 vessels. Thus the no of skids (S_T) is:

Equation 4: $S_T = \frac{M_T}{40}$

$$= \frac{160}{40}$$
$$= 4\ skids\ in\ total$$

The UF feed flow (Q_{FD}) is:

Equation 5: $Q_{FD} = F_G \times A_T$

$$= 70 \times 25620$$
$$= 1793\ m^3/h$$

The recovery (R_C) on the UF system is:

Equation 6: $R_C = \left(1 - \left(\frac{B_V}{Q_N}\right)\right) \times 100$

$$= \left(1 - \left(\frac{195}{1445}\right)\right) \times 100$$

$$= 86.5\%$$

3.3.4.2 UF system Backwash design – Current situation

The UF system requires a backwash to remove the suspended matter from the membrane surface. From the supplier specification it is required to backwash at a flow rate of 250 $l/m^2/h$. Only one skid will be backwashed at a time.
Thus the backwash flow rate (Q_{BW}) is:

Equation 8: $Q_{BW} = F_{BW} \times A_S$

$$= 250 \times \left(\frac{25620.567}{4}\right)$$

$$= 1601.28\, m^3/h$$

3.3.4.3 UF system Chemical enhanced backwash design – Current situation

The UF system will use chemicals in combination with a backwash. The chemicals used are:

- Sodium hydroxide
- Sodium hypochlorite
- Sulphuric acid

Sodium hydroxide dosing flow and consumption calculation is:

Equation 9: $Q_{SH} = \frac{(D_{SH} \times Q_{CEB})}{SH_{CN}}$

$$= \frac{(610 \times 800\,000)}{319}$$

$$= 1529.78\, l/h$$

Equation 13: $$SH_C = \left(\frac{Q_{SH}}{3600}\right) \times CEB_T \times CEB_C \times S_T$$
$$= \left(\frac{1529.78}{3600}\right) \times 60 \times 1.363 \times 4$$
$$= 139\ litres/day$$

Sodium hypochlorite dosing flow and consumption calculation is:

Equation 10: $$Q_{CL} = \frac{(D_{CL} \times Q_{CEB})}{CL_{CN}}$$
$$= \frac{(200 \times 800\ 000)}{150}$$
$$= 1066.637\, l/h$$

Equation 14: $$CL_C = \left(\frac{Q_{CL}}{3600}\right) \times CEB_T \times CEB_C \times S_T$$
$$= \left(\frac{1066.67}{3600}\right) \times 60 \times 1.636 \times 4$$
$$= 96.92\, \frac{litres}{day}$$

Sulphuric acid dosing flow and consumption calculation is:

Equation 11: $$Q_S = \frac{(D_S \times Q_{CEB})}{S_{CN}}$$
$$= \frac{(560 \times 800\,00)}{1800}$$
$$= 248\ l/h$$

Equation 15: $$S_C = \left(\frac{Q_{SH}}{3600}\right) \times CEB_T \times CEB_C \times S_T$$
$$= \left(\frac{248}{3600}\right) \times 60 \times 1.363 \times 4$$
$$= 22.53\, \frac{litres}{day}$$

3.3.4.4 UF hydraulic design – Optimised situation

From the mass balance description it is clear that the required net flow production is 1294.5 m^3/h.

Thus, required membrane surface area (A_T) is:

Equation 1: $A_T = \frac{Q_N}{F_N}$

$$= \frac{1294500}{56.4}$$

$$= 22952.13\ m^2$$

From here we can calculate the number of membranes (M_T):

Equation 2: $M_T = \frac{A_T}{A_M}$

$$= \frac{22952.13}{40}$$

$$= 573.8\ membranes, rounded\ off\ to\ 576$$

Each pressure vessels can be loaded with 4 membranes. Thus the number of pressure vessels (P_T) is:

Equation 3: $P_T = \frac{M_T}{4}$

$$= \frac{576}{4}$$

$$= 144\ vessels$$

The number of skids will remain 4, as per the current situation. Thus each skid will have 36 vessels.

The UF feed flow (Q_{FD}) is:

Equation 5: $Q_{FD} = F_G \times A_T$

$$= 70 \times 22952.13$$

$$= 1607\ m^3/h$$

Equation 6: $R_C = \left(1 - \left(\frac{B_V}{Q_N}\right)\right) \times 100$

$$= \left(1 - \left(\frac{195}{1445}\right)\right) \times 100$$

$$= 86.5\%$$

3.3.4.5 UF system Backwash design – Optimised situation

The UF system requires a backwash to remove the suspended matter from the membrane surface. From the supplier specification it is required to backwash at a flow rate of 250 l/m^2/h. Only one skid will be backwashed at a time.
Thus the backwash flow rate (Q_{BW}) is:

Equation 8: $Q_{BW} = F_{BW} \times A_S$

$$= 250 \times \left(\frac{22952.13}{4}\right)$$

$$= 1434.5\ m^3/h$$

3.3.4.6 UF system Chemical enhanced backwash design – Optimised situation

The UF system will use chemicals in combination with a backwash. The chemicals used are:

- Sodium hydroxide
- Sodium hypochlorite
- Sulphuric acid

Sodium hydroxide dosing flow and consumption calculation is:

Equation 9: $Q_{SH} = \frac{(D_{SH} \times SH_{CN})}{SH_{CN}}$

$$= \frac{(610 \times 717254)}{319}$$

$$= 1371.55\ l/h$$

Equation 13: $SH_C = \left(\frac{Q_{SH}}{3600}\right) \times CEB_T \times CEB_C \times S_T$

$$= \left(\frac{1371.55}{3600}\right) \times 60 \times 1.363 \times 4$$

$$= 124.6\ litres/day$$

Sodium hypochlorite dosing flow and consumption calculation is:

Equation 10:
$$Q_{CL} = \frac{(D_{CL} \times Q_{CEB})}{CL_{CN}}$$
$$= \frac{(200 \times 717254)}{150}$$
$$= 956.33\ l/h$$

Equation 14:
$$CL_C = \left(\frac{Q_{CL}}{3600}\right) \times CEB_T \times CEB_C \times S_T$$
$$= \left(\frac{956.33}{3600}\right) \times 60 \times 1.363 \times 4$$
$$= 86.89\ litres/day$$

Sulphuric acid dosing flow and consumption calculation is:

Equation 11:
$$Q_S = \frac{(D_S \times Q_{CEB})}{S_{CN}}$$
$$= \frac{(560 \times 717254)}{1800}$$
$$= 223\ l/h$$

Equation 15:
$$S_C = \left(\frac{Q_{SH}}{3600}\right) \times CEB_T \times CEB_C \times S_T$$
$$= \left(\frac{223}{3600}\right) \times 60 \times 1.363 \times 4$$
$$= 20.26\ /day$$

3.3.4.7 CIP consumption

The following chemical will be used when a CIP is required, as per design document from supplier, and summarised in **table 3**:

- Hydrogen peroxide, 2 litres / skid / CIP regime. Thus 8 litres / CIP for total system
- Sodium hypochlorite, 40 litres / skid / CIP regime. Thus 160 litres / CIP total for the system.
- Hydrochloric acid, 5 litres / skid / CIP regime. Thus 20 litres / CIP for total system.

The total cost of the chemicals for one CIP cycle is approximately R1000.00. This is a cost every 3 months. CIP cost will not be included in the LCC. This cost is very low and will not have an influence on the LCC.

3.3.4.8 Energy consumption

For the application of the Medupi power station the energy consumed will not be used in the LCC. For other users of the modelling tool this can be added.

3.3.4.9 Membrane expected life

The supplier of the membranes states that a typical life of the membrane is 3-5 years under normal operating conditions. From the supplier design data, taking into account the feed water and backwash water quality, number of hydraulic cleans and the estimated number of chemically enhanced backwashes we will assume a membrane life of 3.5 years for the current situation. The membrane replacement cost will by taking the total membrane cost from the construction cost, and dividing it by 42 months. It will be assumed that the optimised design will have a 15% increase in CIPs. Thus we will assume a membrane life of 15% less than the current situation. The membrane life is an estimate based on the recommendations by the membrane supplier. Their experience is the cornerstone of the assumption on membrane life.

3.3.4.10 Raw water feed cost

Medupi power station receives raw water from 2 different sources. For the initial start up the Mokolo dam feed source will be used. The current cost for this water, as received from the Medupi site personnel is R12-15/m^3. For our LCC we will use R12/m^3. The other source that they might use in the future is the Crocodile River. The current cost for this source is R25-R29/m^3.

3.4.4.11 Summary of Medupi UF design – Current and optimised situation:

From the calculations above, the Medupi UF configuration is summarised in **Table 7:** Summary of UF Design – Current Situation.

Nr.	Description	Unit	Current situation	Optimised situation
1	Total Number of membranes (M_T)	Off	640	576
2	Total number of pressure vessels (P_T)	Off	160	144
3	Total number of skids (S_T)	Off	4	4
4	Required Net flow production (QN):	m^3/h	1445	1295
4	Backwash flow rate (Q_{BW})	m^3/h	1600	1434
5	Amount of raw water filtered	m^3/ month	1 040 400	932760
6	Current cost for water	Rand / m^3	12	12
7	UF membrane expected life	Months	42	36*
8	Sodium hydroxide dosing flow (Q_{SH})	l/h	1530	1372
9	Sodium hypochlorite dosing flow (Q_{CL})	l/h	139	125
10	Sulphuric acid dosing flow (Q_S)	l/h	1067	956
11	Sodium hydroxide consumption (S_{HC})	Litres/day	97	87
12	Sodium hypochlorite consumption (C_{LC})	Litres/day	248	223
13	Sulphuric acid consumption (S_C)	Litres/day	23	20

Table 7: Summary of UF design - Current situation. Values rounded off. Duration for a month is 24 hours / day at 30 days / month. * Life of optimised membrane reduced by 15%, due to assumption of 15% more CIP.

3.4.4.12 Summary of assumption made for LCC evaluation

The following assumptions were made to assist in achieving results to compare:

No	Assumption	Basis of assumption
1	With the use of RO brine number of required cleaning cycles (CIP) will increase by 15%.	The scaling tendency of water is a field of study that justifies a research study on masters-degree level. Thus for the purpose of this dissertation the assumption is made.
2	Membrane life will be 15% less for optimised situation.	See explanation in point 1 of table.
3	Water consumption is based on 24 hour operation.	System operation from design documents include for 24 hour operation.
4	CIP cost will be excluded from LCC	Cost is very low and does not impact the LCC.

Table 8: Summary of assumptions

3.3.5 Life–cycle evaluation – step 5

Identifying the cost parameters is an extremely important step. The exclusion of some of the parameters will reduce unnecessary effort from the available workforce. Only cost that will change from the current to the optimised situation will be evaluated. The end result will indicate percentage difference and the real value cost will be used on the areas where a change is expected.

For the specific study the following cost items is incorporated into the management model:

- Construction cost – Fabrication of system including component costs, testing and commissioning of system. The fabrication cost will show a difference. The actual capacity of the system will change from the current to the optimised design.
- Operation of system – Utilities and consumable costs of system. The amount of chemicals required and the cost of raw water intake will be different for the 2 test conditions. Membrane replacement cost will also differ.

Maintenance cost was originally included but limited to the calculation of CIP costs. Due to the fact that the 2 test conditions include for the same type of equipment, only different capacities, it was assumed that the maintenance cost will be the same. This type of maintenance is however a field of study that can be explored in a separate research proposal. After calculating the chemical requirement for a CIP on the 2 test conditions, assuming the labour cost portion will be the same, it was concluded that the effect of this cost on the LCC will be negligible. Thus, this cost will also be excluded from the LCC calculation.

The following cost was assumed to be the same for the current Medupi system as well as for the proposed study:

- Professional fees
- Temporary works cost
- Taxes
- Design cost
- Installation cost
- Transport cost
- Instrumentation cost
- Plant downtime cost (maintenance and breakdown)

3.3.6 LCC evaluation - Current system – Step 6

Construction cost for current system:

	Description	Current situation
1	Mechanical fabrication costs (skid and piping)	R 3 264 994.00
2	Electrical fabrication costs	R 450 000.00
3	Pressure vessels	R 1 438 272.00
4	Membranes	R 12 943 744.00
5	Valves (total)	R 597 300.00
6	Pumps	R 390 003.00
	Total	R 19 084 313.00

Table 9: Cost for Current system

LCC – Current situation	
Parameter	**Value**
Construction cost	
Total construction costs	R 19 084 313.00
Operational expenditure – Monthly	
Chemical consumption cost per month	R 34 217.00
Membrane replacement cost per month	R 308 184.00
Raw feed water cost	R 12 484 800.00
Maintenance cost - Monthly	
Cost is negligible and will be excluded.	
Monthly cost – Operational expenditure	R 12 827 201.00

Table 10: LCC of current situation

Due to the sensitivity of these costs estimates, the details are only available on request from the author.

Construction cost for optimised system:

	Description	Optimised situation
1	Mechanical fabrication costs (skid and piping)	R 2 920 481.00
2	Electrical fabrication costs	R 410 000.00
3	Pressure vessels	R 1 294 445.00
4	Membranes	R 11 649 370.00
5	Valves (total)	R 534 941.00
6	Pumps	R 162 553.00
	Total	**R 16 971 790.00**

Table 11: Construction cost – Optimised system

LCC – Optimised situation	
Parameter	**Value**
Construction cost	
Total construction costs	R 16 971 790.00
Operational expenditure – Monthly	
Chemical consumption cost per month	R 30 665.00
Membrane replacement cost per month	R 323 594.00
Raw feed water cost	R 11 193 120.00
Maintenance cost - Monthly	
Cost is negligible and will be excluded.	
Monthly cost – Operational expenditure	R 11 547 379.00

Table 12: LCC of optimised situation

3.3.7 Comparison of LCC – Step 7

LCC comparison: Current vs optimised situation				
Cost	**Current situation**	**Optimised situation**	**Difference (percentage)**	**Comment**
Construction cost	19 084 313.00	16 971 790.00	11.07%	Optimised cost beneficial
Operating cost, monthly	12 827 201.00	11 547 379.00	9.98%	Optimised cost beneficial
Maintenance cost	0.00	0.00	0.00%	Parameter not part of LCC

Table 13: LCC comparison, current situation vs optimised situation

3.3.8 Management decision – Step 8

The conclusion of the process is the final decision by management, based on relevant information as supplied by the deliverables from the model. Please see section 3.4 Results and findings.

3.4 Results and findings

The goal of the empirical investigation was to follow the steps as indicated in **Figure 10:** Flow

Sheet of Optimisation Management Model (Medupi), to assess the viability to re-use the brine from the RO system as backwash water on the UF system at the Medupi power station. Consideration for the process selection by the Medupi management team highlighted that the following must form part of the process for selection:

- Minimisation of raw water usage.
- Maximisation of water reclamation, recycling and re-use.

This expressed the need to investigate the use of RO brine as backwash water on a UF system.

Technical evaluation and LCC was conducted on the current system and the optimised system. The results were compared and it was found that:

1. The number of membranes was reduced from 640 in total to 576.
2. The number of pressure vessels was reduced from 160 in total to 144.
3. The backwash flow rate can be reduced from 1600m^3/h to 1434 m^3/h.
4. The chemical consumption difference between the 2 options for CEB was very small (Less than R3,700.00/month).
5. The chemical cost for CIP purposes as described in section 3.3.4.7 was indicated to be less than R1000.00 every 3 months, and thus the influence on the LCC outcome from these parameters were deemed to be negligible and not considered.
6. When comparing the construction costs it was found that the current system would cost approximately 11.07% more than the optimised system.
7. On a monthly basis the operating cost of the current system was found to be 9.98% more than the cost would be for the optimised design.

3.5 Discussions of results

The management model highlighted the areas of saving for the team at Medupi. Indication from the results was that the construction cost for the current system was 11.07% more than for the optimised design. The difference in cost can be attributed to:

- Reduced number of membranes and pressure vessel due to lower capacity required.
- Reduced physical size of constructed skid. This equates to a labour and material saving on construction cost.

The operational cost showed a difference between the current system and optimised system of 9.98%. The difference in monthly costs can be attributed to:

- Reduction in raw water intake.
- Difference in membrane replacement costs due to the optimised system utilising less membranes.

The construction cost saving of 11.07% and the operational cost saving of 9.98% is significant enough to justify the implementation of the change to use the RO brine reject as backwash water on the UF system. If management feels that further validation is required before implementation of the re-use of RO brine then the following areas can be further investigated:

- Effect of scaling on UF membranes.
- Conduct trials to check the effect of RO brine on a UF system as backwash water.

4 Case study Company X

4.1 Company X system description

The author do not have authorisation to name the company that will be used in this case study. The facts and figures used in this case study are relevant and true.

Company X is a global consumer products company serving millions of consumers worldwide. This company was started 200 years ago and sells their product in over 200 countries. As read from their website and stated by their president, they believe in:

- Caring
- Global teamwork
- Continuous improvement

Company X has manufacturing facilities in South Africa. This case study is based on the facility in Boksburg, Gauteng. Company X established a global manufacturing water reduction team in 2012, with the mission to drive water reduction goals. One of these goals is to reduce water consumed in manufacturing of product by 40% in the year 2015 compared to the amount of water consumed in manufacturing of product in the year 2005.

The water treatment system at the Boksburg facility of company X consists of a UF system followed by a primary RO system. Feed water is municipal supply. **Appendix 5:** Water analysis – main RO brine Company X shows the quality of the raw feed water from the municipal supply (sample A) and an analysis of the primary RO system brine reject (sample B). Company X have realised the importance of re-use and reduction of water consumed and thus the birth of a water reduction team. One of the initiatives which are currently in implementation phase was the introduction of a secondary RO system to recover up to 65% of the brine from the main RO system. **Appendix 6:** PFD current system Company X illustrates the current process flow.

The current system configuration is a standard system with the UF as pre-treatment to the RO system. The UF operation includes periodical backwashes and chemical enhanced backwash operations. The RO operates with a conservative recovery of 75%. The UF system was not always part of the pre-treatment section and was implemented in 2011 to alleviate the fouling problem on the RO system. At one stage the RO membranes fouled on a weekly basis, requiring CIP's frequently. It was recognised that the feed water quality deteriorated to a point where an absolute physical barrier, like UF system, was required as pre-treatment. Prior to the

UF installation cartridge filtration formed part of the pre-treatment. Installation and commissioning of the UF system was extremely effective in reducing the fouling rate on the RO system. The RO system only required a periodical clean every 2-3 months, after UF commissioning. The UF system did however increase the amount of waste water by contributing with the backwash stream. After the success of reducing the constant fouling on the RO system the attention was drawn to reducing the amount of waste water generated.

Phase 1 of the waste stream reduction was born. The systems were investigated and it was decided to install a secondary RO system, which will be known as the recovery RO. **Appendix 7:** PFD phase 1 system – Company X, illustrates the process flow of phase 1. It can be seen that the brine stream from the main RO system will be diverted to a storage tank and from this tank the recovery RO will be fed. Permeate recovered from the recovery RO will be diverted to the filtered water break tank, ahead of the main RO. This will allow the feed water from the municipality to be reduced with the recovered volume of water. Phase 1 is in the implementation stage and should be operational in the next few months.

Phase 2 of the project will entail reducing the amount of waste to achieve even higher recoveries on the system. As part of Company X's main goal of 40% reduction of water consumed by manufacturing of product by 2015, compared to the amount of water consumed in manufacturing of product in the year 2005 all initiatives are investigated to achieve this goal. The purpose and aim of this case study is to use the management model to see what saving and reduction can be achieved at company X. **Appendix 8:** PFD phase 2 system – Company X illustrates the process flow of phase 2. **Table 14:** Different phases of reduction of waste at Company X summarises the different phases involved.

Phase	Feed flow (m^3/h)	RO permeate flow (m^3/h)	RO Brine Flow (main or secondary) (m^3/h)	UF waste flow (m^3/h)	Total waste flow (m^3/h)	System Recovery, percentage
Original system	35.83	25	8.33	2.508	10.838	69.77
Phase 1	30.83	25	3.33	2.508	5.838	81.08
Phase 2	28.32	25	0.82	2.508	3.33	88.27

Table 14: Different phases of reduction of waste water at Company X

4.1.1 Background of project – need and requirement – step 1

From the statement above it is clear that Company X needs to reduce the amount of water used for manufacturing of product by 40% in 2015 in comparison to the amount of water used for manufacturing of product in 2005. It is clear that water needs to be re-used or recycle. Company

X utilises UF and RO technology to treat the raw inlet water to the required outlet quality. The RO brine attributes to the waste water generated. RO brine water can be re-used as backwash water on the UF system.

4.1.2 How to address the need – Step 2

Step 2 of the modelling process flow diagram has been answered and the use of secondary RO brine as backwash water on the UF system will be investigated.

4.1.3 Technical evaluation of the process flow of system Company X – Step 3

4.1.3.1 Define the process parameters - Phase 1 UF system

Current installed UF system Design parameters	Value
Required Net flow production (Q_N):	30.83 m^3/h
Net flux rate (F_N):	70 $l/m^2/h$
Gross flux (F_G):	94 $l/m^2/h$
Backwash flux rate (F_{BW}):	230 $l/m^2/h$
Filtration time:	90 minutes before backwash is required
Maximum feed pressure:	3 bar
Frequency chemical enhanced backwash (CEB_F):	22.5 hours
Recovery (R_C):	93%
Estimated clean in (CIP) place frequency	Once every 12-18 months

Table 15: Current installed UF system parameters

4.1.3.2 Process description - RO system at Company X

The RO system is used to reduce the total dissolved solids (TDS) of the feed water by rejecting the dissolved salts in the membrane. The membrane used is a poly amide spiral wound membrane. The membrane size is an 8 inch diameter with a 40 m^2 surface area. The specific membrane at the facility of Company X can be heat sanitised at a temperature of 85°C.

Design parameter – Main RO system	**Value**
Required net production flow	25 m^3/h
Net flux rate	19.16 $l/m^2/h$
Recovery	75 %
Feed flow rate	33.33 m^3/h
Reject brine flow rate	8.33 m^3/h
Total number of skids	1
Total number of pressure vessels / skid	6 off
Total number of membranes / skid	36 off
Design parameter – Secondary RO system (Recovery RO)	**Value**
Required net production flow	5 m^3/h
Net flux rate	17.25 $l/m^2/h$
Recovery	60 %
Feed flow rate	8.33 m^3/h
Reject brine flow rate	3.33 m^3/h
Total number of skids	1
Total number of pressure vessels / skid	2 off
Total number of membranes / skid	8 off

Table 16: Design parameters main and secondary RO system - Company X

Appendix 5: Water analysis – main RO brine Company X shows the quality of the brine reject water from the main RO system (sample B). From the analysis we can calculate the concentration factor of the secondary RO system:

$$Concentration\,factor\ (C_F) = \frac{1}{(1 - recovery\ (R_{RO}))}$$

Equation 23:

$$C_F = \frac{1}{(1 - R_{RO})}$$

With

- C_F no unit
- R_{RO} Recovery of RO as a fraction

Thus the Concentration factor is $= \frac{1}{(1-0.6)}$

$$= 2.5$$

This means that the salts in the reject stream will have an approximate concentration of 2.5 times that in the feed stream.

4.1.3.3 LSI calculation of reject water of secondary RO

The LSI of the water, as mentioned, indicates the scaling tendency of the water. This is included in the study to ensure that the relevant information is given to management regarding the scaling tendency of the water.

For the reject water from the secondary RO at Company X we will use **Appendix 5:** Water analysis – main RO brine Company X with the concentration factor used to estimate the secondary RO brine reject quality. The estimated reject TDS will be 1257.5 mg/l.

$$LSI = pH_W - pH_S$$

pH_s is the pH at saturation in calcite or calcium and is defined as:

$$pH_S = (9.3 + A + B) - (C + D)$$
$$A = \frac{(\log_{10}[TDS] - 1)}{10}$$
$$B = -13.12 \times \log_{10}(°C + 273) + 34.55$$
$$C = \log_{10}[Ca^{2+}\ as\ CaCO_3] - 0.4$$
$$D = \log_{10}[alkalinity\ as\ CaCO_3]$$

$$A = \frac{(\log[TDS] - 1)}{10}$$
$$= \frac{(\log[1257.5] - 1)}{10}$$
$$= 0.2099$$

$$B = -13.12 \times \log(°C + 273) + 34.55$$
$$= -13.12 \times \log(25 + 273) + 34.55$$
$$= 2.08828$$

$$
\begin{aligned}
C &= \log[Ca^{2+} \ as\ CaCO_3] - 0.4 \\
&= \log[470.63] - 0.4 \\
&= 2.2726
\end{aligned}
$$

$$
\begin{aligned}
D &= \log[Alkalinity\ as\ CaCO_3] \\
&= \log[245.88] \\
&= 2.3907
\end{aligned}
$$

Thus

$$
\begin{aligned}
pH_S &= (9.3 + A + B) - (C + D) \\
&= (9.3 + 0.2099 + 2.088280 - (2.2729 + 2.3907) \\
&= 6.9348
\end{aligned}
$$

Finally

$$
\begin{aligned}
LSI &= pH_W - pH_S \\
&= 6.8 - 6.93488 \\
&= -0.13488
\end{aligned}
$$

From the calculation we can see that the LSI is less than 0. LSI value of less than 0 indicates that the water is under saturated and tends to dissolve solid $CaCO_3$.

4.1.4 Current situation – Company X - step 4

The UF system at Company X is an existing system. The evaluation of the configuration will not be as comprehensive as for the Medupi system, which was a system in design phase. One calculation that was conducted, for information purpose is the number of module required at the optimised condition of phase 2:

From **Appendix 8**: PDF phase 2 system – CompanyX, the process flow diagram indicates that phase 2 UF capacity required will be 28,322 m^3/h.

Thus, required membrane surface area (A_T) is:

Equation 1: $A_T = \frac{Q_N}{F_N}$

$$= \frac{28322}{70.4}$$

$$= 404.6\ m^2$$

From here we can calculate the number of membranes (M_T):

Equation 2: $M_T = \frac{A_T}{A_M}$

$$= \frac{404.6}{60}$$

$$= 6.74\ membranes, rounded\ off\ to\ 7$$

The calculation indicates that the number of membranes for phase 2 can be reduced to 7. The configuration of the UF system is 1 skid with 2 rows of 4 membranes each. If we reduce the number of membranes to 7 it would result in the backwash flowrate of the 2 rows to be different. Thus for hydraulic balance we will not consider reducing the number of membranes. The overall system flux will be lower for the optimised phase 2 implementation. From this calculation we can now assume the following:

- Consumption of chemicals will be the same for phase 1 and phase 2 configuration.
- CIP will be the same.

Capital expenditure will only include required changes to utilise the secondary RO brine for backwash on the UF system. This includes an addition of storage tanks and alterations on piping and control.

4.1.4.1 Energy consumption

For the application of the system at Company X, the energy consumed will not be used in the LCC. For other users of the modelling tool this can be added.

4.1.4.2 Membrane expected life

The supplier of the membranes states that a typical life of the membrane is 3-5 years under normal operating conditions. For our application and LCC we will assume a membrane life of 3.5 years for the both situations. The membrane replacement cost will by taking the total membrane cost from the construction cost, and dividing it by 42 months. The membrane life is an estimate based on the recommendations by the membrane supplier. Their experience is the cornerstone of the assumption on membrane life.

4.1.4.3 Raw water feed cost

The feed water source for Company X is the municipality feed. The current cost for this water, as received from Company X personnel is R12/m^3. The effluent cost, used as a rate from the municipality in the area where Company X is situated is R13.52/m^3.

4.1.4.4 Summary of Company X UF design – Current and optimised situation:

From the calculations above, the UF configuration at Company X is summarised in **Table 17:** Summary of UF Configuration.

Nr.	Description	Unit	Current situation	Optimised situation (phase 2)
1	Total Number of membranes (M_T)	Off	8	7
4	Backwash flow rate (Q_{BW})	m^3/h	28.8	28.8
5	Amount of raw water filtered	m^3/ month	22 198	20 392
6	Current cost for water	Rand / m^3	12	12
7	UF membrane expected life	Months	42	42
8	Amount of waste generated	m3/ month	4 204	2 396
9	Current cost of waste discharge	Rand / m3	13.52	13.52

Table 17: Summary of UF configuration - Current and optimised (phase2)

4.1.4.5 Summary of assumption made for LCC

The following assumptions were made to assist in achieving results to compare:

No	Assumption	Basis of assumption
1	With the use of secondary RO brine the required number of cleaning cycles (CIP) will not increase for the optimised design in phase 2.	The LSI of the secondary RO brine reject indicates that the water will not have a scaling tendency.
2	Membrane life will be the same for the 2 situations.	Estimated cleaning cycles will be the same.
3	Water consumption is based on 24 hour operation.	System operation from design documents include for 24 hour operation.
4	CIP cost will be excluded from LCC	Cost for 2 options will be the same.

Table 18: Assumptions made for LCC completion

4.1.5 Life –cycle evaluation – step 5

For the specific case study the following cost items is incorporated into the management model:

- Construction cost – Only the addition of the required tanks, pipes and control to enable the system to operate with the reject brine from the secondary RO.
- Operation of system – Utilities (feed water and waste water treatment) costs of system.

4.1.6 LCC evaluation - Current system – Step 6

LCC – Current situation	
Parameter	**Value**
Construction cost	
Total construction costs	Not included
Operational expenditure – Monthly	
Chemical consumption cost per month	Not included
Membrane replacement cost per month	Not included
Raw feed water cost	R 266,376.00
Waste water discharge cost	R 56,838.00
Maintenance cost - Monthly	
Not included	
Monthly cost – Operational expenditure	R 323,214.00

Table 19: LCC current situation Company X

Construction cost for optimised system:

	Description	**Optimised situation**
1	Mechanical and control costs (tank and piping)	R 101,560.00
	Total	**R 101,560.00**

Table 20: Construction costs - Optimised situation (phase 2) - Company X

LCC – Optimised situation (phase 2)	
Parameter	**Value**
Construction cost	
Total construction costs	R 101,560.00
Operational expenditure – Monthly	
Chemical consumption cost per month	Not included
Membrane replacement cost per month	Not included
Raw feed water cost	R 244,704.00
Waste water discharge cost	R 32,394.00
Maintenance cost - Monthly	
Cost is negligible and will be excluded.	
Monthly cost – Operational expenditure	R 277,098.00

Table 21: LCC Optimised situation Company X

4.1.7 Comparison of LCC – Step 7

LCC comparison: Current (Phase 1) vs optimised situation (Phase 2)				
Cost	**Current situation - Phase 1**	**Optimised situation - Phase 2**	**Difference (percentage)**	**Comment**
Construction cost	0.00	101 560.00	0.0%	System Installed and operating. Only optimised system requires capital.
Operating cost, monthly	323 214.00	277 098.00	14.27%	Optimised cost beneficial.
Maintenance cost	0.00	0.00	0.00%	Parameter not part of LCC.

Table 22: Comparison current vs optimised situation - Company X

4.1.8 Management decision – Step 8

The conclusion of the process is the final decision by management, based on relevant information as supplied by the deliverables from the model.

4.2 Results and findings

The goal of the case study was to follow the steps as indicated in **Figure 10:** Flow Sheet of Optimisation Management Model (Medupi) to assess the viability to re-use the brine reject from the RO system as backwash water on the UF system.

Company X have water saving goal of reducing the amount of water required for manufacturing of product with 40% by 2015 in comparison to the amount of water used for manufacturing product in 2005. To achieve this goal different phases of water reduction have been considered. The use of RO brine reject as backwash water on a UF system will be proposed as phase 2.

Technical evaluation and LCC was conducted on the current system and the optimised system. The results were compared and it was found that:

1. The number of membranes can be reduced from 8 to 7, but this will cause the required backwash flow rates to be different. Thus it will not be reduced.
2. The chemical consumption for CEB purposes for the 2 options will be the same.
3. The chemical cost for CIP purposes will be the same. Thus this parameter did not form part of the LCC.
4. The only additional construction costs would be the additional tanks, piping and control required to divert the RO brine to a new storage tank for use as backwash water on the UF system.
5. On a monthly basis the operating cost of the current system was found to be 14.27% more than the cost would be for the optimised design.

4.3 Discussions of results

The management model highlighted the areas of saving for the team at Company X. The optimised design for phase 2 would require a capital expenditure for the construction cost. Due to the fact that this is an existing system the current system configuration does not have a construction costs parameter.

The operational cost showed a difference between the current system and optimised system of 14.27%. The difference in monthly costs can be attributed to:

- Reduction in raw water intake.
- Reduction in waste water discharge.

The operational saving of approximately 14.27% is a significant cost. The overall system recovery can also be increased from 81% to 89%, assisting in achieving the goal water reduction as explained above.

The estimated construction cost for phase 2 implementation is R101,560.00. With the savings achieved on a monthly basis the project will have a payback period of 3 months.

5 Conclusion

5.1 Summary of scope and achievements

The study was conducted to provide a modelling tool, assisting management to optimise the use of RO brine as backwash water on the UF system at the Medupi power station. Utilising the same modelling tool for the case study of the UF and RO system at Company X, it was evident that the modelling tool also applies to existing plants.

The final deliverable for the study was **Figure 10:** Flow sheet of the optimisation management model (Medupi) with the 8 steps to be followed, clearly indicated.

The modelling tool consists of a technical component where the process and hydraulic calculations are conducted and a LCC evaluation. Results obtained from the LCC on the current and optimised situations are compared and the information is used by the project or plant management team to consider the next step.

The main objective of the study was:

Present management of the Medupi Power Station with a modelling tool to optimise the use of RO brine as backwash water on the UF system. By evaluating the results obtained from the modelling tool it was observed that there was a reduction in construction costs of 11.07% from the current system construction to the optimised system at the Medupi power station. This was due to the reduced number of membranes and vessels required for the optimised system as well as the smaller size of the constructed skid. Operational costs showed a reduction of 9.98% from the current system to the optimised system. Factors assisting in the reduced costs were the reduced intake of raw water and the difference in membrane replacement costs for the optimised system. It is believed by the author that the main objective was achieved by supplying the required information to the management team at the Medupi power station for consideration in final decision making. By following the steps shown in **Figure 10:** Flow Sheet of Optimisation Management Model (Medupi) the management team of the Medupi power station was presented with a solution for optimised re-use of RO brine to backwash the UF system.

The secondary objective of the study was:

The development of a modelling tool which can be used for other projects new or existing, as a measure and indication of the usability of RO brine as backwash water on UF systems. The steps indicated in **Figure 10:** Flow Sheet of Optimisation Management Model (Medupi) was followed to obtain results on the optimisation of re-use of RO brine as backwash water for the system at Company X. It was observed from the results on phase 2 of the project that the number of membranes on the current system can be reduced from 8 to 7. The operating cost will be reduced with 14.27% from the current system to the optimised system. Overall system recovery can be increased from 69.77% to 88.27%. The application of the modelling tool was on an existing operating system. It is believed by the author that the secondary objective was achieved by applying the modelling tool to an existing system and achieving results that can be presented to the management team at Company X for optimisation of re-use of the recovery RO brine to backwash the UF system.

5.2 Future study

The prediction of scaling on membrane systems is a field of study which justifies research on a master’s degree level by itself. For the purpose of this study, developing a model to optimise the use of reverse osmosis as backwash water for a UF system only the LSI indicator was used for predicting the scaling tendencies of the water used. It is however the opinion of the author that future study on the prediction and effect of scaling on UF membranes will be required.

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Appendix 1: Membrane questionnaire

1. What influences life of membrane?
2. What is the pore size of the membrane?
3. What is the operating pH of the membrane?
4. What is the maximum backwash flux rate?
5. What is the estimated average number of backwash cycles conducted on a membrane during the life of the membrane?
6. What parameter dictates that the membrane life is over?
7. What are the main causes of membrane failure?
8. What is the membrane compatibility in ppm-hours with cleaning chemicals:
   a. Hydrochloric acid
   b. Sulphuric acid
   c. Sodium hydroxide
   d. Sodium hypochlorite
9. How is the max and optimum backwash flux rate calculated/established?
10. How many of your UF modules are used as part of the pre-treatment system for RO units? (percentage and flow capacity if possible)
11. Do you have any installations using RO brine as backwash water to UF systems?
12. Do you have any case studies/write up on UF-RO combination plants which you can forward?

Appendix 2: Design Water analysis – Medupi power station

Constituent	Units	Croc West Average	Design Values
pH, @ 25°C		9	9,10
Conductivity, @ 25°C, K$_{25}$	µS/cm	792	950,4
Turbidity	NTU	14,3	17.16
Suspended Solids, TSS	mg/l	29	34,8
Dissolved Solids, @ 180°C, TDS	mg/l	496	595,2
Estimated TDS	mg/l	534,3	641,112
Major Cations			
Sodium, Na	mg/l	84	100,8
Potassium, K	mg/l	13	15.,6
Calcium, Ca	mg/l	42,8	51.36
Magnesium, Mg	mg/l	23,8	28,56
Ammonia, NH_3	mg/l	0,36	0,44
Hardness			
Calcium, CaH	mg/l as $CaCO_3$	107,0	128,4
Magnesium, MgH	mg/l as $CaCO_3$	99,2	119
Total, TH	mg/l as $CaCO_3$	206,2	247,4
Carbonate, CH	mg/l as $CaCO_3$	208,7	250,44
Non-Carbonate, NCH	mg/l as $CaCO_3$	0	0
Major Anions			
Chloride, Cl	mg/l	89,7	107,6
Sulphate, SO_4	mg/l	74,8	89,8
Fluoride, F	mg/l	0,53	0.64
Nitrate, NO_3	mg/l	3,9	4,68
Nitrate, NO_2	mg/l	0,329	0,39
Orthoposphate, PO_4	mg/l as PO_4	3,1	3,72
Alkalinity			
P-Alk	mg/l as $CaCO_3$	30,3	36,36
M-Alk	mg/l as $CaCO_3$	208,7	250,44

Bicarbonate Alkalinity, HCO_3-Alk	mg/l as $CaCO_3$	148,1	177,72
Carbonate Alkalinity, CO_3-Alk	mg/l as $CaCO_3$	60,6	72,72
Hydroxide Alkalinity, OH-Alk	mg/l as $CaCO_3$	0	0
Total Alkalinity, T-Alk	mg/l as $CaCO_3$	208,7	250,44
Ionic Balance			
Total cations, TC	mg/l	164,0	196,8
Total Anions, TA	mg/l	398,4	467.3
Organics			
Oxygen Absorbed, OA	mg/l as O_2	Not tested	Not tested
Chemical Oxygen Demand, COD	mg/l		17**
Dissolved Organic Carbon, DOC	mg/l as C	Not tested	Not tested
Total Organic Carbon, TOC	mg/l as C		8.8**
Ration DOC: TOC		N/a	N/a
Ration DOC: COD		N/a	N/a
Silica			
Total Silica, SiO_2	mg/l	14,3	17,16
Reactive (Soluble/ionic) Silica, SiO_2	mg/l	10,9	13,08
Non-Reactive colloidal/particulate)Silica, SiO2	mg/l	3,4	4,08
Other (Trace) Constituents			
Barium, Ba	mg/l	0,08	0,10
Strontium, Sr	mg/l	0.24	0.24
Iron, Fe (Total)	mg/l	0,2	0,24
Manganese, Mn	mg/l	0,02	0,02
Boron, B	mg/l	0,27	0,32
Aluminium, Al	mg/l	0,03	0.04
Arsenic, As	mg/l	NR	
Beryllium, Be	mg/l	0,005	0,01
Cadmium, Cd	mg/l	0,005	0,01
Chromium, Cr	mg/l	0,024	0,03
Cobalt, Co	mg/l	0,01	0,01
Copper, Cu	mg/l	0,01	0,01
Cyanide, CN	mg/l	0,025	0,03

Lead, Pb	mg/l	0,03	0,04
Nickel, Ni	mg/l	0,01	0,01
Phosphorus, P	mg/l	1	1,20
Selenium, Se	mg/l	NR	
Strontium, Sr	mg/l	0,2	0,24
Vanadium, V	mg/l	0,023	0,03
Zinc, Zn	mg/l	0,039	0,05

Appendix 3: Presentation slides

Re-use and Optimization

of the

Waste stream from UF and RO

system at the Boksburg Facility

Company X

2012/03/09

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Current system: Overview

- Feed water is municipal supply.
- Current system include UF followed by RO system.
- UF system capacity = 35.83m^3/h
- RO capacity = 25m^3/h

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Water Solutions

Current system: investigation

- **Situational question**:
- How much water currently is going to drain?
- 10.838 m^3/h
- What is the current system recovery?
- 69.77%

Current system: investigation

- **Problem questions:**
- What is currently done about the amount of waste?
- Recovery RO is being installed.
- **Implication Question:**
- What is the effect of the waste stream on costs?
- The waste stream from the UF and RO adds to the cost of services.

NanoTech
Water Solutions

Current system: investigation

- **Need Pay-off question?**
- What will the benefit be to Re-use the water?
  - Reduction in waste effluent costs.
  - Reduction in raw water intake.
  - Reduction of waste loading on environment.

Proposal:

- **Phase 1: Recovery RO system (currently being implemented)**
- RO brine will be send to a storage tank and will be treated with another RO system (Recovery RO).
- The recovery RO will produce 5m^3/h permeate that will be returned to the Raw water storage tank, reducing the amount of raw water intake. It also reduce the amount of waste discharge.
- Recovery RO system will operate at 65% recovery, increasing overall recovery to 81.1% (from 69.77%)

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Water Solutions

Proposal:

- **Phase 2: Re-use Recovery RO brine for backwashing UF system**
- Recovery RO brine will be send to a storage tank and will be re-used to backwash UF system.
- The waste stream will be reduced to 3.32 m^3/h from 5.83 m^3/h.
- The system overall recovery will be increased from 81.1% to 88.27%.

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Summary of phase 1 and 2 recoveries:

Phase	Feed flow (m³/h)	RO permeate flow (m³/h)	RO Brine Flow (main or secondary) (m³/h)	UF waste flow (m³/h)	Total waste flow (m³/h)	System Recovery, percentage
Original system	35.83	25	8.33	2.508	10.838	69.77
Phase 1	30.83	25	3.33	2.508	5.838	81.08
Phase 2	28.32	25	0.82	2.508	3.33	88.27

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Assumptions made:

No	Assumption	Basis of assumption
1	With the use of secondary RO brine the required number of cleaning cycles (CIP) will not increase for the optimised design in phase 2.	The LSI of the secondary RO brine reject indicates that the water will not have a scaling tendency.
2	Membrane life will be the same for the 2 situations.	Estimated cleaning cycles will be the same.
3	Water consumption is based on 24 hour operation.	System operation from design documents include for 24 hour operation.
4	CIP cost will be excluded from LCC	Cost for 2 options will be the same.

LCC – Current system:

LCC – Current situation	
Parameter	Value
Construction cost	
Total construction costs	Not included
Operational expenditure - Monthly	
Chemical consumption cost per month	Not included
Membrane replacement cost per month	Not included
Raw feed water cost	R 266,376.00
Waste water discharge cost	R 56,838.00
Maintenance cost - Monthly	
Not included	
Monthly cost – Operational expenditure	R 323,214.00

LCC Phase 2:

LCC – Optimised situation (phase 2)	
Parameter	Value
Construction cost	
Total construction costs	R 101,560.00
Operational expenditure - Monthly	
Chemical consumption cost per month	Not included
Membrane replacement cost per month	Not included
Raw feed water cost	R 244,704.00
Waste water discharge cost	R 32,394.00
Maintenance cost - Monthly	
Cost is negligible and will be excluded.	
Monthly cost – Operational expenditure	R 277,098.00

LCC Comparison:

LCC comparison: Current (Phase 1) vs optimised situation (Phase 2)				
Cost	Current situation - Phase 1	Optimised situation - Phase 2	Difference (percentage)	Comment
Construction cost	0.00	101 560.00	0.0%	System Installed and operating. Only optimised system requires capital.
Operating cost, monthly	323 214.00	277 098.00	14.27%	Optimised cost beneficial.
Maintenance cost	0.00	0.00	0.00%	Parameter not part of LCC.

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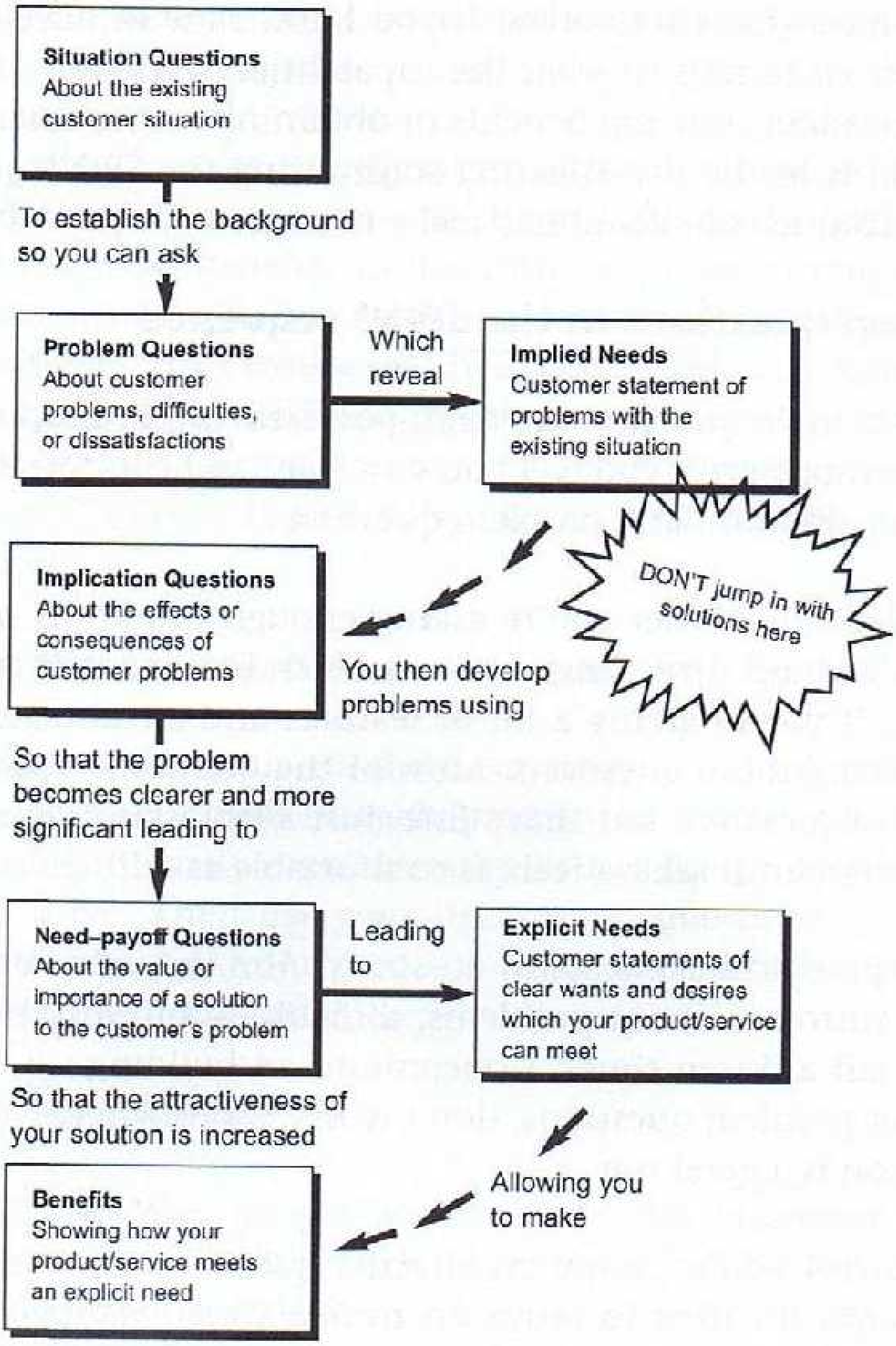
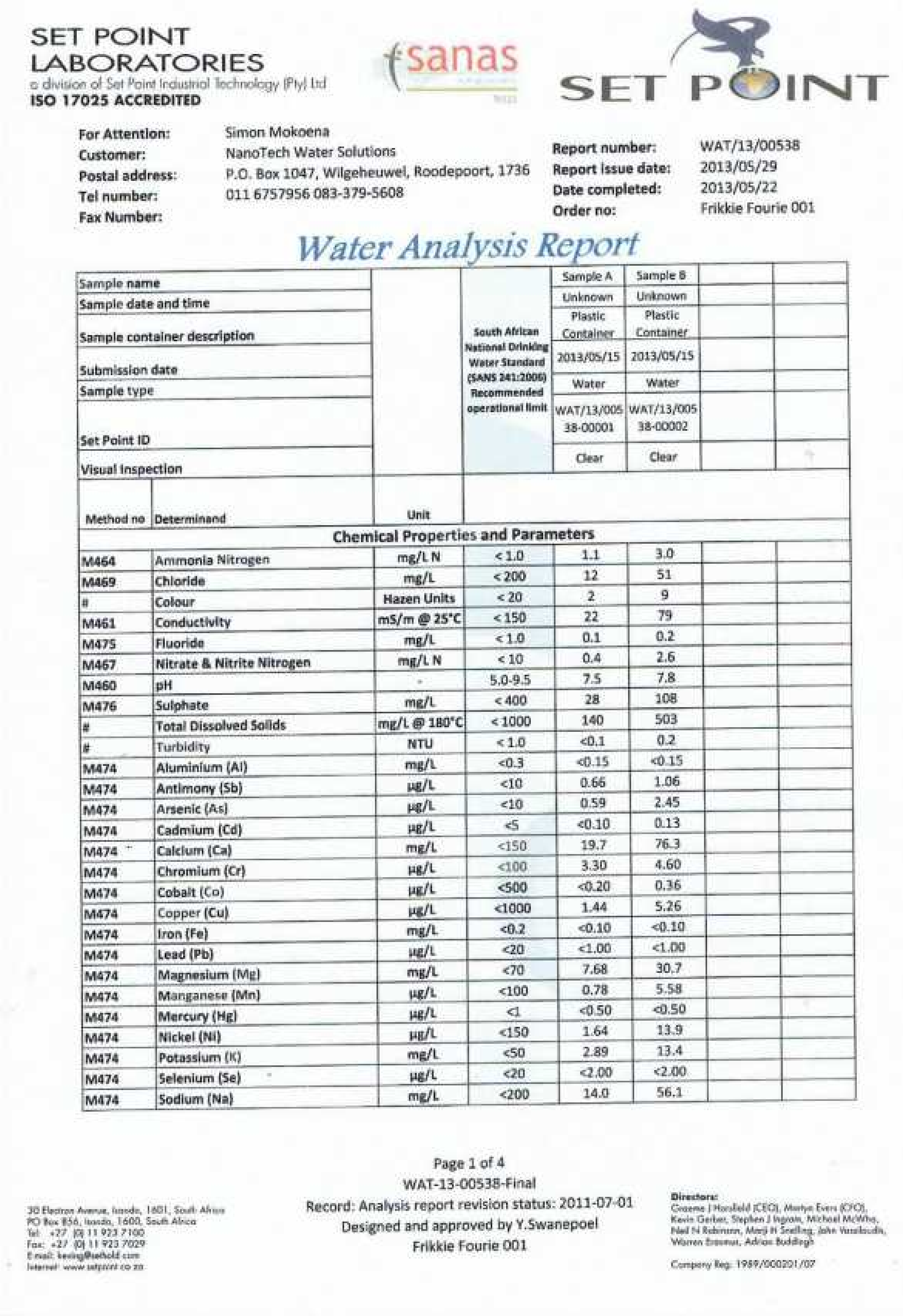
Final discussion:

- The operational saving of approximately 14.27% is a significant cost.
- The overall system recovery can also be increased from 81% to 89%.
- The estimated construction cost for phase 2 implementation is R101,560.00.
- With the savings achieved on a monthly basis the project will have a payback period of 3 months.

Appendix 4: The Spin® Model flow sheet



Appendix 5: Water analysis – Main RO Brine Company X



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ISO 17025 ACCREDITED

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Report issue date: 2013/05/29
Date completed: 2013/05/22
Order no: Frikkie Fourie 001

Water Analysis Report

Sample name			**South African National Drinking Water Standard (SANS 241:2006) Recommended operational limit**	Sample A	Sample B		
Sample date and time				Unknown	Unknown		
Sample container description				Plastic Container	Plastic Container		
Submission date				2013/05/15	2013/05/15		
Sample type				Water	Water		
Set Point ID				WAT/13/00538-00001	WAT/13/00538-00002		
Visual Inspection				Clear	Clear		
Method no	**Determinand**	**Unit**					
Chemical Properties and Parameters							
M464	Ammonia Nitrogen	mg/L N	< 1.0	1.1	3.0		
M469	Chloride	mg/L	< 200	12	51		
#	Colour	Hazen Units	< 20	2	9		
M461	Conductivity	mS/m @ 25°C	< 150	22	79		
M475	Fluoride	mg/L	< 1.0	0.1	0.2		
M467	Nitrate & Nitrite Nitrogen	mg/L N	< 10	0.4	2.6		
M460	pH	-	5.0-9.5	7.5	7.8		
M476	Sulphate	mg/L	< 400	28	108		
#	Total Dissolved Solids	mg/L @ 180°C	< 1000	140	503		
#	Turbidity	NTU	< 1.0	<0.1	0.2		
M474	Aluminium (Al)	mg/L	<0.3	<0.15	<0.15		
M474	Antimony (Sb)	µg/L	<10	0.66	1.06		
M474	Arsenic (As)	µg/L	<10	0.59	2.45		
M474	Cadmium (Cd)	µg/L	<5	<0.10	0.13		
M474	Calcium (Ca)	mg/L	<150	19.7	76.3		
M474	Chromium (Cr)	µg/L	<100	3.30	4.60		
M474	Cobalt (Co)	µg/L	<500	<0.20	0.36		
M474	Copper (Cu)	µg/L	<1000	1.44	5.26		
M474	Iron (Fe)	mg/L	<0.2	<0.10	<0.10		
M474	Lead (Pb)	µg/L	<20	<1.00	<1.00		
M474	Magnesium (Mg)	mg/L	<70	7.68	30.7		
M474	Manganese (Mn)	µg/L	<100	0.78	5.58		
M474	Mercury (Hg)	µg/L	<1	<0.50	<0.50		
M474	Nickel (Ni)	µg/L	<150	1.64	13.9		
M474	Potassium (K)	mg/L	<50	2.89	13.4		
M474	Selenium (Se)	µg/L	<20	<2.00	<2.00		
M474	Sodium (Na)	mg/L	<200	14.0	56.1		

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WAT-13-00538-Final
Record: Analysis report revision status: 2011-07-01
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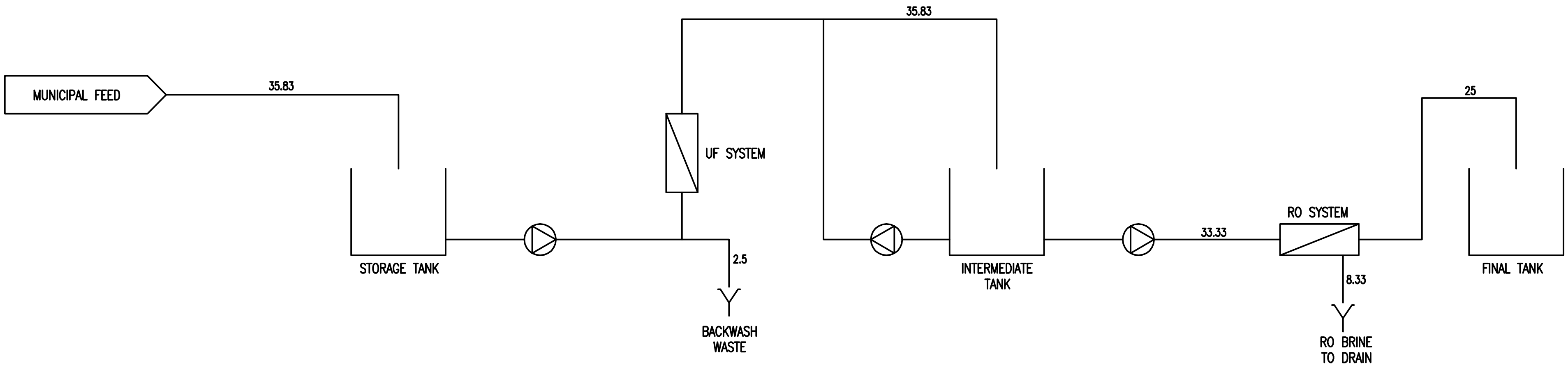
Company Reg: 1989/000201/07

Appendix 6: PFD current system Company X

PROCESS FLOW DIAGRAM: COMPANY X – ORIGINAL

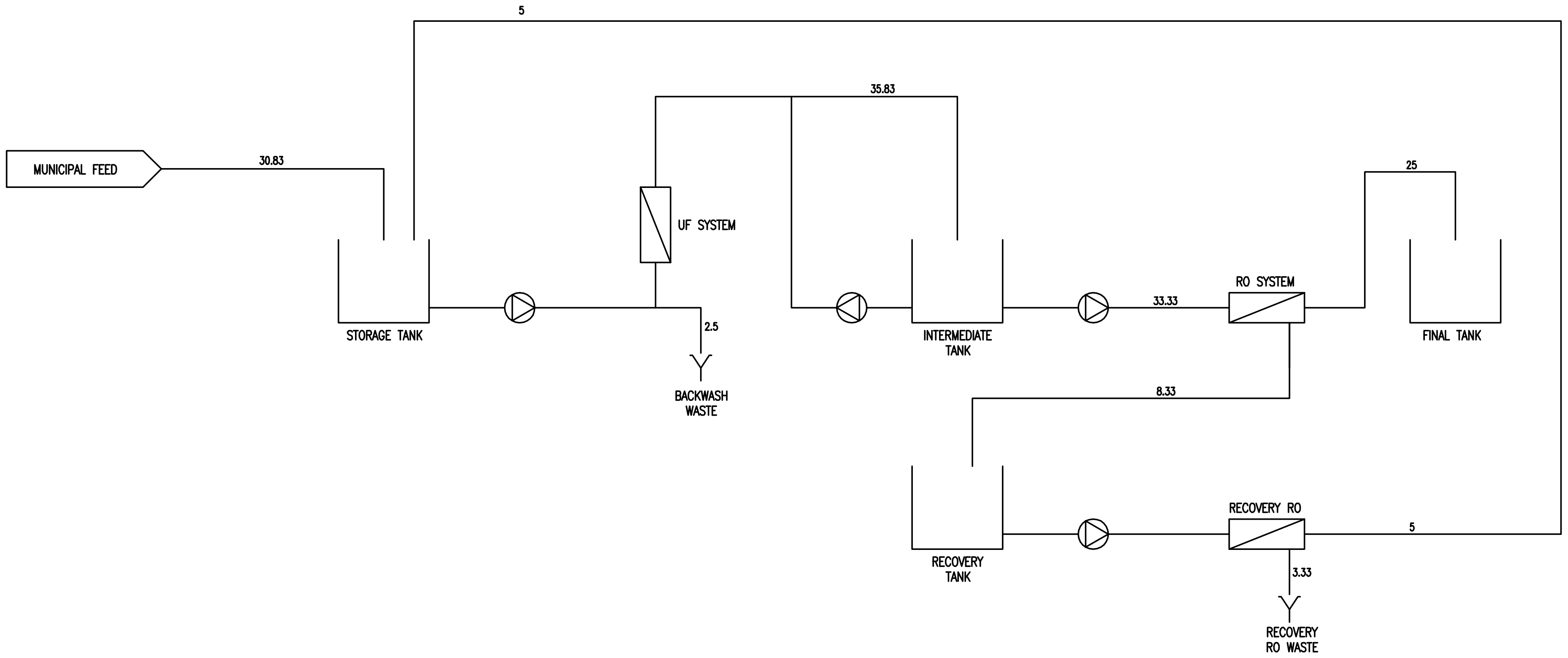


NOTES:

- FLOW IN m^3/h
- TOTAL RECOVERY = 69.77%

Appendix 7: PFD phase 1 system - Company X

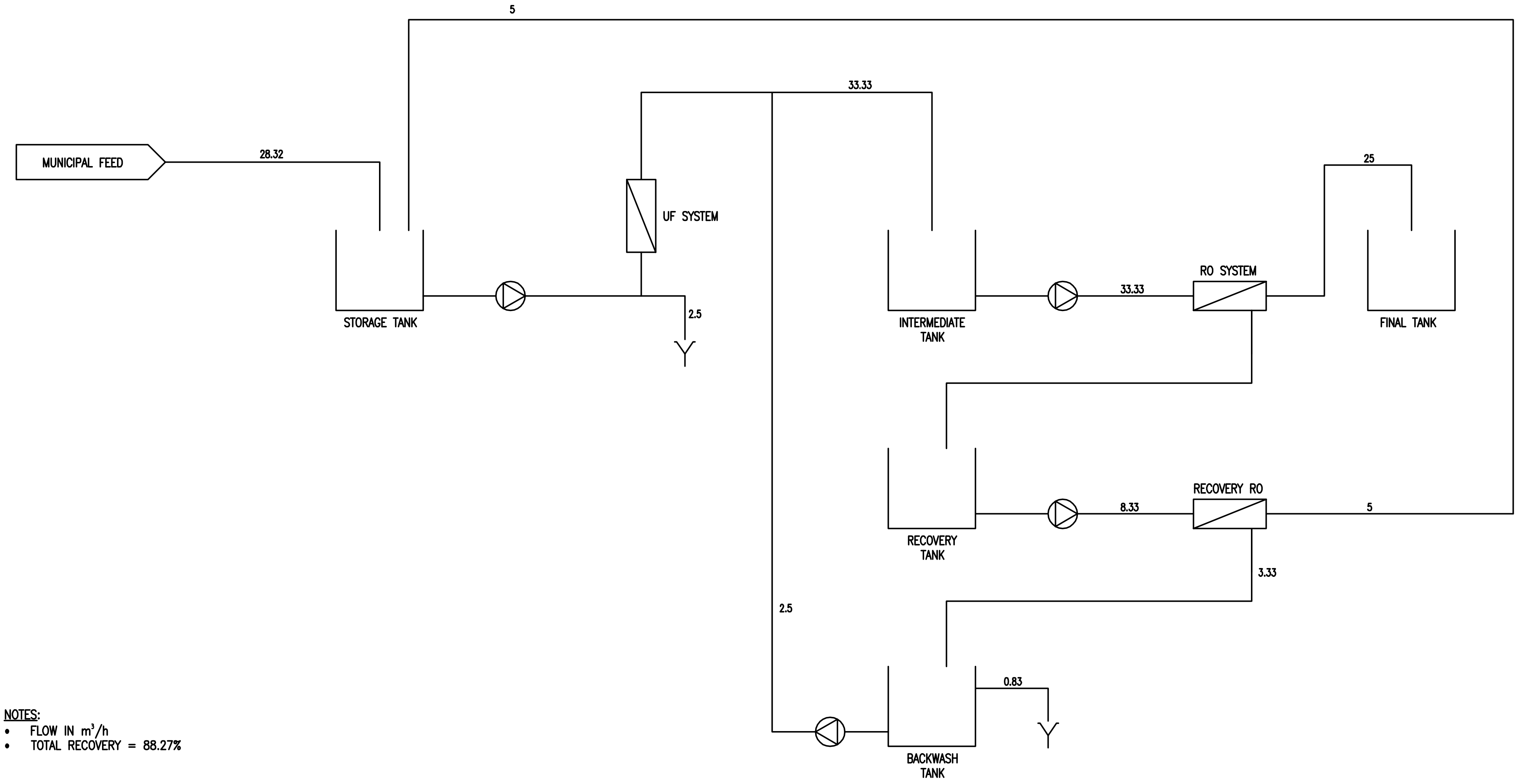
PROCESS FLOW DIAGRAM: COMPANY X – PHASE 1



NOTES:
- FLOW IN m^3/h
- TOTAL RECOVERY = 81.1%

Appendix 8: PFD phase 2 system – Company X

PROCESS FLOW DIAGRAM: COMPANY X – PHASE 2



NOTES:
- FLOW IN m^3/h
- TOTAL RECOVERY = 88.27%