UNIVERSITY OF KWAZULU-NATAL

A COMBINATION OF EXPERIMENTAL AND PROGRAMMING BASED MATERIAL BALANCING USED WITH A NUMERICAL PINCH ANALYSIS TO REDUCE THE WATER CONSUMPTION AT A TISSUE MILL

VOLUME ONE

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In fulfilment of the degree of Master of Science in Engineering, Faculty of Engineering, University of KwaZulu-Natal

20-10-2012

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Acknowledgements

I would like to acknowledge the following individuals and institutions:

- My supervisors at the University of Kwazulu-Natal, Prof C. A. Buckley, Mr I. Kerr and Dr K. Foxon as well as Mr F. Roets and Mr F. Hansen from Kimberly-Clark South Africa, for all of their knowledge and guidance
- Mr N.M. Mkhize and Mr K.S. Mphasha at Kimberly-Clark South Africa for all their assistance
- Kimberly-Clark South Africa and The National Research Foundation (NRF) for their financial assistance
- Mr M. Lasich for all his guidance and assistance
- Mr T. Moodley for his assistance
- My fellow postgraduates and colleagues, and the academic and support staff of the Pollution Research Group, for creating a pleasant working and learning environment
- My friends and family, for all of their support during this project

ABSTRACT

The pulping and paper industry of South Africa relies on two primary raw materials; fibre and water. These materials are used in large quantities and the increasing water and wastewater tariffs have impacted heavily on the industry. A South African tissue mill therefore wishes to reduce its specific water consumption.

The aim of the research was to investigate the use of process simulation, water recycle, water reuse and the application of best practices to reduce the specific water consumption for the both the tissue machines at the mill.

Rather than looking at equipment changes pinch analysis was the approach used because it offers a more cost effective and long term solution. After a literature review the water cascade analysis approach proposed by Ng et al. (2007) was selected. This numerical method defines the pinch point clearly. Whilst graphical methods also define the pinch point, it is difficult to identify this point if the streams near the pinch point have similar contaminant concentrations.

A detailed material balance is required to carry out a water pinch. Examination of the mill's process flow diagram showed that insufficient information was available to complete the material balance with an accurate representation of the mill's processes.

Due to the large number of streams to be determined for each tissue machine as well as the large stream flows, physical sampling would have been impractical. Hence it was decided to combine the sampling and mass balance programming methods.

All flows where determined by back-calculation using mean production rates corresponding to the month during which samples were taken, to ensure data consistency. Statistical data analysis was performed to determine the degree of variance in the data so that all possible operating conditions were considered in the pinch analysis.

Then the water cascade analysis was performed to determine the pinch point which indicated where regeneration efforts should be focused.

Various scenarios where considered such that the true pinch point could be determined and also to compare the various regeneration configurations.

A rotary-disc filter was selected as the regeneration unit for tissue machine number one and a microfiltration unit for tissue machine number two. The network necessary to achieve the minimum targets calculated from the pinch was determined from the nearest neighbours algorithm proposed by Prakash and Shenoy (2005). Various network configurations were considered from a quality perspective.

It was determined that the specific water consumption could be reduced from 21 $m^3.ton^{-1}$ of tissue manufactured to 7 $m^3.ton^{-1}$ tissue manufactured (i.e. 66.67% reduction) on tissue machine number one and from 21 $m^3.ton^{-1}$ tissue manufactured to 8 $m^3.ton^{-1}$ tissue manufactured (i.e. 61.91% reduction) on tissue machine number two.

There is a corresponding reduction in wastewater flow to effluent plant treatment (ETP). There is no extra contaminant loading to the effluent treatment plant and as there is increased fibre recovery in the production process. Current chemical oxygen demand and biological oxygen demand control systems can still be utilised therefore there will be no appreciable accumulation in the system. The potential for energy savings is limited to heating of fresh water by the vacuum seal water as no other feasible temperature gradient exists.

Engineering and operational feasibility analyses need to be undertaken in conjunction with the factory management.

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Glossary

Accepts	:	Accepted portion of pulp/stream after cleaning and/or screening operations and separation processes
Adsorbtion	:	The accumulation of gases, liquids, or solutes on the surface of a solid or liquid
Basis	:	An amount (mass or moles) or flow rate (mass or molar) of one stream or stream component in a process
Batch process	:	The feed charged into a vessel at the beginning of the process and the vessel contents are removed sometime later. No mass crosses the system boundaries between the time the feed is charged and the time the product is removed
Battery limit	:	A geographical boundary defining the coverage
Biological oxygen demand	:	A measure of the organic pollution of water. The amount of oxygen, in mg per litre of water, absorbed by a sample kept at 20°C for five days
Broke	:	Paper/tissue that is unusable because of damage or non-conformity to the specifications. It is put back into the pulping system
Cationic Demand	:	The cationic demand of a sample of paper/tissue making furnish or process water equals the amount of highly charged cationic polymer required to neutralize the charge of fibres, particles and colloids in the furnish
Chemical oxygen demand	:	The amount of oxygen (in mg) required for the complete chemical oxidation of organic and inorganic material in 1 litre of an effluent
Chromophore	:	A chemical compound capable of selective light absorption resulting in the colouration of that compound
Clarified Water	:	Water of a higher purity than that of the cloudy water removed from the *save-all*
Cloudy Water	:	Water of a low purity removed from the save-all
Consistency	:	The fraction of bone-dry solids by weight in pulp or stock
Continuous process	:	The inputs and outputs flow continuously throughout the duration of the process

Countercurrent	:	A current that flows in an opposite direction to the flow of another current
Deaeration	:	Removal of gas or air from a liquid
Deflocculation	:	The dispersion of solids that have stuck together
Denitrification	:	Denitrification is essentially the conversion of nitrate to nitrogen gas
Desorption	:	The process of removing a sorbed substance by the reverse of adsorption or absorption
Electrodialysis	:	Electrodialysis is an electrically driven membrane separation process that is capable of separating, concentrating, and purifying selected ions from aqueous solutions (as well as some organic solvents
Filtrate	:	Water removed from a regeneration unit
Fixed load problem	:	Fixed load problems are the mass transfer based water-using processes. Water losses are negligible; water flows into and out of the system is constant. The main concern is the transfer of some fixed load impurity
Fixed rate problem	:	Fixed rate problems are those in which the water flows into and out of the system are not constant. The concern is the water usage in the system; it applies the concept of water source and sink
Floc	:	A small loosely aggregated mass of flocculent material suspended in or precipitated from a liquid
Fourdrinier	:	Named after its inventor, the Fourdrinier papermaking machine is structured on a continuously moving wire belt on to which a watery slurry of pulp is spread. As the wire moves, the water is drained off and pressed out, and the paper is then dried.
Furnish	:	A blend of fibres, pigments, dyes, fillers and other material that is fed to the wet end of the paper/tissue machine
Grass-roots plant	:	Complete plant erected on a new site
Intervention	:	To change the outcome of a condition or process. In the context of this thesis is refers to what was done to address the pinch point.
Kraft pulp and paper	:	Chemical wood pulp produced by digesting (see digester) wood by the sulphate cooking (pulping) process. This pulp is used to make Kraft bag paper and Kraft paper

Level	:	In pinch analysis it is the different concentration levels in the water cascade analysis
Nip	:	Point where two squeeze rolls meet on the paper/tissue
Ozonation	:	Ozonation is a water treatment process that destroys bacteria and other microorganisms through an infusion of ozone, a gas produced by subjecting oxygen molecules to high electrical voltage.
Pinch point	:	In pinch analysis it is the constraint condition which limits further reduction of a utility (water or steam). There will exist at a certain concentration and purity level k where $F_{FW,k} = 0$. This concentration is referred to as the pinch. It is the point where the source switches from being below a demand (deficit) to being above a demand (surplus)
Recovered paper	:	Paper recovered for recycling into new paper products. Recovered paper can be collected from industrial sources or from household collections
Recycle	:	Process water/effluent is allowed to re-enter the unit from where it has been previously used
Recycled Fibre	:	Fibre obtained from recovered paper
Regeneration	:	In pinch analysis regeneration refers to the partial or total upgrading of water purity using purification techniques
Rejects	:	Material removed and discarded during the cleaning, screening and separation operations
Relative standard deviation	:	The percentage difference between the standard deviation and the mean
Re-use	:	The process water/effluent produced in one unit is used in another unit but it will not re-enter the unit from which it had left
Scale down	:	Final stream quantities are smaller than the original quantities
Scale up	:	Final stream quantities are larger than the original quantities
Scaling	:	The procedure of changing the values of all stream amounts or flow rates by a proportional amount while leaving the stream compositions unchanged
Semi batch process	:	Any process that is a neither batch nor a continuous process
Sink	:	In pinch analysis a *sink* refers to a unit or stage of a process where water of a particular quality is required to be added to a process

Soluble : Capable of being dissolved, especially easily dissolved in some solvent, usually water

Source: : In pinch analysis a *source* refers to water which is removed from a process which has the potential for reuse, recycle, regeneration and a combination thereof

Stickies : *Sticky* materials in recycled papermaking pulp, often resulting from pressure-sensitive labels

Stock : A term used to define pulp after mechanical (refining or beating) and /or chemical treatment (sizing, loading, dying etc.) in the paper/tissue making process. A pulp ready to make paper/tissue.

Sweetening stock : This is a portion of the fibre stock that is sent to the *save-all* which contributes to the fibre-matt formation. This fibre-matt is responsible for the filtering of the process water.

Virgin Fibre: : Fibre that has never been used before in the manufacture of paper/tissue or other products

Wads : Bundles of fibres

Web : This is used to describe the full width of the paper/tissue sheet in the process of being formed, pressed, finished and/or converted

White water : Water removed from the wet end of the paper/tissue machine by gravity, vacuum or mechanical action. Also referred to as process water

Wire : The moving ''screen'' at the wet end of a paper/tissue machine where the sheet is formed

Yankee : A type of Fourdrinier paper machine employing a single dryer of large circumference with highly polished surface

Zeta potential : The zeta potential (ζ-potential) is the potential difference across phase boundaries between solids and liquids. In colloids, zeta potential is the electric potential difference across the ionic layer around a charged colloid ion. Typically, the higher the zeta-potential, the more stable the colloid. When the zeta-potential equals zero, the colloid will precipitate into a solid

Abbreviations

BOD	:	Biological oxygen demand
CD	:	Cross machine direction (edge-to-edge)
COD	:	Chemical oxygen demand
DCS	:	Digital control system
Dev	:	Deviation
ECF	:	Elemental chlorine free
FWR	:	Fresh Water Region. The sources and sinks in the fresh water region are those which have a concentration lower than the concentration of the water stream leaving the regeneration unit
KCC	:	Kimberly-Clark Corporation
KCSA	:	Kimberly-Clark South Africa
MD	:	Machine direction (end-to-end)
NSSC	:	Neutral sulphite semi-chemical pulping
PAMSA	:	Paper manufacturers association of South Africa
RR	:	Removal ratio
RWB	:	RWB- Rand Water Board (source of fresh water)
RWR	:	Regenerated Water Region: The sources and sinks in the regenerated water region are those which have concentrations higher than that of the regeneration unit
SBR	:	Single breast roll
Std	:	Standard
TM1	:	Tissue machine number one
TM2	:	Tissue Machine Number Two
USA	:	United States of America
VOC	:	Volatile organic compounds
WCA	:	Water Cascade Analysis: Numerical procedure used to determine the minimum water targets
WCT	:	Water cascade table: Used in the water cascade analysis technique

Nomenclature

$F_{C,k}$	:	Cumulative surplus or deficit flowrates (ℓ.min^{-1})
$F_{FW,k}$	:	Interval feed water flowrate (ℓ.min^{-1})
$F_{i,A}$	:	Additional source flow to be reallocated to the fresh water region, which has to be equal to the additional sink flow since these must be equal to avoid imbalance in the regenerated water region (ℓ.min^{-1})
Δm_k	:	Impurity load (ℓ.min^{-11})
C	:	Concentration (mg. ℓ^{-1})
$C_{i,A}$	:	Limiting concentration of the additional source to be allocated to the fresh water region (mg. ℓ^{-1})
$C_{j,A}$	:	Limiting concentration of the additional sink to be allocated to the fresh water region (mg. ℓ^{-1})
C_{pinch}	:	Pinch concentration (mg. ℓ^{-1})
$Cum\Delta m_k$	:	Cumulative impurity load (ℓ.min^{-1})
D	:	Demand (-)
Dp	:	Demand of given concentration level (-)
F	:	Flowrates (ℓ.min^{-1})
F_{FW}	:	Minimum fresh water flowrate (ℓ.min^{-1})
F_jC_j	:	Additional load which can be accepted by the sink in the fresh water region (ℓ.min^{-1})
F_{WW}	:	Minimum wastewater flowrate (ℓ.min^{-1})
S	:	Source (-)
$S(k+1)$	:	Source with contaminant concentration just higher than that of *Dp (-)*
Sk	:	Source with contaminant concentration just lower than the concentration of demand *Dp* (-)

Subscripts

i	:	source
j	:	sink
k	:	level
m	:	Number of demands (sinks)
n	:	Number of sources

Outline of thesis

This provides an overview of the chapters present in the thesis and the details which are included in each.

Chapter 1 - Introduction

In **Chapter 1** the introduction, history of the mill, importance of the study, aims and objectives and the hypothesis are highlighted. The aim of the resulting dissertation was to:

- Construct a calibrated and verified mass balance process model of the mill (only considering each tissue machine and associated stock preparation independently)
- Use the model to assess the corresponding change in specific water consumption for each machine through rerouting of process streams and installation of new equipment and the environmental impacts thereof
- Produce an improvement strategy with an outline of trials which should be undertaken

The primary hypothesis which was tested: *A calibrated and verified mass balance process model of a tissue mill can be used to rationally reduce the specific water consumption of the mill.*

Chapter 2 - The tissue making process

In **Chapter 2** the tissue making process is described. It is divided into the following processing sections:

- Stock preparation
- White-water circuit
- Press section
- Drying section

The specifications in terms of water purity requirements for use in the water pinch analysis are described. The need in the pulp and paper industry for water reuse, recycle and regeneration is also discussed. From the description of the tissue making process presented, the process is defined as a fixed-rate type of problem from a water pinch perspective.

Chapter 3 - Literature review – process integration and water pinch analysis

One of the aims of the project (which commenced in 2010) was to find a suitable approach to systematically reduce the specific water consumption at a tissue mill with associated application at other papermaking mills. The significant factors were the total suspended solids concentration, tissue quality constraints, process water quality constraints, effluent water quality constraints, plant space, economics and a long term solution.

A limitation was not placed on the way that the objective had to be achieved, therefore one of two options could be selected, that is, equipment unit modifications or process integration. For this project, process integration techniques, specifically water pinch analysis was selected as the more effective approach; this is due to process integration being a more cost effective and long term solution (Ng and Foo, 2007; Foo et al., 2008). The process integration approach identifies the problem in the system clearly and therefore indicates where further improvement efforts should be focused. The equipment unit modification approach would not allow for this and may therefore not alleviate the system bottlenecks.

Chapter 3 presents a survey of the various water pinch analysis techniques available and their applicability to the tissue making process. Process integration is described, the concepts of fixed-load and fixed-rate type of problems are introduced and the pinch point is defined and the importance of the pinch point is highlighted.

The pinch point is significant because it identifies the bottleneck in the system which limits the reuse of utilities. It is around this point that regeneration and recovery efforts should be focused in order to ensure maximum reuse of utilities.

Since the tissue making process was defined as a fixed-rate type of problem in **Chapter 2** and therefore these methods are described in Chapter 3. The fixed-load type of problem is not focused on in this survey and must be referred to in their original works.

From the comparison of the various methods described in **section 3.1** to **section 3.5**, an appropriate method was selected in **section 3.6**. This selected method was the ultimate flowrate targeting technique of Ng et al. (2009). It is a water cascade analysis technique which is capable of determining the pinch point and the minimum fresh water, regenerated water and minimum effluent water flowrates in a single calculation step (not via an iterative process). The method can also be applied to systems with multiple fresh water sources and threshold problems.

The detail of application of the method is discussed in **Chapter 4**.

Chapter 4 - Ultimate flow rate targeting technique of Ng et al with regeneration placement (2009)

In **Chapter 4** the concepts of water reuse, recycle and regeneration are discussed. The calculation procedure applied in the ultimate flowrate targeting technique of Ng et al. (2009) is described in **section 4.1** to **section 4.5.** The method is then applied to the tissue making process in **Chapter 6** through to **Chapter 8**. The requirements for the application of the pinch analysis method are also discussed; this includes contaminants of significance, utility flows and contaminant concentrations.

Chapter 5 - Material balances

In order to apply the pinch analysis method the material flows into and out of the process units were required. Piping and instrumentation diagrams were used to develop detailed process flow diagrams for the material balance approach.

Due to gaps in the process flow information available and the large quantity of information required to be gathered in order to have a full material balance a combined sampling and process modelling approach was selected.

The reason for the numerous sample points to be tested (**Appendix C**) was because all the water and stock streams were not monitored in detail on a daily basis. Firstly because every unit was not accessible for sampling and secondly, only certain streams were required to be monitored because if these are controlled correctly then downstream units and lines should be at the process conditions required for efficient operation.

Since stream property data were not being monitored regularly, there was not any historical mill data available for all the required streams of the material balance; therefore a rigorous sampling campaign had to be undertaken. The sampling was necessary because exact contaminant concentrations of the monitored water lines were needed to ensure an accurate representation of the processing systems and hence ensure an accurate pinch calculation. All data taken from the distributed control system (DCS) were the set-points as these indicated the ideal operating conditions of the tissue machine and would be the desired steady-state values.

Three samples were taken of each stream investigated because this is the minimum number of samples that can be taken which can describe the distribution of data within reasonable accuracy. This was selected as a compromise between accuracy, the number of different sample points and the total time for analysis.

Data statistical analysis was performed on all samples to give an indication of the spread of the data, that is, to see how the data varies across a unit as well as through the system. A normal distribution was assumed due to the data being dependent on a number of variables which were not being monitored as part of the study.

From the data statistical analysis the mean values were used for normal operating conditions and the upper limit of the confidence interval was used for worst case operating conditions. In this way the pinch analysis can consider all ranges of operating conditions.

The material balance was then performed using this sample data. The Matlab code was developed to facilitate the application of Cramer's rule (**Appendix B**) and was used in association with Excel to calculate material balances for both the tissue machines. The models developed were input to Excel, data from Excel were entered to Matlab, output data from Matlab was once again entered into Excel. This process was iterated until the material balance converged (**Figure 5-1**). The data obtained from the calculation method were checked against process data which were recorded on the digital control system (**Appendix D**) this was also to investigate and confirm the consistency on the material balance.

The combination of Matlab and Excel was selected because Matlab quickly and accurately performs matrix calculations and eliminated the need for hand-based calculations and Excel outputs the data in a more user-friendly way than Matlab. Each equipment unit was reduced to a system of n independent equations with n unknowns to produce a $n \times n$ matrix. This was done for two reasons, for each unit, all streams were not required to be tested if Cramer's rule was applied and second, all sample points around the units were not accessible hence Cramer's rule allowed for the calculation of all necessary streams with minimal amount of data sampling.

The advantage of having a detailed material balance of the process was that it allowed the analysis to be done even if one was not physically present at the mill. One of the limitations of the project was the distance between the plant where sampling was conducted and the university where data analysis was performed. Therefore having an accurate material balance representation of the mill tissue making processes was essential and facilitated the analysis of the process system.

The preliminary work discussed could have been tackled in an alternate approach, that is, assumptions regarding mill operations could have been made in respect to operating flowrates, contaminant concentrations and equipment operation based on existing mill information. Using this assumed information, the pinch point could have been determined and then a sampling campaign could have been undertaken for only the streams around the pinch point because it is only these streams which will affect the minimum water targets. This would have reduced the amount of sampling which had to be done, leading to a shorter sampling period.

However it must be noted that due to the limitation of not being constantly present at the mill (mill located in Springs, Gauteng, whilst analysis was performed at UKZN), a detailed material balance was more useful as it allowed analysis of the mill's system to be conducted even while away from the mill. Therefore the extensive sampling period was necessary.

The results of the material balance procedure are highlighted in **section 5.4.1** and **section 5.4.2** for tissue machine one and tissue machine two respectively. These material flows were used in the water cascade analyses.

It was important that the representation of the sources and sinks in terms of contaminant concentration and flowrate was accurate because these properties of the source and sink impacts on the pinch point determined; this must be considered when applying the pinch analysis methods.

Chapter 6 - Initial pinch analysis

The pinch analysis method of Ng et al. (2009) discussed in **Chapter 4** was applied to tissue machine number one and to tissue machine number two to determine the pinch point for each of the machines in **Chapter 6**. This section describes the various water cascade analyses performed on each of the tissue machines with further analyses in **Chapter 8**.

According to Ng et al (2009), regeneration should occur across the pinch point, that is, the stream which is identified as the pinch causing stream is where regeneration efforts should be focused. For determining the minimum regeneration flow rate, the system must be divided into the fresh water region and the regenerated water region. These regions and the various reallocations of sources and sinks which can occur are described in **section 6.1**. When reallocations were performed, source and sink streams were shifted entirely, that is, stream splitting did not occur unless the stream splits were practical; the reallocations were conducted in this way and it was performed such that the source and sink flows in the fresh water region and regenerated water region were as close as possible to being evenly - balanced

The various water pinch analyses which were performed on tissue machine one and tissue machine two are described in **Table 6-1**.

From the initial water cascade analysis performed the following was determined:

	Tissue machine number one	Tissue machine number two
Pinch point	Vibrating screen accepts	Main vacuum separator and single breast roll/vacuum pumps
Pinch flowrate	8401 ℓ.min^{-1}	783 ℓ.min^{-1}/1500 ℓ.min^{-1}
Pinch contaminant concentration	1885 mg.ℓ$^{-1}$	6 mg.ℓ$^{-1}$/42 mg.ℓ$^{-1}$

The difference in pinch points between the machines results from the difference in water purity constraints for each of the machines (as described in **Chapter 2**). This indicates that he pinch point was sensitive to the differences in contaminant concentrations allowed to the process units (sinks). The more relaxed the purity requirements, the lower the regeneration flowrate required; also if the purity requirements are relaxed it will result in the higher purity sinks being the limitation in process water recycle because it will require higher purity water than the process water available and hence fresh water will have to be used to supply the sink.

The implications of these different pinch points are that different degrees of regeneration will be required for each of the tissue machines in order to reduce the specific water consumption. The various regeneration schemes are discussed in **Chapter 7**.

Chapter 7 - Intervention

From the pinch analysis results obtained Chapter 6, it was determined that a solid-liquid separation unit would be required to alleviate the pinch point.

Considering the different degrees of regeneration needed, two different regeneration units would be required for the two tissue machines. Necessary regeneration unit outlet concentrations are required before the source-sink reallocation procedure described by Ng et al. (2009) can be performed.

The following procedure was used to determine the degree of regeneration required:

1. Use the water cascade analysis to determine the implication of various regeneration concentrations on the pinch point and associated fresh water usage
2. Investigate various regeneration units capable of achieving the regeneration concentration determined in (1)
3. Apply regeneration concentration in the method of Ng et al. (2009)

It is important to determine the degree of regeneration required because if it is required to regenerate to a very low regeneration concentration, then a greater amount of work will be required to be performed by the regeneration units, therefore, only what regeneration is necessary should be performed. By investigating the effect of various regeneration concentrations on the fresh water required, one can determine the degree to which the process water needs to be treated i.e. how big a difference does a lower regeneration concentration make on the fresh water consumption? The pinch analysis can be used to determine this degree of regeneration required as described in **Figure 7-7.**

Before a regeneration concentration can be selected, it needs to be determined which regeneration concentration would reduce the fresh water consumption sufficiently with the least possible regeneration. Therefore various regeneration concentrations were investigated (**Appendix G**). The resulting fresh water flowrates with corresponding regeneration concentration is displayed in **Figure 7-7.**

Figure 7-7 was obtained by applying the water cascade analysis technique with the various assumed regeneration concentrations and determining the effect on the fresh water consumption.

In order to perform the ultimate flowrate targeting technique, the appropriate regeneration concentration needs to be determined. The effect of different regeneration concentrations was investigated by performing water cascade analyses assuming an available regenerated water source at varied regeneration concentrations.

It was determined by using various water cascade analyses that a fine-filtration unit would be required for tissue machine number one (**Figure 7-7**) and a microfiltration unit would be required for tissue machine number two. Considering all available information regarding regeneration unit capabilities required for each of the tissue machines and the associated pinch point determined in **Chapter 6**, the regeneration units assumed to be applied in the process for the purpose of the water cascade analysis were the Petax™ for tissue machine number one and a microfiltration membrane for tissue machine number two.

These regeneration units were assumed in to be providing the regeneration duty across the pinch point when the ultimate flowrate targeting technique of Ng et al. (2009) was applied.

Chapter 8 - Application of the ultimate flowrate targeting technique with the selected regeneration units

In **Chapter 8**, the various water source-sink reallocation scenarios as described in **section 6.1** were investigated. The regeneration units selected from **Chapter 7** were applied to each of the respective tissue machines. Assuming the regeneration unit placed across the pinch point, it was verified that the method did identify the global pinch point of a multiple pinch problem. When the pinch causing stream was appropriately regenerated, the pinch point shifted to the effluent stream as this would now limit reuse as it must be sent to effluent treatment. This occurred for both machines for both normal and worst case operating conditions indicating that the method did identify the global pinch point.

The purpose of performing various water cascades analyses with different fresh water region – regenerated water region combinations was to determine which would produce the lowest fresh water, regenerated water and effluent flowrates. In doing this it can also be verified if the method of Ng et al. (2009) does provide the minimum water targets via the water cascade analysis. Using these minimum water targets, effective water networks can then be developed to achieve the minimum water targets.

It has been determined from the water cascade analyses performed and discussed in **section 8.1** and **section 8.2** that the method of Ng et al. (2009) did produce the lowest fresh water, regenerated water and effluent flowrates and the system where current regeneration was replaced by an appropriate regeneration unit across the pinch point had the lower targets than the current regeneration scheme. These minimum targets are described in the table below.

Water targets applied for the development of the water networks	
Tissue Machine number one	
Fresh water target (**Figure 8-2**)	250 ℓ.min^{-1} to 300 ℓ.min^{-1}
Regenerated water target (**Figure 8-3**)	5000 ℓ.min^{-1} to 6000 ℓ.min^{-1}
Effluent water target (**Figure 8-4**)	5000 ℓ.min^{-1}
Tissue Machine number two	
Fresh water target (**Figure J-2**)	500 ℓ.min^{-1} to 550 ℓ.min^{-1}
Regenerated water target (**Figure J-3**)	915 ℓ.min^{-1}
Effluent water target (**Figure J-4**)	100 ℓ.min^{-1} to 900 ℓ.min^{-1}

The water targets determined from the reallocation process and associated water cascade analyses of Ng et al. (2009) were used in **Chapter 9** to develop the water networks to achieve the ultimate flowrate targets.

By considering all possible reallocation schemes it ensured that the networks developed will achieve the targeted water flowrates and that the targeted flowrates are the absolute minimum for the system.

Chapter 9 – Water network synthesis

In **Chapter 9** the water networks developed to achieve the minimum water targets determined in **Chapter 8** are presented. The water networks were developed by applying the nearest neighbours' algorithm of Prakash and Shenoy (2005). A stepwise progression in moving from the existing water network to the proposed network as determined from the pinch analysis is presented in **section 9.3** and **section 9.4**. All associated calculations are presented in **Appendix K**.

Chapter 10 – Cationic demand

This section describes in theory how the cationic demand will vary through the system, for both tissue machine number one and tissue machine number two, if uncontrolled. This is to provide some insight to the degree of variation of properties which are currently not posing a problem to the efficient operation of the system. As the water system becomes more tightly closed, problems may arise where properties, such as the cationic demand, which were previously not a control problem, may now become a factor which adversely affects operation

For present operation, the cationic demand increased (more negative) and decreased (more positive) periodically indicating the effectiveness of the system control in place. The cationic demand values were also always well above three standard deviations indicating that the control is effective.

Observing the predicted plots for cationic demand for the sampled units for both tissue machines (**section 10.2** and **section 10.3**), it was noted that the cationic demand values were very high after the third or fourth iteration. This was an exaggerated value because in the iterations the lower cationic demands were used, but the iteration procedure does not incorporate cationic demand control. From the graphs of the predicted cationic demand variation at the various sampled units, it was observed that in order to maintain efficient operation of the system, the cationic demand must be efficiently monitored and controlled.

It must be noted that it has been assumed that the regeneration unit will have no effect on the cationic demand. From the literature it was noted that the unit will reduce the cationic demand (more positive) which has a favourable effect on retention. Therefore the predictions were an exaggeration. In practice the trends would appear as they appear for current operation.

The regeneration units selected will aid in controlling the cationic demand due to the removal of the cationic contaminants in the system. Together with this and the associated control of cationic demand, the system will not become over-cationised.

Chapter 11 - Costing

This section contains the results obtained from the costing calculations performed. All quotes, indexes, and discounted operating cost statements and the discounted cash flow statements can be viewed in **Appendix M** (all calculation sheets are available on the memory stick.). It was assumed that the mill operates 365 days a year.

The fixed costs were assumed to be zero because it was assumed that engineers at the mill will be monitoring the operation of the unit and that mill's insurance will cover the newly installed units.

It was determined that to implement the new system on tissue machine one require a total capital investment of R11.48 million with a return of investment of 17.4%. For tissue machine two a total capital investment of R3.07 million with a return on investment of 30.79%.

Chapter 12 - Summary of results

Chapter 12 contains a comprehensive summary of the main points considered in the pinch analysis as well as a summary of the results obtained for tissue machine one and tissue machine number two.

Chapter 13 - Overall discussion for the project

Chapter 13 presents a discussion of the project. It considers the:

- methodology applied
- decisions made during the study
- suitability of applying a pinch analysis method
- application of the pinch analysis method
- the implications of the results obtained

Chapter 14 - Conclusions

The aims of the study were highlighted in **Chapter 1**. A calibrated and verified mass balance of the mill's tissue making processes was developed as described in **Chapter 5, Appendix E** and **Appendix F**.

These material balance models were used to assess the corresponding change in specific water consumption for each machine through rerouting of process streams and installation of new equipment and the environmental impacts thereof by applying the method of Ng et al. (2009). This is presented in **Chapter 6, Chapter 7, Chapter 8** and **Chapter 9**.

An improvement strategy is presented in **Chapter 9** in moving from the current water system to the proposed system which was a result of the pinch analysis.

The pinch analysis technique proved to be effective in providing a systematic approach to reduce the specific water consumption.

Chapter 14 also details all other conclusions drawn through the application of the project such as the:

- dependencies of the pinch point
- disadvantage of the pinch analysis method applied
- possible accumulation of contaminants in the system and the associated mitigation
- placement of the regeneration units and
- an alternate approach to the pinch analysis application

Chapter 15 - Recommendations

This study has shown that a pinch analysis method can be an effective tool to reduce the specific water consumption. It is therefore recommended that:

1. A consulting company should be approached to perform a pinch analysis which incorporates more contaminants and consider more process properties into the analysis. The consulting company will also be able to simulate various process scenarios.
2. A simulation package which is specifically designed for the pulp and paper industry be used in conjunction with a water pinch analysis package to perform the analysis on the tissue machines

In the simulation of the process and associated water pinch analysis, the effect of a more closed water network on the biological oxygen demand and the chemical oxygen demand and also investigate the possibility of precipitation on the Yankee dryer.

In addition to this the following has been identified that the vacuum, wire and press sections must be carefully monitored to ensure that the system is maintained at the appropriate operating conditions.

Process parameters which need to be monitored include:

- Vacuum levels

- First pass retentions
- Refining energies
- Chemical dosing rates in the system
- Chemical dosing at the dissolved air flotation units
- Dissolved air flotation unit efficiencies

Chapter 16 – References

All references used in the study are available in **Chapter 16**.

Chapter 1 Introduction

The pulping and paper making industries of South Africa and around the world rely on two primary raw materials i.e. wood and water. The fibrous material required is obtained from trees or other fibrous vegetable matter. It depends on optimum weather conditions for growth as well as suitable land available for growth of fibre sources.

The source of the fibrous material is not considered in the following study. The primary concern here is the specific water consumption (i.e. the amount of fresh water used per ton of tissue produced) at the Kimberly-Clark South Africa (KCSA) Enstra mill. In the process of attempting to reduce the mill's specific water usage, consideration will be given to the unnecessary loss of fibre (which is the more valuable raw material).

Water is not as abundantly available as it was previously due to lower rainfall and rainfall shifting to areas where water collecting facilities, such as dams, are not present. There has also been an increase in the competing demand for water consumption from other industries and for municipal use. Water rationing has resulted from the water shortages experienced throughout the country. The water industry could not ignore this and as a result, the cost of fresh water for process industries has escalated and continues to do so. This impacts heavily on the pulp and paper industry as water is an essential commodity in the mill processes and is used in very large quantities. There are also associated costs with the effluent discharged from the mill; it is therefore desired to reduce the amount of effluent removed from the system by increasing re-use of process water within the system. There has been increased pressure from Asia, China and South America because the tissue imported from these countries sells cheaper than the brand produced by KCSA. If the production costs can be reduced it will have a corresponding reduction in the selling price of the products which will increase consumption at the consumer level; this is, like in any production industry, one of the main goals.

In a study by *MacDonald (2004)*, the water usage at various pulp and paper mills in South Africa was investigated. **Table 1-1** taken from this study shows the estimated process-water usage in the mills.

Table 1-1: Typical Water Usage at Pulp and Paper Mills (MacDonald, 2004)

Process Train	Usage Range, kℓ.ton^{-1}		
	Lower	Upper	Normal
Unbleached Kraft including woodyard	9	20	12
Bleached Kraft including woodyard (conventional or ECF)	27	42	32
Unbleached NSSC including woodyard	1	34	6
Bleached sulphite including woodyard (Calcium based)	70	130	75
Bleached sulphite including woodyard (Magnesium based)	40	100	75
Recycled fibre based carton board (uncoated)	2	10	5
Recycled fibre based carton board (coated)	7	15	8
Recycled fibre based packaging papers	1.5	10	5
Recycled fibre based newsprint	10	20	15
Recycled fibre based tissue	5	100	20
Recycled fibre based fine paper	7	12	12
General printings and writings not integrated	7	20	12
General linerboard/packaging papers	3	20	10
General corrugated medium including unbleached pulp mill	12	30	15
Newsprint/Sack-kraft paper	6	30	16

It is noted that most normal process water usages were well above the minimum. Clearly there is a need to reduce the specific water consumption to the lowest possible value without adversely affecting the final product properties as well as the efficiency of the process.

Tissue production has the highest normal water usage as compared to all other recycled fibre based paper products and compared to other paper grades being produced at other paper mills; the upper limit of the range is also the highest (**Table 1-1**). Therefore there is an opportunity for reducing the fresh water consumption in this industry.

Simultaneously, as part of the same ecological awareness, the imposition of ever-stricter discharge regulations has driven up waste treatment costs. This is because the water being discharged to the rivers or to the wastewater treatment facilities has to be of a certain quality. This means, in order to achieve the allowed discharge concentrations, more capital must be invested in treatment operations which may have little or no productive return.

Therefore a reduction in the process water usage will result in lower water costs as well as less effluent to be treated.

The purpose of this chapter is to provide a brief background of the Kimberly-Clark Enstra Mill and to provide an insight as to why this study is important and relevant in its application to the pulp and paper industry.

1.1 The history of Kimberly-Clark Enstra mill

The Kimberly-Clark Corporation (KCC) was established in 1872 in Wisconsin, USA and has grown to be a leading global manufacturer of a wide range of Health Care, Personal Care, Family Care and Professional products. Products are manufactured from natural and synthetic fibres and are used in homes, businesses and industry.

Today the KCC has manufacturing operations in 40 countries and products are sold in over 150 countries worldwide.

Kimberly-Clark South Africa (KCSA): The history of KCSA goes back to when KCC appointed agents to import and sell Kotex® napkins from the USA. Noticing an opportunity for manufacture, they progressed to local manufacture of tissue in 1948, followed by feminine care products in 1950.

KCSA has two factories i.e. the Enstra Mill and the Cape Town Factory. The Enstra Mill in Springs (Gauteng Province) is the company's major producer of toilet tissue, paper towel, diapers and facial tissue products. The mill incorporates a Recycled Fibre Plant (RFP) for the processing of waste paper, a diaper plant, and various tissue converting equipment.

The focus of this study is on the tissue machines which produce the various grades of tissue paper for conversion into the many tissue products.

1.2 Importance of this study

Due to increased fresh water costs and environmental awareness, emphasis is being placed on effective water management in process industries. Water is an essential commodity in the paper and pulping industries.

The Kimberly-Clark South Africa Enstra Mill (referred to as 'the mill' hereafter) is using a larger amount of water in their tissue making process than is desired. Therefore the mill wishes to reduce its specific water consumption. The aim of this project was to investigate the use of process modelling to monitor the effects of various process changes, water recycle, water reuse, and the application of best practices to reduce the specific water consumption for the tissue machines. The investigation was to determine the best approach to reducing the mill's specific water consumption.

The methodology and procedure followed here can be used by other paper/tissue mills to manage their water systems more efficiently and reach their desired water usage targets.

1.3 Aims and objectives

The aim of the resulting dissertation was to:

- Construct a calibrated and verified mass balance process model of the mill (only considering each tissue machine and associated stock preparation independently)
- Use the model to assess the corresponding change in specific water consumption for each machine through rerouting of process streams and installation of new equipment and the environmental impacts thereof
- Produce an improvement strategy with an outline of trials which should be undertaken

1.4 Hypothesis

The primary hypothesis which was tested: *A calibrated and verified mass balance process model of a tissue mill can be used to rationally reduce the specific water consumption of the mill.*

The chapters which follow details the theory and methodology followed in verifying the above hypothesis.

Chapter 2 The tissue making process

The Kimberly-Clark Enstra Mill incorporates diaper machines, a recycled fibre plant, an effluent treatment plant and two tissue machines. The focus of this study will be on the reduction of the specific water consumption on both of the tissue machines. The tissue making process consists of the following operations:

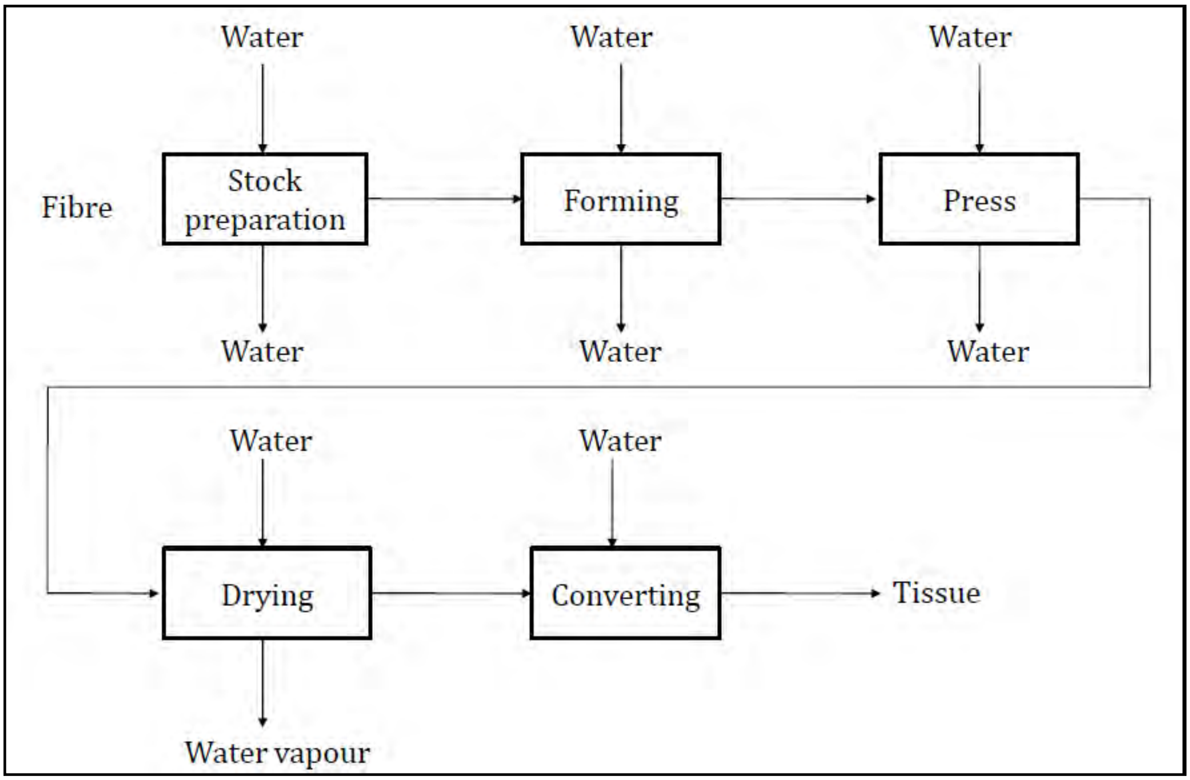

Figure 2-1: The tissue making process

In the stock preparation section (stock prep) section, the stock (fibre-water suspension), is appropriately treated to obtain the desired final paper/tissue properties. Treatment operations include *pulping, cleaning, screening and refining* of the stock.

The paper/tissue sheet is made in the forming section. This section consists of the *headbox* and the *wire*. The stock flows from the headbox onto the moving wire where water is removed by a vacuum system. The sheet which is formed then passes through a press section where water is mechanically removed from the sheet.

The *Yankee* dryer is a large single cylinder over which the sheet is dried. Finally the sheet which comes off the paper/tissue machine as a large roll and is sent to the *converters* where the tissue is cut and packaged according the customer's requirements.

These processing sections and units will be discussed in more detail in this chapter.

The speciality product on tissue machine number one is premium quality two-ply bathroom tissue (toilet paper). Tissue machine number one utilises *virgin* fibre only as its stock furnish. The machine can operate at speeds of up to 1050 $m.min^{-1}$ and has an average daily production of 65 $tons.day^{-1}$ with a specific water consumption of 21 $k\ell.ton^{-1}$ tissue manufactured.

Tissue machine number two is the larger of the two machines and its specialty product is two-ply bathroom tissue and industrial towelling. This machine utilises a combination of virgin fibre, *broke* from tissue machine number one and tissue machine number two and *recycled* fibre, blended according to the required final product properties, as its furnish. This machine can operate at speeds of up to 1200 $m.min^{-1}$ and has an average daily production of 92 $tons.day^{-1}$ with a specific water consumption of 21 $k\ell.ton^{-1}$ tissue manufactured.

Figure 2-2: Image of a tissue machine (headbox to the Yankee) (www.paperonweb.com)

Figure 2-2 depicts a typical tissue machine. The process flow diagrams for tissue machine one and two are shown with all equipment along the process line in **Figure 2-3** and **Figure** 2-4 respectively. A detailed description of the operation of the equipment and the significance of the equipment with regards to the process is discussed in **section 2.1**.

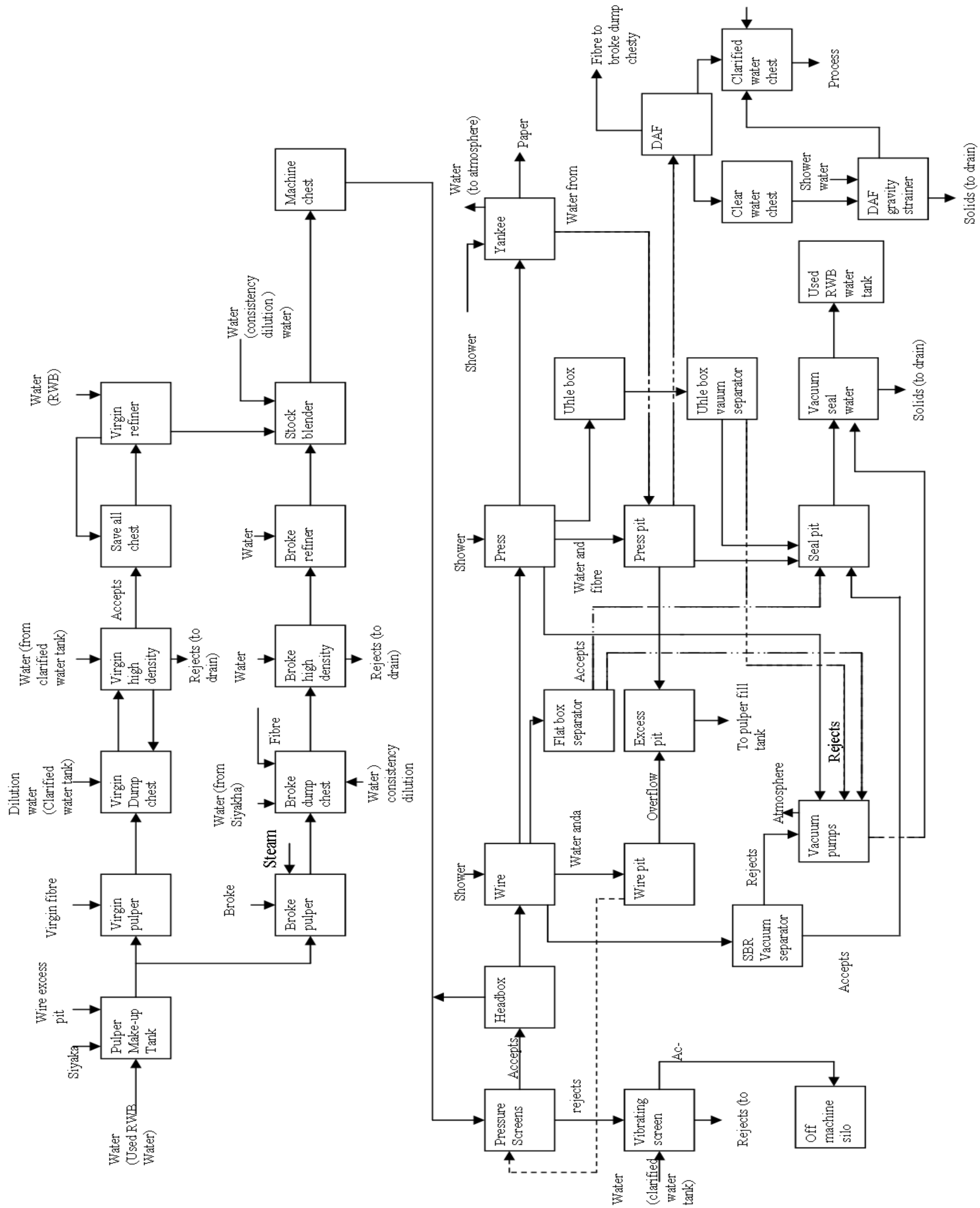

Figure 2-3: Process flow diagram for tissue machine number one

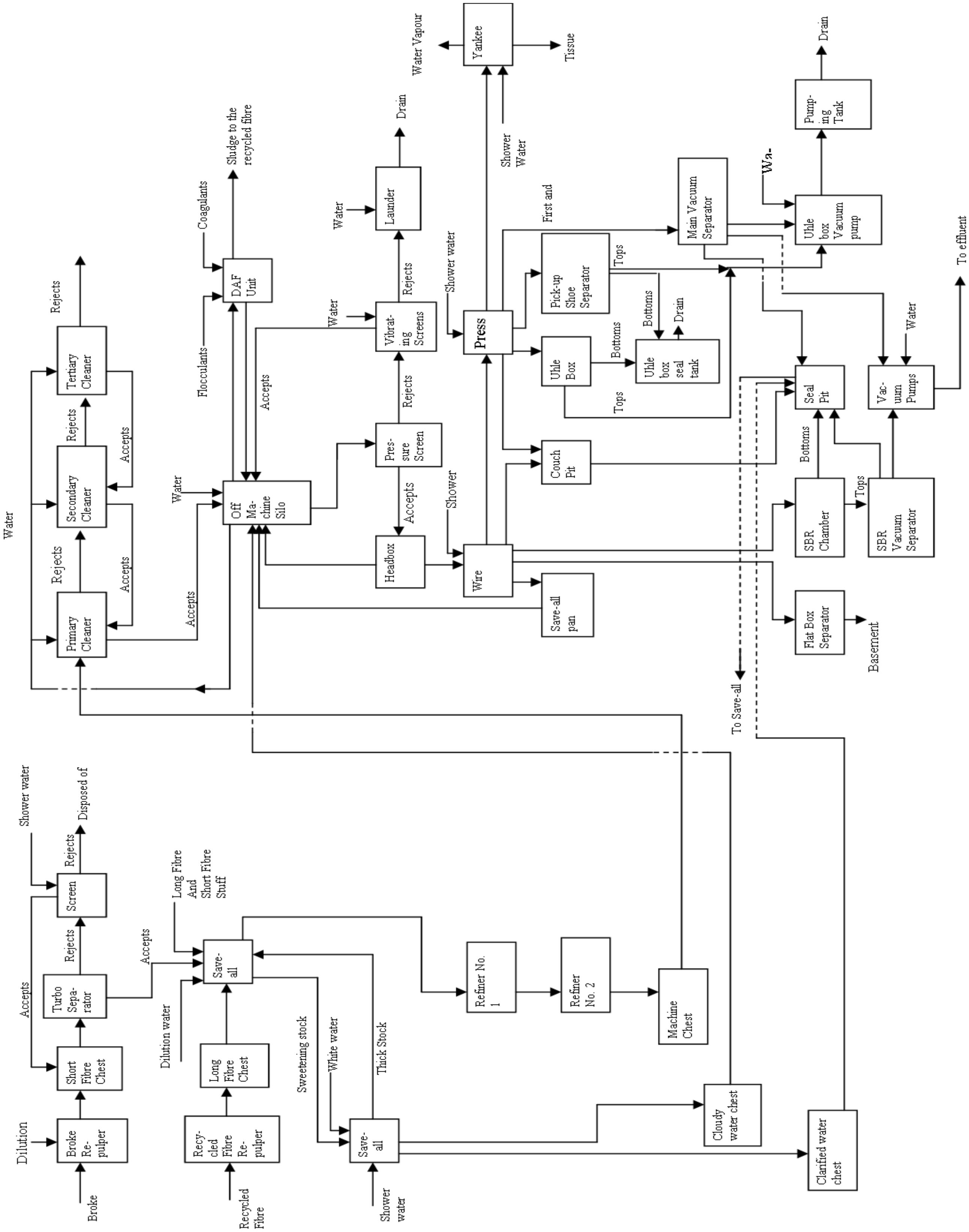

Figure 2-4: Process flow diagram for tissue machine number two

2.1 Equipment description

The equipment present in the process lines for both tissue machines is discussed as they occur in the tissue making operations are discussed in this section. The position of the units in the system is shown in **Figure 2-3** and **Figure 2-4**. After each process unit there is brief summary of the important pinch considerations.

2.1.1 Stock preparation section

In the stock preparation section, the wood fibres are appropriately treated and diluted such that the pulp slurry has the required physical characteristics and consistency for good sheet formation on the tissue machine. This section describes the various unit operations and their purpose in the stock preparation section; the water requirements are also explained.

2.1.1.1 Pulper

The fibre sources used are dry and must be converted into pumpable slurry. This is done in a pulper. The dry fibre source with water is added to the pulper vat. In the pulper vat, the pulper rotor creates strong disintegration forces to create a fibre slurry.

The main objective of a pulper is to:

- disintegrate the broke and recycled fibre into a pumpable slurry by releasing the fibre bond created in the pulp dewatering and drying processes (Paulapuro, 2000)
- disintegrate the slurry so that there are no visible flakes or fibre bundles (Paulapuro, 2000)
- and to disintegrate the slurry so that the fibres are separated, wetted and flexible

before being sent to the refining stage. The consistency is reduced from approximately 96 % to approximately 5 % at the pulper. The water purity requirement for dilution at the pulper is the least stringent and generally can be up to 600 mg. ℓ^{-1}.

Requirements for the pinch analysis:

Material balances	:	It is a water sink. Water is added at the pulper to dilute the dry fibre into a pumpable slurry.
Water quality	:	There is no quality requirement for the water added to the pulper from the pinch analysis perspective and process quality perspective.

Contaminants	:	Contaminants in the water added to the pulper include total suspended solids and total dissolved solids. Primary concern is the total suspended solids content of water.
Equipment specification	:	There is no water quality requirement from an equipment perspective.

2.1.1.2 Turbo-separator and cleaners

These are hydrocyclones. This type of separator fractionates the feed to the unit by density difference through centrifugal action. The path of suspension through a hydrocyclone involves a double vortex (Refer to **Figure 2-5**).

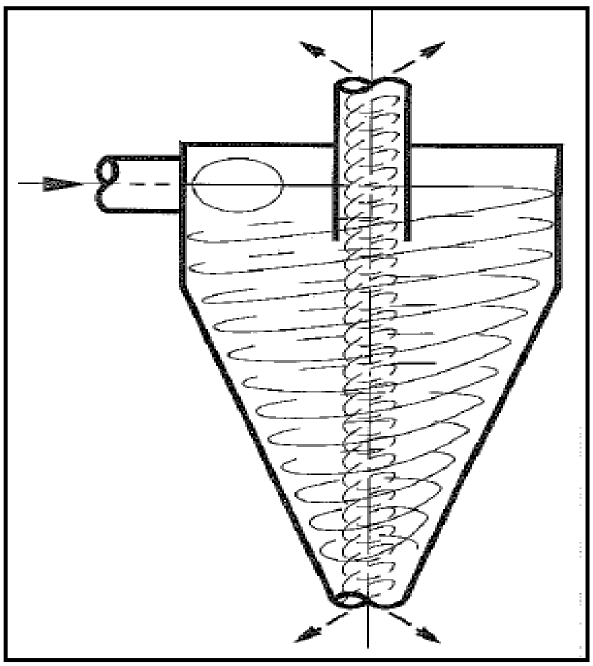

Figure 2-5: Flow Pattern in a Hydrocyclone - This figure illustrates the tangential motion of stock through a feed forward cleaner. A double vortex is formed causing the heavy debris to be removed from the bottom and the light debris from the top of the cleaner

The stock enters the cleaner and circular motion is imparted to it by the feed pipe. The tangential velocity increases as the radius increases. The double vortex is such that the suspension moves downwards on the outside and upward on the inside. With the centrifugal cleaners there is no critical particle diameter or cut-off size. The fractionation (separation) depends on the centrifugal and shear forces. The factors which govern the operation of the cleaner are the stock flow rate and feed pressure; the reject ratio i.e. the ratio of the underflow to the overflow; feed consistency and back pressure on the reject side. Depending on these parameters a certain pressure drop and reject thickening occurs (Paulapuro, 2000).

The centrifugal cleaners are used to remove dense debris of fibre size or smaller within the short circulation, which are not removed by screens. The debris consists of sand, grit and *pitch*. The overall debris removal efficiency is best in the cascade system. The higher the number of stages, the higher is the debris concentration in the rejects and the smaller the reject stream. Stock is diluted to very low consistencies (~0.8 %) to avoid plugging.

In the stock preparation process the turbo separator will function so as to remove contaminants (such as plastics and staples) introduced into the system with the stock and the cleaners will operate so as to remove dirt from the system. Water is used in the hydrocyclones to dilute the stock to very low concentrations such that it can be cleaned in the units. Water is required in large quantities for this dilution. In this dilution process, the stock is reduced from approximately 4.5 % to 0.25 %. For a production rate around 60 ton.d^{-1}, this corresponds to approximately 30 000 ℓ.min^{-1} of water required for dilution. There is no subsequent concentration of the stock leaving the hydrocyclone because a very low consistency is required over the headbox (to be discussed later).

The turbo-separator however operates at higher consistencies (around 4 %) and there is no dilution of the stock.

Requirements for the pinch analysis for the turbo-separator:

Material balances	:	These are considered as water sinks. The reason for this being the very low consistencies required for the efficient operation of these units. Hence a large quantity of water must be added to achieve the necessary consistencies.
Water quality	:	From a water pinch perspective the water used must have a total suspended solids content of <1200 mg. ℓ^{-1}
Contaminants	:	Contaminants in the water added to the cleaners include fibre and total dissolved solids. Primary concern is the total suspended solids content of water.
Equipment specification	:	There is no water quality requirement from an equipment perspective.

Requirements for the pinch analysis for the virgin and broke high density cleaners:

Material balances	:	Considered as a water sink because water is being added to reduce the consistency of the stock
Water quality	:	Water must have a total suspended solids content <600 mg. ℓ^{-1}
Contaminants	:	Total suspended solids and total dissolved solids (TDS). Primary concern is the total suspended solids content of the water
Equipment specification	:	There is no water quality requirement from an equipment perspective.

Requirements for the pinch analysis for the first, second and tertiary cleaners:

Material balances	:	Considered as a water sink because water is being added to reduce the consistency of the stock
Water quality	:	Water must have a total suspended solids content <1200 mg. ℓ^{-1}
Contaminants	:	Total suspended solids and total dissolved solids (TDS). Primary concern is the total suspended solids content of the water
Equipment specification	:	There is no water quality requirement from an equipment perspective.

2.1.1.3 Refiners

The purpose of refining is to improve the bonding ability of fibres so that they form a strong, smooth paper/tissue sheet with the required properties. Refining is a process where fibres are treated in the presence of water with metallic bars. The plates of the refiner are grooved so that the bars that treat fibres and the grooves between bars allow fibre transportation through the refiner (Paulapuro, 2000). **Figure 2-6** illustrates the process of pulp refining.

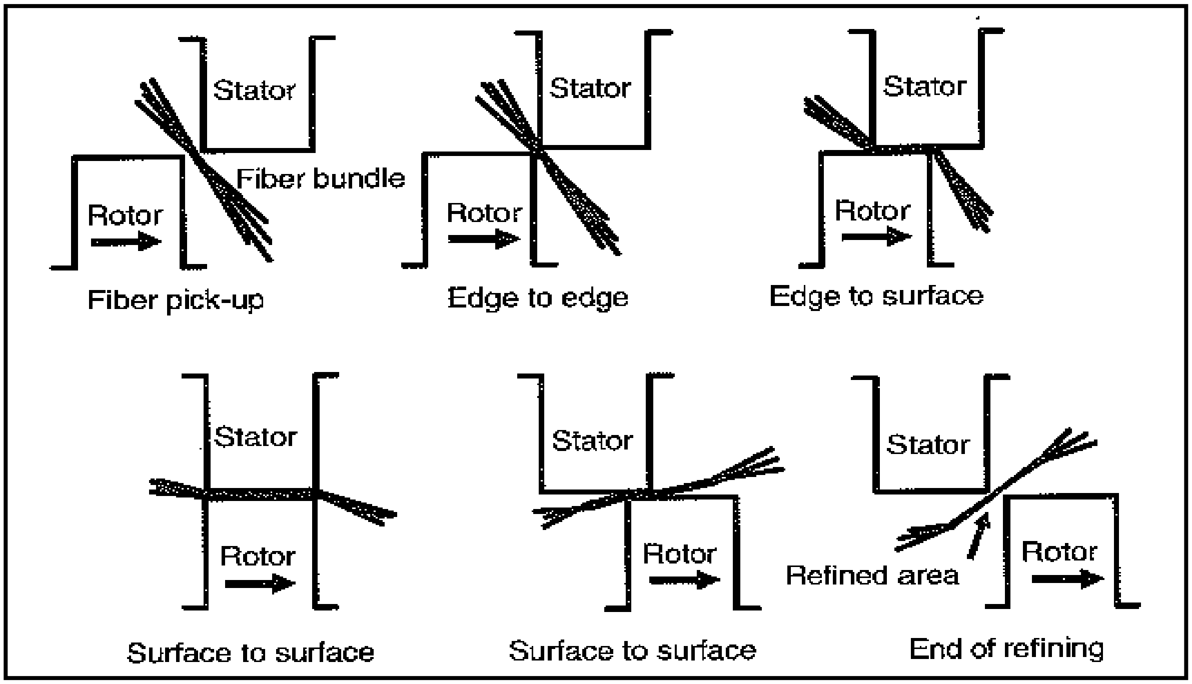

Figure 2-6: The Mechanism of Refining (Paulapuro, 2000)

The refiner has the following effects on the fibres (Paulapuro, 2000):

- cutting and shortening of fibres
- fines production and complete removal of parts from fibre walls, creating debris in suspension
- external fibrillation, the partial removal of the fibre wall, leaving it still attached to the fibre
- internal changes in the wall structure, variously described as delamination, internal fibrillation, or swelling
- curling the fibre or straightening the fibre
- creating nodes, kinks, slip planes, microcompressions on the cell wall, or removing those from the cell wall
- dissolving or leaching out colloidal material into the external liquor
- redistribution of hemicelluloses from the interior of the fibre to the exterior
- abrasion of the surface at the molecular level to produce a more gelatinous surface

As a result of the above effects, fibres after refining are collapsed more flexible, and their bonding surface area is increased as a result. The measurable fibre and sheet properties, after refining chemical pulps, can be seen as follows (Paulapuro, 2000):

- drainage resistance (water removal resistance) increases
- tensile strength, tensile stiffness, burst strength, internal bonding strength, and fracture toughness increases
- tear strength increases initially but after prolonged refining decreases
- air permeability, bulk, absorbency, opacity and light scattering decreases
- brightness decreases slightly

Water usage at the refiners is considered negligible in most paper making processes and it is responsible for property changes of the pulp, not concentration changes.

2.1.1.4 Gravity strainer

The gravity strainers are used in the pulp and paper industries to reduce the fibre content, to remove felt hairs, fibre bundles, to separate long fibres and organic solids from surface and ground waters and process debris from recycled plant waters (http://www.filterteknikbw.se, 2010). The unit captures fibres on a screen and can be used for different duties:

1. Removal of unwanted material – felt hairs and debris
2. To concentrate fibre containing streams

Depending on the feed either of these duties can be achieved. The gravity strainer has an inner and outer jacket. The water is fed tangentially between these two jackets. The water is pumped up and over the edge of the internal vessel and it then flows down the filter cloth; this causes unwanted suspended solids to be blocked by the filter cloth and clean water runs through the filter cloth and exits the bottom of the vessel (http://www.filterteknikbw.se, 2010). The filter is suitable for fibre contents up to 600 mg.ℓ^{-1} (ppm). If a smaller unit is used, solid content up to 1000 mg.ℓ^{-1} (ppm) can be filtered. The gravity strainer is in used to recover fibre from the process water. Water is used at the gravity strainer for the showers which clean the screens. The shower water purity will depend on the nozzle diameter of the showers and generally does not have a contaminant concentration of >100 mg.ℓ^{-1}.

Water is required here for the showers used to clean the screens.

Requirements for the pinch analysis (Tissue machine number one and tissue machine number two):

Material balances : These are considered as water sinks. This is due to the water

		required for the showers which clean the filter medium.
Water quality	:	From a water pinch perspective the water used must have a total suspended solids content of <100 mg. ℓ^{-1}.
Contaminants	:	Contaminants in the water added to the gravity strainer include total suspended solids and total dissolved solids. Primary concern is the total suspended solids content of water.
Equipment specification	:	Refer to the water quality required

2.1.1.5 Dissolved air flotation units

The dissolved air flotation unit removes dissolved and dispersed air from the stock as well as other suspended solids such as residual ink particles and *stickies*. Air is required to be removed due to its adverse effects on the production process as well as on the final product quality. The air removal is not the purpose of the dissolved air flotation unit – it is essential for the operation of the system. From water treatment knowledge, dissolved air is introduced into a side stream by passing it through a high pressure saturator where it is contacted with high pressure air.. This water is saturated with air at a high pressure. When it is mixed with the process stream the high pressure is released and the air comes out of solution. In order to ensure good functioning downstream – all dissolved air needs to be removed. This is in contrast to a deaerator on a boiler for example where the air is removed prior to entering the boiler circuit so as to prevent oxygen or carbon dioxide corrosion or the build-up of inert gases.

The DAF unit removes the air by desorbtion above the boiling point and drives the air out when a large fluid surface is created. The deaeration tank treats the stock by the following processes:

- spraying
- impingement
- boiling

For the spraying and impingement processes, a large fluid surface is created and the trapped or bound bubbles are released and removed (Paulapuro, 2000). Impingement occurs against the interior surface of the tank. Boiling occurs under vacuum. The vacuum is kept high enough so that the suspension requires no added heating. To support the required amount of vacuum, the deaeration tank is placed at an elevated location and all flows from the unit are barometric drop-leg lines (Paulapuro, 2000). The removed air is exhausted using a silencer. The silencer is used to reduce the discharge noise and also assists in separation of the liquid and vapour.

High purity water (e.g. < 10 mg. ℓ^{-1} total solids) is required for the make-up of the chemicals dosed to the dissolved air floation unit. The chemical dosage is high (e.g. 1% of feed). The DAF product water can be used for dilution water or shower water.

Requirements for the pinch analysis (Tissue machine number one and tissue machine number two):

Material balances	:	The dissolved air flotation unit is considered as both a water sink and a water source. It is a water source from the perspective that cleaner water is produced from the system but a sink because water is required for the chemical dosing at the dissolved air flotation units.
Water quality required	:	Water at 0 mg. ℓ^{-1} (total suspended solids) is required for the dissolved air flotation unit chemical dilution water.
Water quality produced	:	≈15 mg. ℓ^{-1} total suspended solids
Contaminants	:	Contaminants in the water added to the dissolved air flotation unit include total suspended solids and total dissolved solids. Primary concern is the total suspended solids content of water.
Equipment specification	:	Refer to the water quality required

2.1.1.6 Pressure screens

The pressure screens are usually found just before the headbox which is the beginning of the forming section. The purpose of having a pressure screen before the headbox is to:

- function as a police filter i.e. it is used to remove any remaining coarse material which can damage the forming fabrics
- remove any remaining debris and dirt
- and it improves formation by causing deflocculation of the stock

Even though the *stock* has previously been sent through screens for the same purposes as mentioned above, bundles, lumps and flakes can be created by, for example, deposits on the chest walls (Paulapuro, 2000).

Due to the screen being situated just before the headbox, it does have some special characteristics (Paulapuro, 2000):

- very low pulsation generating operation
- polished surfaces
- metal-to-metal flanged connections, especially on the accept side
- highest possible availability i.e. virtually trouble free operation
- dimensioning according to simplicity in layout, often use of a single screen is preferred
- optimised design to prevent air pockets

Efficient screening results in a product (sheet) with fewer spots and holes.

The pressure screens are the last units before the forming section. At the pressure screens the stock is diluted to the consistency required for sheet formation because this needs to be stable before the headbox. This dilution at the pressure screens usually requires a large quantity of water because of the larger flowrate and low consistency required for formation. The stock concentration is reduced from approximately 0.25 % to approximately 0.18 % across the pressure screens. It is therefore one of the most demanding units in terms of water requirement.

Requirements for the pinch analysis for the pressure screens:

Material balances	:	The pressure screens are considered as water sink because of the large amount of water which is required for the dilution of the tissue making furnish before it can be admitted to the pressure screens.
Water quality	:	Water must have a total suspended solids <600 mg. ℓ^{-1} on tissue machine number one and <1200 mg. ℓ^{-1} on tissue machine number two
Contaminants	:	Contaminants in the water added to the pressure screens include total suspended solids fibre and total dissolved solids. Primary concern is the total suspended solids content of water.

Equipment specification	:	Refer to the water quality required

Requirements for the pinch analysis for vibrating screens:

Material balances	:	Considered as a water sink because water is being added via showers to clean the screens
Water quality	:	Water must have a total suspended solids content <600 mg. ℓ^{-1} to avoid plugging of showers
Contaminants	:	Total suspended solids and total dissolved solids (TDS). Primary concern is the total suspended solids content of the water
Equipment specification	:	Refer to water quality

2.1.2 The white-water circuit

The *white-water circuit* refers to water removed from the process in the forming and pressing sections which is re-used in the manufacturing process as process water. The purpose of a *save-all* is to recover fibre from the white-water circuit as well as produce water which is of a quality which can be reused within the system. The save-all is a poly-disc filter. In the disc filter, multiple discs rotate in a vat. Each disc is made of several segments which are covered by a fine mesh. These discs rotate over stationary filtration zones (Paulapuro, 2000).

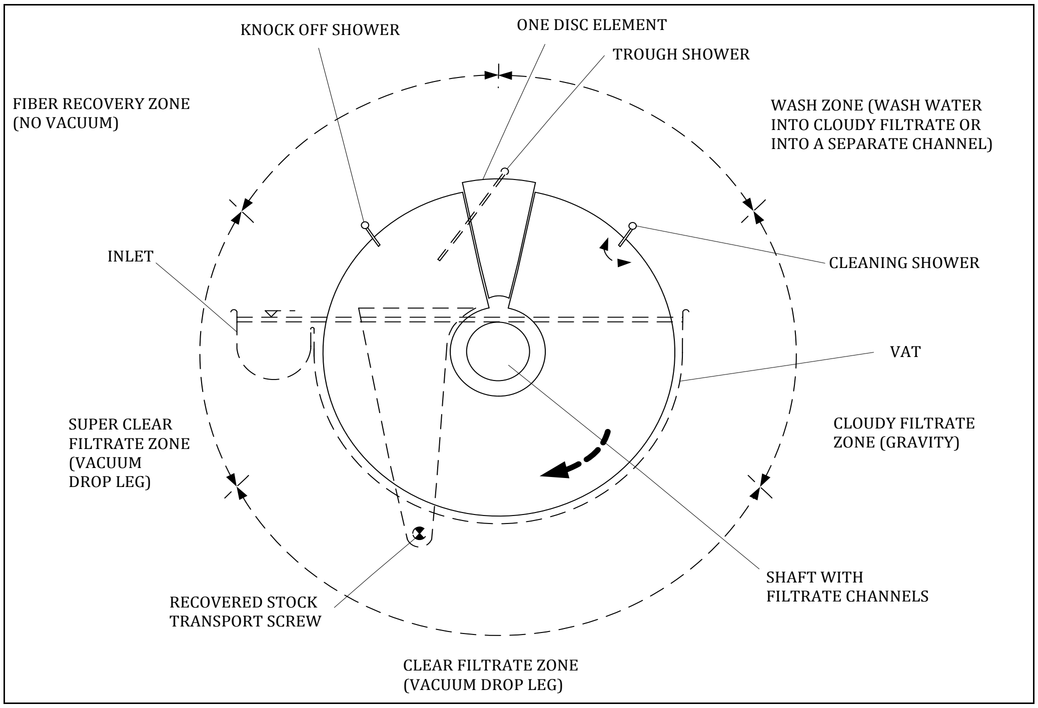

Figure 2-7: Filtration Principle of the Disc Filter (Paulapuro, 2000)

During this process, a fibre mat is built up with the aid of the *sweetening stock*. Sweetening stock is of high consistency stock (~4.5 %) from a fibre chest which is used to aid in the filtration of the white-water; it contributes to fibre-matt formation which is responsible for the filtration of the white-water. The save-all serves to recover fibre from the white water circuit as well as produce water which is of a quality which can be re-used within the system.

The thicker and denser the filter cake becomes during vacuum filtration, the fewer solids are passed through. The quality of the filtrate improves as the filtration cycle proceeds, until the filtration process is interrupted, when the filter mat emerges from the filled vat. The filtrate of the different phases is therefore collected separately in the cloudy water chest and the clarified water chest (Paulapuro, 2000). Cloudy water produced is $\sim\frac{2}{3}$ of the total filtrate flowrate.

Once the vacuum is released, the mat is removed from the wire by the knock-off shower. Another shower keeps the trough clean from the discharged pulp. An oscillating shower cleans the filter. The water from these showers enters the cloudy filtrate chest.

Water from the save-all is used in the process depending on the allowable contaminant concentration, in the various units requiring a water input. Water is used by the save-all for the save-all shower.

Requirements for the pinch analysis:

Material balances	:	The save-all is considered as both a water source and a water sink. It is a source from the perspective that water filtered by the save-all can be used elsewhere in the process and a sink because water is required for the showers on the save-all.
Water quality required	:	< 90 mg. ℓ^{-1}
Water quality produced	:	89 mg. ℓ^{-1}
Contaminants	:	Contaminants in the water added to the save-all include total suspended solids and total dissolved solids. Primary concern is the total suspended solids content of water.
Equipment specification	:	Refer to the water quality required

2.1.3 Forming section

The forming section follows the approach flow section and starts with the headbox. It is in the forming section in which the paper/tissue sheet is produced. It ends with the wire.

2.1.3.1 Headbox

The main function of the *headbox* is to distribute the water-fibre suspension evenly across the width (CD – cross direction i.e. from one edge of the machine to the other) of the wire section. This means, for example, that the flow from a pipe with a diameter of 800 mm shall be transformed into a 10 mm thick 10 000 mm wide jet, with absolutely the same flow rate and flow direction at all points across the width (Paulapuro, 2000).

This change of flow occurs in three steps:

i. the CD distributor makes a first distribution of the mix across the machine width
ii. pressure drop elements are introduced to even out the CD flow profile
iii. the headbox nozzle generates the final jet

There is no water input at the headbox nor is water removed at the headbox. It is only used to distribute the stock evenly over the wire.

2.1.3.2 Wire

The stock is sprayed from the headbox slice onto the *wire*. The temperature of the stock will be slightly higher than room temperature but it is governed by the temperature of the process water used in the system. The water is drained from the water-fibre suspension in the wire section of the paper/tissue machine, resulting in a wet web. The wire fabric is a woven, endless fabric. The wire fabric has the following functions:

- it acts as a filtration medium
- it acts as a smooth support base for the slurry flowing from the headbox (Paulapuro, 2000)
- transfers the *web* from the headbox to the press section

Along the wire, various dewatering elements are present which aid the water removal process. Such elements include foil groups, forming rolls, suction rolls and suction boxes which are under vacuum.

There are various types of forming fabrics; the one applied to a particular paper machine will depend on the process and conditions under which the fabric will be operated. The most vital properties of the forming fabric quality are (Paulapuro, 2000):

- dewatering ability
- retention ability
- stability
- wear resistance
- non-marking structure

It is essential that these properties are repeatable to ensure that the conditions of the wire section remain constant.

The dewatering process can be one of two processes i.e. filtration or thickening. The filtration type of dewatering dominates conventional forming. During this dewatering process fibres are successively deposited flat in a wet web as the suspension water is removed. Above the web a suspension with the same conditions as the mix in the headbox, is present.

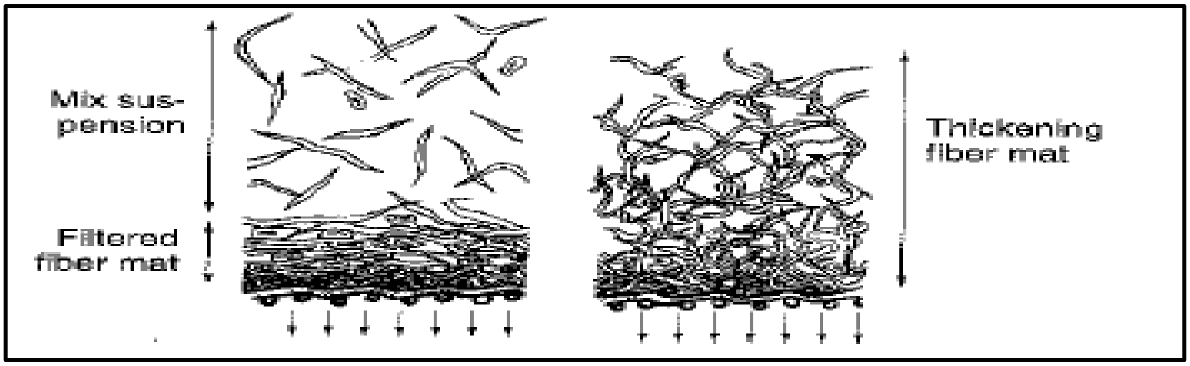

Figure 2-8: Dewatering through filtration (Left) and thickening (Right) (Paulapuro, 2000)

When all of the free suspension has been dewatered, further dewatering takes place as a thickening process. This means that a progressive compression of the fibre network takes place. The dewatering of fibre flocs remaining in the mix also takes place according to the thickening principle.

The water removed in the wire section, either by gravity, vacuum pressure or at the suction boxes, is reused in the system as dilution water or sent to drain depending on the origin of the water; this is to prevent accumulation of contaminants in the system.

Requirements for the pinch analysis (tissue machine number one):

Material balances	:	Considered as a water sink and source. Water is drained from the wet web and joins the white-water circuit (as a source). Water is added (sink) to the unit at the showers which cleans the wire fabric.
Water quality required	:	Requirements of the showers to avoid plugging is total suspended solids < 100 mg. ℓ^{-1}
Water quality produced	:	To SBR vacuum separator - 1092 mg. ℓ^{-1} To wire pit – 588 mg. ℓ^{-1} To flatbox separator - 59 mg. ℓ^{-1}
Contaminants	:	Total suspended solids and total dissolved solids (TDS). Primary concern is the total suspended solids content of the water
Equipment specification	:	Refer to water quality

Requirements for the pinch analysis (Tissue machine number two):

Material balances	:	Considered as a water sink and a water source. Water is drained from the wet web and joins the white-water circuit (source). Water is also required at the showers which clean the wire fabric and hence it is also a sink.
Water quality required	:	Requirements of the showers to avoid plugging: SBR needle shower – Rand water board (RWB) water Nip shower – total suspended solids content of water <300 mg. ℓ^{-1} Knock-off shower – total suspended solids content of water <300 mg. ℓ^{-1} Breaker-roll shower – total suspended solids content of water <300 mg. ℓ^{-1}
Water quality produced	:	To save-all pan – 723 mg. ℓ^{-1} To flatbox separator – 1313 mg. ℓ^{-1} To SBR chamber – 6 mg. ℓ^{-1} To couch pit – 828 mg. ℓ^{-1}
Contaminants	:	Total suspended solids and total dissolved solids (TDS). Primary concern is the total suspended solids content of the water
Equipment specification	:	Refer to water quality required

2.1.3.3 Vacuum system

The dewatering process in the tissue machine is divided across two zones. Zone 1 extends from the headbox slice and ends at the leading edge of the first suction box. The rest of the wire section falls into Zone 2.

Dewatering in Zone 1 is by the filtration mechanism previously described. In **Zone 2**, dewatering is a vacuum operation. There exist both low- and high-vacuum zones. The low vacuum region occurs before the high-vacuum zone and the high-vacuum zone occurs just before the press. The 'flat boxes' are used in the high-vacuum region to bring about the necessary dewatering. The vacuum on the flat boxes is obtained by using external pumps.

Water separators (e.g. main vacuum separator) are installed after suction points. This is done due to the following benefits:

- water from the various suction points can be used for its most suitable purpose.
- the penetration of felt and wire cleaning chemicals and tissue making chemicals can be avoided
- air sucked in with the water and fibre is vented to the atmosphere from the vacuum pumps

Water used as vacuum pump seal water is reused as seal water; the reuse is limited due to temperature build-up. The vacuum seal water can have contaminant concentration limited to 250 mg. ℓ^{-1}. The water removed to the vacuum applied by the vacuum pumps can be reused as seal water or as process water.

Requirements for the pinch analysis:

Material balances	:	Considered as a water sink and a water source. Water is required for seal water (sink) and this water can be reused as seal water (source) with some make-up water
Water quality required	:	Seal water can have a total suspended solids contaminant concentration limited to < 250 mg. ℓ^{-1}
Contaminants	:	Total suspended solids and total dissolved solids (TDS). Primary concern is the total suspended solids content of the water
Equipment specification	:	Refer to water quality required

2.1.4 Press section

From the wire section, the wet web passes through the press section. At the press section water is mechanically removed from the wet web. This occurs by mechanical compression of the web in the nip formed by two rolls or a roll and a shoe. Heat is often applied to the web to assist the water removal. It increases the temperature of the fibrous web and the water contained therein (Paulapuro, 2000). The water removed at the nip is received by the felt fabric and by the suction roll. Water flows from the felt into the holes of the suction roll, assisted by a vacuum inside the roll (Paulapuro, 2000).

The efficient removal at the press section is important as a 1 % increase in the solids content results in a roughly 4 % decrease in the energy consumption in the dryer section. The high solids content also results in an increase in the wet web strength which in turn improves the runability of the wet web.

The water removed from the press section is used in the system as consistency dilution water; this water is usually of a poorer quality than the water removed at the wire.

Requirements for the pinch analysis (Tissue machine number one):

Material balances	:	The press is considered as a source and a sink. Water is removed from the press section (source) by mechanical action and water is required for the pressure nip rolls as well as showers (sink).
Water quality required	:	Requirements of the shower water to avoid plugging < 30 ppm
Water quality produced	:	To press pit - 881 mg. ℓ^{-1} To uhle-box – 59 mg. ℓ^{-1}
Contaminants	:	Contaminants in the water added to the press section include total suspended solids and total dissolved solids. Primary concern is the total suspended solids content of the water.
Equipment specification	:	Refer to the water quality required

Requirements for the pinch analysis (tissue machine number two):

Material balances	:	The press is considered as a source and a sink. Water is removed from the press section (source) by mechanical action and water is required for the pressure nip rolls as well as showers (sink).
Water quality required	:	Uhle box lube – total suspended solids content of water <300 mg. ℓ^{-1} Requirements of the showers to avoid plugging: Nip shower – total suspended solids content of water <15 mg. ℓ^{-1} PLU shower – total suspended solids content of water <15 mg. ℓ^{-1} Press internal showers – RWB water (0 mg. ℓ^{-1})

Water quality produced		To couch pit - 155 mg. ℓ$^{-1}$ To main vacuum separator - 6 mg. ℓ$^{-1}$
Contaminants	:	Contaminants in the water added to the press section include total suspended solids and total dissolved solids. Primary concern is the total suspended solids content of water.
Equipment specification	:	Refer to the water quality required

2.1.5 Drying section

The sheet from the wire is then delivered to the Yankee dryer. Unlike conventional paper machines, the tissue machine has just a single drying cylinder instead of multiple drying cylinders. The paper/tissue making process is essentially a very large water removal operation (Karlsson, 2000). Drying is a thermal operation. This means that heat is applied to vaporise the remaining water from the sheet. The sheet after drying will still contain a residual amount of moisture (5 % to 9 %).

It is desired to remove as much water as possible in the wire and press section because it is much more cost effective to remove water mechanically in these sections than in the dryer section. Also, the more water removed in the wire and press sections, greater the amount available for reuse because less will be lost to the atmosphere in the dryer section. This section is one of the main losses of water.

The dryness achieved after the press section is limited by the press technology and the *bulk* of the web. If a sheet with a higher bulk is required then a lower dryness is required before the dryer. The drying process is a critical one for achieving the final paper/tissue properties.

The dryer section is required to have the following properties:

- drying capacity – drying equipment is large and expensive (Karlsson, 2000). Therefore the equipment must be efficient giving maximum evaporation rates per unit for any paper grade being produced.
- evaporation profiles - paper quality should remain high even with high evaporation efficiency
- runnability of the dryer section – this is important for production efficiency. One of the major causes of lost production time is paper breaks occurring in the drying section.

Runnability is especially important for high speed operations such as the tissue making process.

- good energy economy – energy requirements should be as low as possible and heat should be recovered for use in other sections of the process

The drying process is achieved by direct contact of the wet web over a rotating drying cylinder. The cylinders are usually heated internally by condensing steam. However, this results in condensate being formed. This condensate will contribute to the overall resistance to heat transfer. Siphons are used to continuously remove condensate from the cylinder.

A hood (Divided in two sections – Wet end and Dry end) covers the Yankee. This hood is filled with holes which blow hot air at high velocity onto the sheet to dry it. Each alternating row of holes "suck" moist air back into the hood. The bulk of the air is re-circulated and re-heated with a natural gas burner to around 350 ˚C. A portion of this circulated air is exhausted through a variable speed drive fan to control moisture build-up in the hoods.

In conventional tissue machines, the wet sheet is dried on a single, large cylinder called a Yankee dryer (mentioned above). Besides providing the required energy for the process, the Yankee also has the following functions (Karlsson, 2000):

- to transport the sheet during the drying process
- to function as a roll in the hot pressing section
- to provide the base for the creping process

The drying capacity of a tissue machine is mainly affected by the size of the Yankee dryer. Bigger cylinders (up to 5.5 m in diameter) are required for higher speed machines. In addition to the dryer, a high velocity impingement hood blows hot air with temperatures up to 500 °C to increase the rate of drying (Karlsson, 2000).
The water vapour from the drying flows up through the voids in the web. The mechanisms responsible for the movement of vapour away from the web are Stephan diffusion, Knudsen diffusion and laminar flow with Stephan diffusion being dominant.

The general paper drying process goes through cycles of evaporation and condensation. The water evaporated from the web and the vapour

Vapour flow can cross virtually impermeable barriers in a wet web through the evaporation and condensation mechanism. Vapour condenses on the other side of the barrier releasing the latent heat of condensation. The heat then conducts through a solid material, liquid material or both and water evaporates on the other side of the barrier (Karlsson, 2000). So in the pores, the water vapour condenses at the cooler end and releases its latent heat. This is taken by the existing water at the cooler end and it evaporates. This process provides efficient water removal

However, tissue paper is very thin compared to other paper grades and has a porous structure. Hence the vapour produced in the hot Yankee section can pass through the open structure of the sheet without condensing (Karlsson, 2000).

The water removed during drying is very hard to recover due to the vapour phase. It is therefore considered as a loss of water from the system.

Requirements for the pinch analysis:

Material balances	:	Water lost to the environment during the drying process which cannot be recovered and water is required for the showers at the Yankee. Therefore considered as a sink.
Water quality	:	Water quality must be 100% to avoid fouling at the Yankee.
Contaminants	:	N/A
Equipment specification	:	Refer to water quality

2.1.6 Chests

Between most major pieces of equipment there are chests. These chests serve to buffer the system such that constant flowrates can be maintained and also serve as points for chemical addition as not all chemical addition can occur at the suction of pumps due to the interaction between chemicals. Depending on the machine and chest the water requirements and contaminant constraints vary. In respect to the tissue machines under question, a summary of the chests and their associated contaminant constraints in terms of the pinch analysis, is presented.

Save-all chest

Pinch analysis	:	Considered as a water sink because water is being added to reduce the consistency of the stock
Water quality required	:	Water must have a total suspended solids content

<800 mg. ℓ^{-1}

Contaminants : Total suspended solids (TSS) and total dissolved solids (TDS). Primary concern is the TSS content of the water

Equipment specification : Nil

Machine chest (tissue machine number two)

Pinch analysis : Considered as a water sink because water is being added to reduce the consistency of the stock

Water quality required : Water must have a TSS content <800 mg. ℓ^{-1}

Contaminants : Total suspended solids (TSS) and total dissolved solids (TDS). Primary concern is the TSS content of the water

Equipment specification : Nil

Off-machine silo

Pinch analysis : Considered as a water source because water is used from the silo to reduce the consistency of the stock

Water quality required : Water must have a TSS content <500 mg. ℓ^{-1}

Contaminants : Total suspended solids (TSS) and total dissolved solids (TDS). Primary concern is the TSS content of the water

Equipment specification : Nil

Virgin and broke dump chests

Pinch analysis : Considered as a water sink because water is being added to reduce the consistency of the stock

Water quality required : Water must have a fibre content <600 mg. ℓ^{-1}

Contaminants : Fibre and total dissolved solids (TDS). Primary concern is the fibre content of the water

Equipment specification : Nil

Stock blender

Pinch analysis	:	Considered as a water sink because water is being added to reduce the consistency of the stock
Water quality required	:	Water must have a fibre content < 600 mg. ℓ^{-1}
Contaminants	:	Fibre and total dissolved solids (TDS). Primary concern is the fibre content of the water
Equipment specification	:	Nil

2.2 Tissue machines considered in the pinch analysis

As previously mentioned, Kimberly-Clark South Africa, Enstra mill, has two tissue machines. These machines produce a wide variety of tissue paper grades.

Tissue machine one is responsible for the premium products which uses virgin fibre only in its tissue making furnish. The process water properties are therefore relatively consistent because of the quality of the raw materials. There is also very few chemicals added during the production of the grades on tissue machine one.

Tissue machine two however produces a variety of grades, each with its respective raw material and chemistry. This amounts to roughly 15 different grades. Many of these grades use a combination of recycled fibre and virgin fibre; the recycled fibre is further separated into 3 different types. This makes the water quality very variable.

Due to the difference in products being manufactured on each machine, and since tissue machine one uses virgin fibre only, it is required that these two water systems be analysed separately because the tissue machine one system must not be contaminated. Therefore there should be no mixing of the process water from tissue machine two onto tissue machine one; the process water from tissue machine one is limited to use on tissue machine one only as make-up cannot be obtained from tissue machine two.

Therefore in the analysis moving forward, the two tissue machines will be analysed separately.

2.3 The need in pulp and paper industry for water reuse, recycle and regeneration

Aside from high water usages being a problem at KCSA, it is a problem experienced by many pulp and paper plants.

A study done by the water research commission (WRC) in collaboration with the University of Durban Westville (2002) details the water usage problems experienced by various mills and the steps taken to remedy this. It contains a detailed literature survey regarding the various approaches taken to reduce the water consumption; the discussions relevant to the study are discussed in the paragraphs which follow.

The study conducted by the Pollution Research Group also describes various regeneration units available for white-water regeneration depending on the extent of regeneration required, as well as problems associated with the increased recirculation of water. Problems include corrosion, chemical and water balances, motivating personnel to adopt new methods, plugging, slime, colour, scale and foam.

Due to the effect of water recycling on slimes and scales, improved control measures will be needed to prevent these deposits. An increase in these deposits results in losses in heat, production and raw materials as well as a reduction in the life of the felts and wires of the machine and a reduced product quality. (Pollution research group – department of chemical engineering, University of Durban Westville, 2002)

The benefits are described as material, energy and chemical savings, elimination of fresh water and wastewater treatment costs and long term freedom from further pollution and control restrictions.

It was determined that the first step towards waste reduction is good housekeeping. Caution should be exercised by all individuals to ensure that conservation and reuse principles are applied and that there are no spills or contamination in the process.

> *…Recycling prevents water pollution while being an important water augmentation system. Several studies have indicated that the most effective way to eliminate pollution is at source. Water reuse is a pollution control technique that can provide valuable by-products and an inexpensive source of process water… Pollution research group – department of chemical engineering, University of Durban Westville (2002)*

It is important to note that for internal reuse of process water, partial treatment will often suffice and complete treatment is not necessary.

The contaminants (pollution sources) in the process water can be divided into two categories:

- total suspended solids (TSS)
    - fibre and fibre particles (fines)
    - coating and filler material
    - settleable solids – colloidal material, inorganic constituents
- total dissolved solids (TDS)
    - mainly soluble organics

The paper machines have the following water needs:

1. dilution
2. showers
3. sealing
4. heating and cooling
5. miscellaneous including hose-pipes

It was determined that the following actions be taken in order to reduce the water consumption at the mill (Pollution research group – department of chemical engineering, University of Durban Westville, 2002):

1. institute external white water treatment for recycle back into the paper/tissue machines
2. reuse excess papermachine white water in the pulp mill (applicable only to integrated pulp and paper mills)
3. improve operation of save-alls to reuse more white water and decrease stock losses
4. installation of closed-loop systems for vacuum pump waters and press waters
5. change wire and press section showers to low-volume high pressure type
6. increase use of excess white water for dilution on papermachine pulpers, broke chest, cleaners and screen rejects
7. install hot and cold water systems to optimise energy conservation and water reuse

Due to the fibre recovery during the treatment processes, the waste treatment costs and equipment requirements can be reduced.

There is a potential for up to 84 % reduction in fresh water cost through process water reuse, this was concluded by Johansson (1976) after a study was done on Kraft and tissue mills. An 80% reduction in fresh water use can be achieved as described by Gropp and Montgomery (1972) using a regeneration system consisting of disk filters, polishing basins and percolating beds (Pollution research group – department of chemical engineering, University of Durban Westville, 2002).

Davis et. al. (1973) argued that filtered water to be reused in the process can be treated with chlorine to prevent slime deposits (Pollution research group – department of chemical engineering (University of Durban Westville, 2002).

> …Mulford and Cooke (1969) reported and evaluated 16 methods of reusing vacuum pump seal water. These were grouped into three categories in order of preference: a) fresh water supply with reuse after the vacuum pumps; b) reuse of previously used water; and c) recirculation of seal water…*Pollution research group – department of chemical engineering, University of Durban Westville (2002).*

A German producing corrugating medium, packaging paper and similar coarse and low grade paper operates its' paper machine with a completely closed water system with no adverse effects on both production rate and the quality of the products. (Pollution research group – department of chemical engineering (University of Durban Westville, 2002).

Chapter 3 Literature review – process integration and water pinch analysis

One of the aims of the project (which commenced in 2010) was to find a suitable approach to systematically reduce the specific water consumption at a tissue mill with associated application at other papermaking mills. The significant factors were the total suspended solids concentration, tissue quality constraints, process water quality constraints, effluent water quality constraints, plant space, economics and a long term solution.

There was no limitation was placed on the way that the objective had to be achieved, therefore one of two options could be selected, that is, equipment unit modifications or process integration. For this project, process integration techniques, specifically water pinch analysis was selected as the more effective approach; this is due to process integration being a more cost effective and long term solution (Ng and Foo, 2007; Foo et al., 2008). The process integration approach identifies the problem in the system clearly and therefore indicates where further improvement efforts should be focused. The equipment unit modification approach would not allow for this and may therefore not alleviate the system bottlenecks.

This section gives an introduction into the need for process integration and also an overview of the developments in pinch analysis methods which are available. A comparison of these methods presented and from this the most appropriate method for application to the tissue making process is decided (**section 3.6** and **section 3.7**). The selected method of pinch analysis will be discussed in **Chapter 4**.

3.1 Process integration

Rudol (1968) first defined *process synthesis.* Its definition has taken many forms over the years, the most commonly accepted being *…the discrete decision-making activities of conjecturing 1) which of many available component parts one should use and 2) how they should be interconnected to structure the optimal solution to a given design problem… Westerberg (1987).*

Buehner and Rossiter (1996) defined *process integration* as a term used for the application of methodologies aimed at designing a new facility or modernising an existing facility by looking at the system as a whole and optimising the connections between units rather than improving the units themselves. Process integration techniques provide a basis for developing and analysing designs in their entirety and can be readily focused on pollution prevention objectives (Mansfield, 2005).

The methods for process integration were originally developed in the 1970s, for energy (thermal) recovery. Heat exchanger networks where then designed to achieve this recovery by the methods proposed by Linnhoff and Flower (1978). They consider the development and optimisation of exchanger networks in two stages, first a preliminary network design is achieved and then this preliminary network is used as a starting point to develop a more satisfactory network. In the first stage a network is achieved for maximum energy recovery. Then the minimum temperature approach was selected between cold and hot streams depending on practical operating considerations. They also present the problem table method used for the determination of the pinch point and the associated heat exchanger network synthesis.

Both graphical and numerical methods exist to achieve the pinch task. Linnhoff and Hindmarsh (1983) determine the pinch and utility targets for a heat exchanger network via the use of composite curves. The problem is separated into a region above the pinch point and a region below the pinch point. In each of the regions, maximum energy recovery is targeted for using ΔT_{min} (minimum temperature approach) and ensuring that ΔT_{min} is not violated. The purpose of determining the pinch point is because in order to achieve utility targets, there can be no heat transfer across the pinch.

For the heat transfer process the composite curves would be as depicted by **Figure 3-1**:

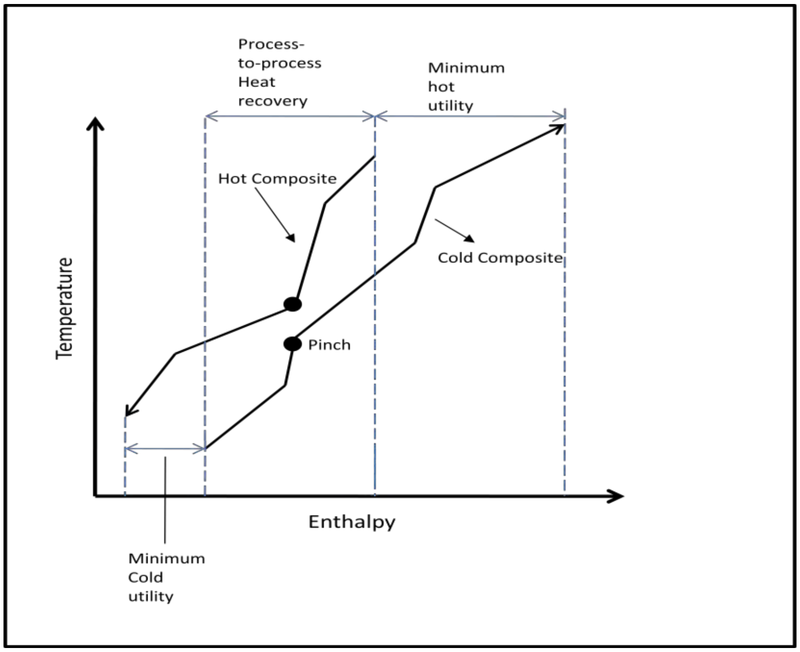

Figure 3-1: Composite curves for energy targeting

Over the years there has been increasing emphasis on the conservation of the environment and has resulted in a greater awareness of the public on the impact of process industries on water resources as well as increasingly stringent environmental regulations. This has resulted in the water management of a plant becoming an important issue for process engineers.

Due to this increased interest in water recovery this heat pinch approach has been adopted to suite mass exchange networks. In this is included water network optimisation.

El-Halwagi and Manousiouthakis (1989) where the first to use the analogy between heat and mass transfer to adapt the method proposed by Linnhoff and Hindmarsh (1983) to develop a procedure for the determination of optimal mass exchange networks. It was developed for systems where water is used as a mass separating agent for single contaminant processes. El-Halwagi (1990) later modified the technique to include regeneration and thereafter automated the technique.

In this method (El-Halwagi, 1990), mass exchange networks and associated regeneration networks are determined simultaneously. The method uses combined mixed-integer non-linear and mixed-integer linear programming to minimise the cost of separation units and to determine the location of the pinch points, optimum flows and minimum number of regeneration units.

Development of process synthesis has been discussed extensively in various research studies. Manousiouthakis and Allen (1995) classified process synthesis into seven broad areas:

1. material synthesis
2. reaction path synthesis
3. reactor network synthesis
4. separation network synthesis
5. heat exchanger network synthesis
6. mass exchanger network synthesis
7. total flowsheet network synthesis

Of the above mentioned process synthesis areas, the most developed area is heat exchanger network synthesis. It has over 460 related works in the past century (Foo, 2009).

> *… A considerable amount of work has been presented for water network synthesis using both the insight-based 'pinch analysis' technique (or water pinch analysis in short) and the mathematical-based optimisation approach… Foo (2009).*

Bagajewicz (2000) and Manan et al. (1999) published a review and textbook respectively on this research area. These references discuss the 'old' techniques; recent developments present a vast variety of new techniques and approaches (Foo, 2009).

In order to reduce water usage two approaches can be taken i.e. (1) changes in process operations e.g. equipment upgrading or (2) by process integration where water reuse, recycle and regeneration is employed (discussed further in the theoretical background).

Network synthesis can be achieved in two steps:

1. flow rate targeting
2. network design

Processes can be divided into fixed load or fixed rate problems. It must be noted that all cited references with regards to network synthesis are for continuous processes. Therefore techniques for batch and semi-batch processes are not discussed. Also only papers available in the English language have been included.

Insight-based techniques for water network synthesis developed between 1994 and 2000 focused on mass transfer based water-using processes. In such processes water is used as a mass separating agent. Water is used to remove a certain load of impurity from the impurity rich stream. An example of such a process is solvent extraction. The concern in these techniques was the amount (load) of impurity required to be removed rather than the water flowrate required to remove this impurity load. These types of problems where named 'fixed load' problems.

Foo (2009) describes the following general problem statement with respect to fixed load problems:

- given a number of water-using processes, designated as PROCESS, or P ={p = 1, 2, 3, ...,N_P}, each with an inlet ($C_{PR,in}$) and outlet ($C_{PR,out}$) impurity concentrations of a targeted species, each process requires an impurity removal load Δm_p.
- in each process, the water source may enter at the maximum inlet concentration (C_{in}) and leave at the maximum outlet concentration (C_{out}) of the targeted species.
- external fresh water source(s) are to be purchased to satisfy the impurity removal requirement of the process.

In fixed load problems water gains or losses are considered negligible and hence the inlet and outlet flows will be constant. These methods did not consider processes where water is considered as a process stream rather than a mass separating agent. Hence there was room for further development.

Process water management may be classified into two activities: the optimum allocation of reusable water to minimise the fresh water requirement, and optimal treatment of waste water generated to meet environmental regulations (Bandyopadhyay, 2008)

Takama et al. (1980) looked at water reduction between water-using units and wastewater treatment units. This was considered for all such units in the entire system and hence developed and introduced the concept of a general system structure called the superstructure. The problem was broken into problems with inequality constraints. This was done by incorporating a *penalty function.* This penalty function removes the initial problem of having to find the feasible points. Either graphical or numerical techniques can be used.

The concept of a limiting composite curve and water supply line was developed by Wang and Smith (1994a and 1995). This is a graphical method to determine the minimum wastewater flowrate and takes into account water reuse, recycle, regeneration-reuse and regeneration recycling as well as multicomponent systems.

This method, however, is complicated and requires breaking loops in the design network (Bagajewicz, 2000).

New design methods presented by Olesen and Polley (1997) and Kuo and Smith (1998a and 1998b) were developed as improved and simplified methods of that proposed by Wang and Smith (1994a and 1995).

Dhole et al. (1996) introduced the *two-composite plot* and a method of water pinch which combines both numerical and graphical techniques. This plot has water surplus/demand purities along the y-axis with flowrates along the x-axis. Using this plot, the freshwater and wastewater targets can be determined similar to the way hot and cold utility targets are found for the heat pinch method.

After 2000 methods for tackling such systems in which water is a main component in the process stream were investigated. In these methods flow rate is the main focus rather than impurity load removal. The problem is viewed from a 'source' and 'sink' perspective. This type of problem is referred to as a fixed flow problem because the inlet and outlet flows of water for a process may not be uniform.

Foo (2009) describes the following general problem statement for fixed rate problems:

- given a number of water-consuming units, designated as SINK, or SK = {j = 1, 2, 3,..., N_{SK}} that each require a feed with a given flow rate, F_j, and a concentration of a targeted impurity, C_j, that satisfies the following constraint:

  $$C_j^{min} \leq C_j \leq C_j^{max}$$

  where C_j^{min} and C_j^{max} are the lowest and the highest concentration limits of the targeted impurity.
- given a number of water-generating units/streams designated as SOURCES, or SR = {i = 1, 2, 3, ..., N_{SR}}, each can be reused/recycled to process sinks. Each source has a given flow rate, F_i, and an impurity concentration C_i.
- external fresh water source(s) is also available to be purchased to satisfy the requirement of sinks.

It must be noted that the objective of both fixed load and fixed rate problems is to minimise the amount of external water used. Fixed load problems can be converted into fixed rate problems as described by Foo (2006).

3.2 Targeting techniques for water reuse/recycle

Methods have been developed for the fixed load and the fixed rate type of problem. The sections which follow describe the progression of the work for targeting techniques for water reuse/recycle for the fixed load and the fixed rate type of problem.

3.2.1 Fixed-load problems

The fixed load type of problem is one in which the primary concern is the transfer of some fixed load of contaminant. The water flows through the system are considered constant. Therefore considering the process description of the tissue making process (**Chapter 2**), the fixed load type of problem does not apply to the tissue making process because water is used as a raw material in the process rather than a mass separating agent. Therefore the methods for the fixed load type of problem are only highlighted below but not explained in detail:

- Limiting composite curve :
    - developed by Wang and Smith (1994)
    - based on the limiting water profile
    - Smith et al. (1994-1998) initiated the insight-based approach and later extended it to wastewater network synthesis analysis
    - Wang and Smith (1994) approach the problem from a composite curve perspective
    - the method focuses on targeting maximum water reuse
    - can be applied to multiple fresh water sources
    - does not take costs into consideration
    - it is iterative
    - limitation is that various problems are encountered when applied to real life situations
    - The transformation of data required in order to plot a limiting composite curve is tedious and hence lead to the development of new targeting procedures

- Two composite plot:
  - Dhole et al (1996) designed this method to overcome the limitation of the method of Wang and Smith (1994)
- Mass problem table (MPT):
  - Olesen and Polley (1997) introduced a new method based on the use of a load table
  - The mass problem table is an algebraic method described by Castro et al. (1999) which can be used to determine the minimum fresh water flow rate for the fixed load problem.
  - Liu et al. (2007) and Agrawal and Shenoy (2006) showed that the method can be applied to the fixed rate type if proper data transformation is conducted
- All methods have been discussed extensively by Foo (2009)

3.2.2 Fixed- rate problems

The development of methods to handle these types of problems was started by consultants Linnhoff March (1996) (Foo, 2009). A vast variety of techniques have since then been developed.

3.2.2.1 Water-source and water-sink composites

The first method employed for flow rate targeting was the water-source and water-sink composites (Dhole et al., 1996; Rossiter, 1996). It is illustrated in **Figure 3-2**:

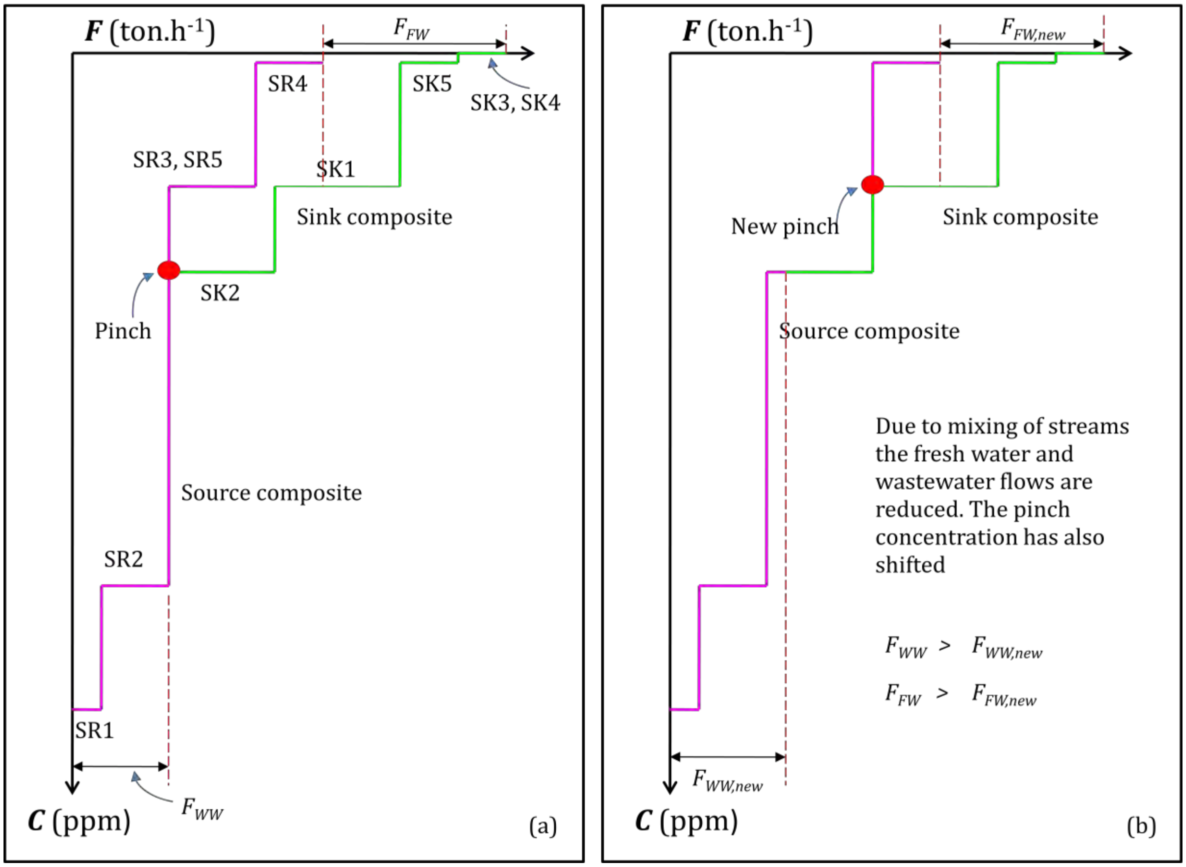

Figure 3-2: Water source-sink diagrams (a) is an illustration of water-source and water-sink composites (not to scale); (b) shows a reduction in both wastewater and fresh water flows due to stream mixing (Dhole et al., 1996; Rossiter, 1996)

The area between the composite curves which overlap is the potential water recovery available for the problem.

3.2.2.2 Evolutionary table

Sorin and Bedard (2001) describe the evolutionary table method. Instead of using the graphical method in **section 3.2.2.1** this equivalent algebraic technique can be utilised.

Hallale (2002) points out that the disadvantage of the two abovementioned targeting methods is that they do not identify the limiting pinch in a multiple pinch problem. Hence this will result in a less than optimum solution and inefficient regeneration unit placement. It was noted by Hallale (2002) that a multi-component problem should rather be tackled using mathematical programming methods.

3.2.2.3 Water surplus diagram

The water surplus diagram was developed by Hallale (2002). It was the first targeting technique which could be used to determine the true (absolute) minimum water flow required for the fixed flow rate problem. Hallale (2002) describes the following steps in constructing a water surplus diagram:

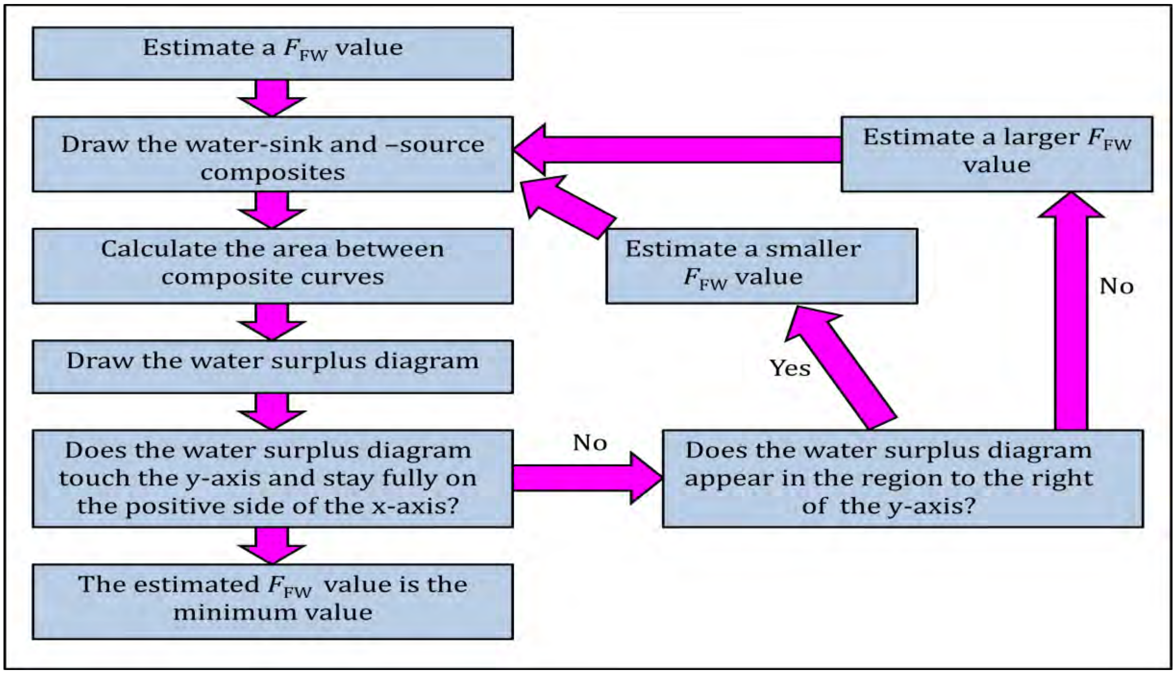

Figure 3-3: Procedure described by Hallale (2002) to construct a water surplus diagram (Foo, 2009).

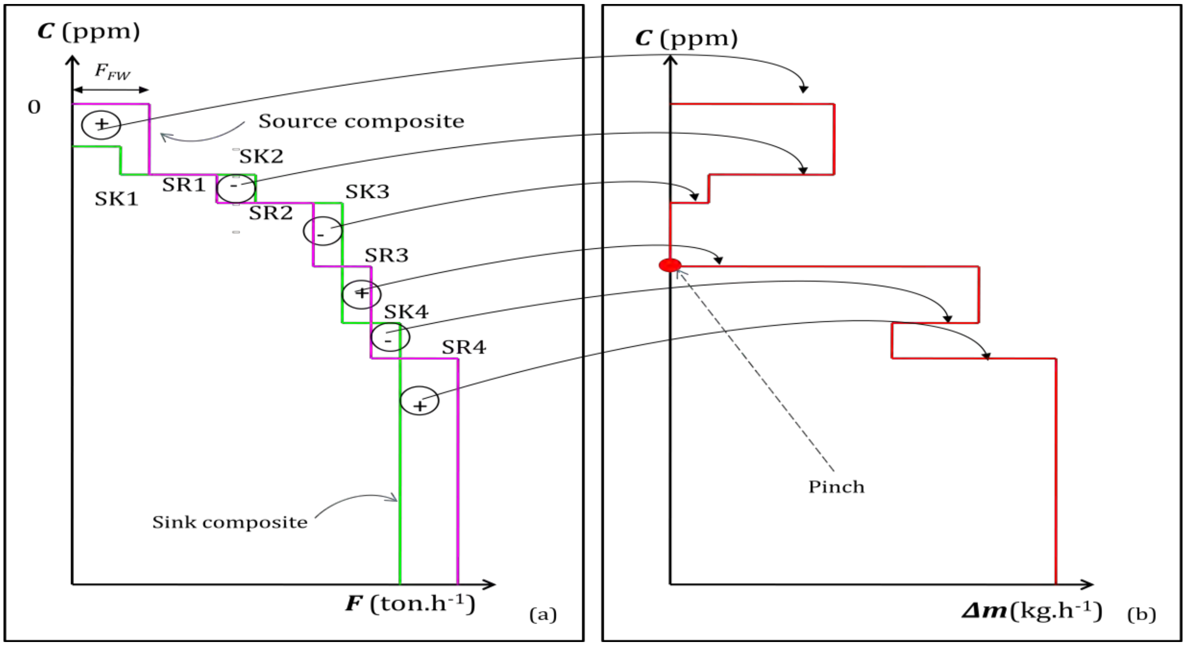

Figure 3-4: Illustration of the results of the targeting procedure proposed by Hallale (2002) as described in Figure 3-3; (a) shows individual source and sink composite curves; (b) shows the resulting water surplus diagram.

This method is reliable in determining the minimum water flow rate targets even when multiple pinch points are concerned but its main limitation is the iterative calculation steps required.

Despite its iterative nature, the water surplus diagram contributed to many subsequent investigations in the field. It was the first work which identified the fact that for fixed rate problems, pinch concentration will always be that of a source concentration. It pointed out the fact that two constraints must be dealt with i.e. impurity load balances and water flow rate. The water surplus diagram is used to analyse the former and the water-sink and source-composites is used to analyse the latter.

3.2.2.4 Material recovery pinch diagram

The material recovery pinch diagram method was developed by two different research groups. It was independently developed by El-Halwagi et al. (2003) in the US and Prakash and Shenoy (2005) in India (Foo, 2009). It was the first graphical tool which eliminated the iterative procedure required to construct a water surplus diagram.

Two algorithms where developed, one to handle situations with a single and pure fresh water source, developed by El-Halwagi (2003) and a second to handle targeting for single and multiple impure fresh water sources, developed by Alwi and Manan (2007).

In the method devised by Alwi and Manan (2007), the assumption that the cost of the secondary fresh water source is negligible in comparison to the primary fresh water source, is made use of. The limitation of this targeting method is the graphical representation. It is difficult to apply when slopes of the composite curve segments are similar (usually near the pinch). This makes it difficult to identify the pinch point exactly.

3.2.2.5 Water cascade analysis

Manan et al. (2004) developed the water cascade analysis method and is analogous to the problem table algorithm in heat integration developed by Linnhoff et al. (1982). It was developed to overcome the iterative water surplus diagram technique.

The method was improved upon by Foo et al. (2006) and extended from being initially applicable to a single pure fresh water source to being able to be used to target for impure fresh water sources (Foo et al., 2007), if these are being used.

Threshold problems describe those situations where there is zero fresh water intake and zero discharge. Foo et al. (2007) modified the water cascade analysis to be applicable to such situations.

3.2.2.6 An algebraic targeting approach

The algebraic targeting approach is a method which is also tabular in nature. It was developed by Almutlaq et al. (2005). This method can be applied for targeting for both a pure fresh water source as well as targeting for an impure water source. Almutlaq et al. (2005) describe the necessary adjustments which have to be made before applying the method when targeting for an impure water source.

3.2.2.7 Source composite curve

Bandyopadhyay et al. (2006) introduced the source composite method and it is a technique which combines both algebraic and graphical approaches. Most of the targeting is performed in table form; the final result can be displayed on a source composite curve.

The method developed by Bandyopadhyay et al. (2006) to target for a single fresh water source was modified by Shenoy and Bandyopadhyay et al. (2007) to target for multiple fresh water sources. The advantage of the targeting procedure is that it incorporates the cost of the impure source.

The main difference between this and other targeting methods is that this method determines the minimum waste water flow before it determines the minimum fresh water flow.

> *… It is very similar to the water cascade analysis technique. Its main advantage over other methods is that "the average concentration of the wastewater stream emitting from the water network is indicated by the wastewater line… Foo (2009).*

Bandyopadhyay et al. (2007) also proposed a rigorous analytical procedure for source composite curves for resource allocation networks. It is based on mathematical proof.

3.2.2.8 Analytical method

The analytical method developed by Liu et al. (2007), determines the pinch concentration before minimum flow rates. This method primarily focuses on determining the pinch causing source. Thereafter the water sinks and sources which fall into the region above and below the pinch are identified. The calculation of the water targets is the last step in this targeting procedure.

3.2.2.9 Automated targeting technique

Graphical and algebraic methods provide a detailed understanding and insight to water network optimisation problems but become more difficult to apply as systems become more complex. Optimisation does not consider factors other than water use i.e. economic factors. Hence mathematical programming methods become more suitable.

El-Halwagi and Hamad (1996) developed a mixed-integer linear programming method to generate waste-inception networks (WINs). It can also be used for handling gaseous and liquid pollution. It works by finding optimum reuse for contaminants rather than having highly contaminated waste streams. This method yields optimal loads, interception locations and separating agents.

It was found by Doyle and Smith (1997) that the limitation of non-linear mathematical programming techniques was that they did not always find the global optimum as it sometimes would determine a local optimum. Therefore to overcome this limitation they present both non-linear and linear formulations of the problem and determined that a combined linear/non-linear approach would overcome the aforementioned limitation.

Alva-Argaez, Kokkosis and Smith (1998) extended the method of Doyle and Smith (1997). Aside from including both linear programming which converges to non-linear programming to eliminate errors it also includes binary variables which corresponds to possible connections in the water network where 1 indicates a possible connection and 0 an impossible connection. This allows the inclusion of many other systems variables. Inclusion of these variables moves the optimisation procedure into the mixed-integer linear programming type.

There is a fairly new technique developed by Ng et al. (2008). It is a mathematical optimisation technique based on the framework of the water cascade analysis technique. It therefore locates the same network targets as the water cascade analysis technique. The main advantage of such a method is that since it is a mathematical optimisation, the objective function can be modified depending on the desired result e.g. to target for the flow rates, to minimise costs etc. This makes the method more flexible. It also allows for a water source flow rate to vary with a specific sink.

This technique is not widely applied or popular because it is relatively new and cannot be applied to multiple fresh water sources or threshold problems.

3.3 Targeting techniques for water regeneration

Water regeneration refers to the partial or total upgrading of water sources by purification techniques. The regenerated water source can then be reused or recycled. Regeneration units fall into two categories i.e. fixed outlet concentration (C_{Rout}) type or the removal ratio (RR) type.

3.3.1 Early works

- Smith, Wang and Kuo (1994-1998) made the main contribution to the early developments on water regeneration targeting; it is based on the limiting composite curves
- The **Figure 3-5** is an illustration of the results produced from the method. Full details of the procedure can be viewed in the original works.

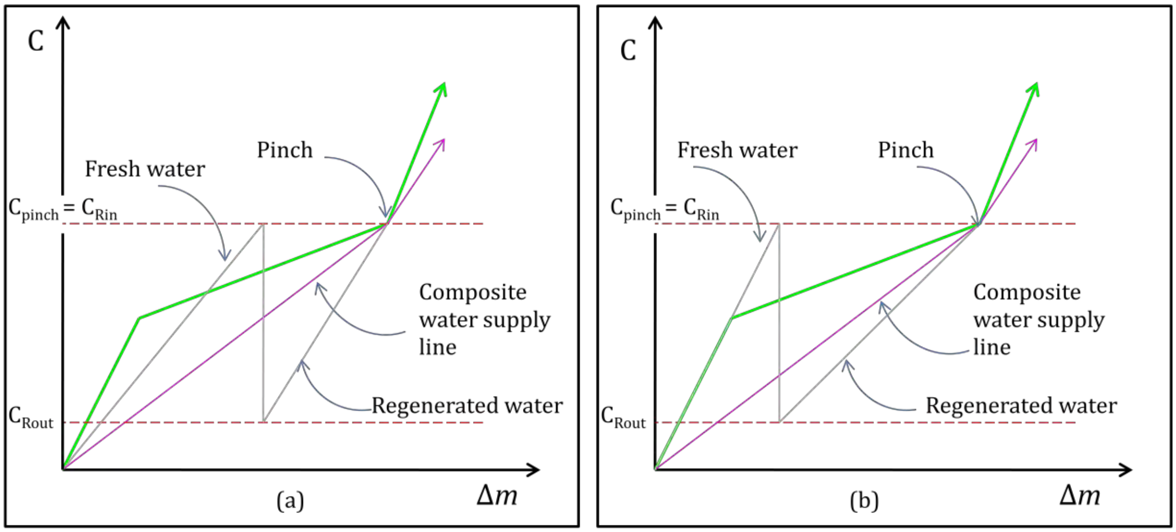

Figure 3-5: An illustration of the targeting using the limiting composite curve of Wang and Smith (1994) for fixed load problems; (a) indicates the curves for regeneration-reuse targeting; (b) indicates the curves for regeneration-recycle targeting.

- The method also allows for options for the use of the regenerated water
- It was later observed by Wang and Smith (1998) and Liu and Manan (1999) that the method did not identify a global pinch point; was not generic enough to be applied to all situations
- Deng et al. (2007-2008) were the next to make headway on this method
- Feng et al. (2007) provide a detailed procedure for targeting for regeneration-reuse systems as well as for targeting regeneration-recycle systems.

These methods can be applied to both types of regeneration equipment i.e. fixed C_{Rout} and RR. However it has only been shown explicitly for fixed C_{Rout} type in the abovementioned research.

3.3.2 Regeneration targeting for fixed flow rate problems

Regeneration targeting methods for fixed flowrate problems are based on the earlier works of Wang and Smith (1994–1998) and therefore consider the pinch concentration as the regeneration inlet concentration.

> *… Hallale (2002) first presented a guideline in placing regeneration units for fixed flow rate problems. In order to reduce the overall water flow rates of the network, regeneration units should be placed across the pinch concentration, where water is drawn from a higher*

concentration region to a lower concentration region… Foo (2009).

Later works by El-Halwagi et al. (2006), Manan et al. (2004) and Foo et al. (2006) all follow this guideline presented by Hallale (2002).

3.3.2.1 Ultimate flow rate targeting

The ultimate flowrate targeting technique proposed by Ng et al. (2007, 2008) was the first method which determines the minimum fresh water and wastewater flows as well as minimum regenerated water flow rate. It is based on the concepts developed by Kuo and Smith (1998).

The only limitation of this approach is that it is developed to apply to systems with fixed outlet regeneration concentration units and therefore not applicable if the reject ratio (RR) type regeneration unit is considered for use.

A flow diagram for the regeneration procedure proposed by Ng et al. (2007, 2008) is given in **Figure 3-6**. Detailed application of the targeting procedure can be viewed in the original works.

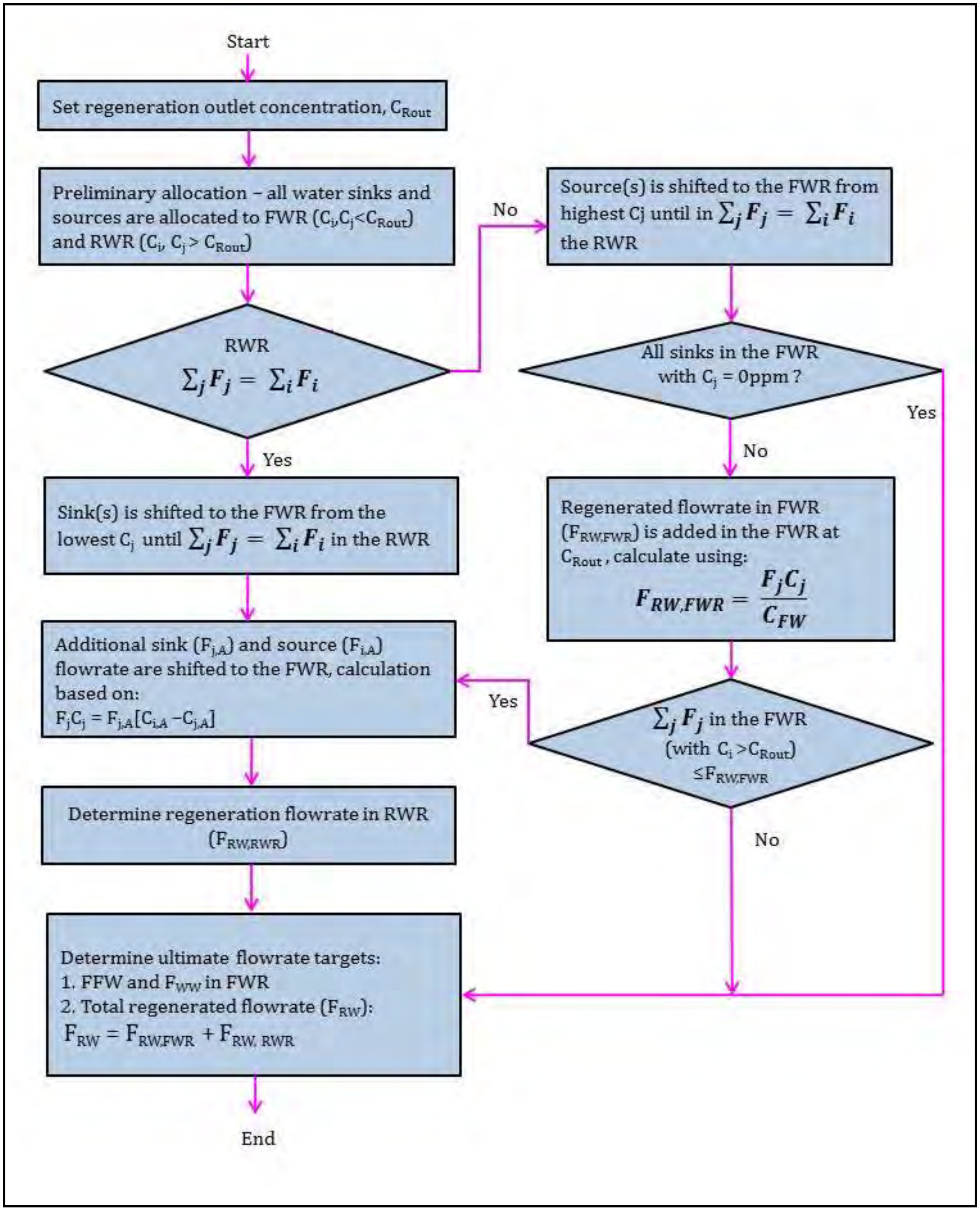

Figure 3-6: The regeneration targeting procedure proposed by Ng et al. (2007, 2008).

3.3.2.2 Source composite curve

A source composite curve method was developed by Bandyopadhyay and Cormos (2008) for the fixed flow rate problems. It can be applied to both C_{Rout} type and RR type regeneration units.

The advantage of this method over others is that during the targeting procedure it allows the maximum inlet concentration to be set for the regeneration unit whereas other targeting methods do not do this directly. *…The regeneration targeting procedure of the source composite curve was originally developed for total water network synthesis, hence it only locates minimum regenerated flow rate for zero discharge cases (after regeneration has taken place). For other more general cases (with wastewater discharge), the treated flow rate includes both regeneration (for reuse/recycle) and wastewater treatment (for final discharge). Hence, one would not be able to obtain the regenerated flow rate alone without considering the waste treatment… Foo (2009)*

3.3.2.3 Automated targeting technique

The previously mentioned ultimate flowrate targeting technique of Ng et al. (2008) was extended to regeneration targeting by Ng et al. (2009).

This method targets for the minimum flow rates for the network but also has the added advantage of being able to add a minimum cost solution during the targeting stage. It also simultaneously produces a mass exchange network. This mass exchange network is used as the regeneration system (Foo, 2009).

The method is only applicable to the C_{Rout} type regeneration unit problem.

3.4 Targeting techniques for wastewater treatment

The techniques for wastewater treatment research field have not been investigated in as much detail as the pinch-based approach. Smith and associates (1994, 1997) reported the approach to fixed load problems with Bandyopadhyay and Cormos (2008) and Ng et al. (2007) producing methods for fixed flow rate problems.

The method of Ng et al. (2007) is based on the material recovery pinch diagram. This method allows for the calculation of the minimum treatment flow rate and also ensures that the wastewater treatment system removes the minimum impurity load. It can be applied to both fixed C_{Rout} and RR type regeneration units. Its limitation is that when many treatment units are used it is unable to determine the minimum treatment flow.

Bandyopadhyay and Cormos (2008) apply a source composite curve method. The minimum flow rate is determined using the same process as when determining the minimum regeneration flowrate

3.5 Targeting for a total water network

Discussed methods thus far consider reuse, recycle, regeneration and wastewater treatment separately. These systems can be considered from a 'total water network' perspective.

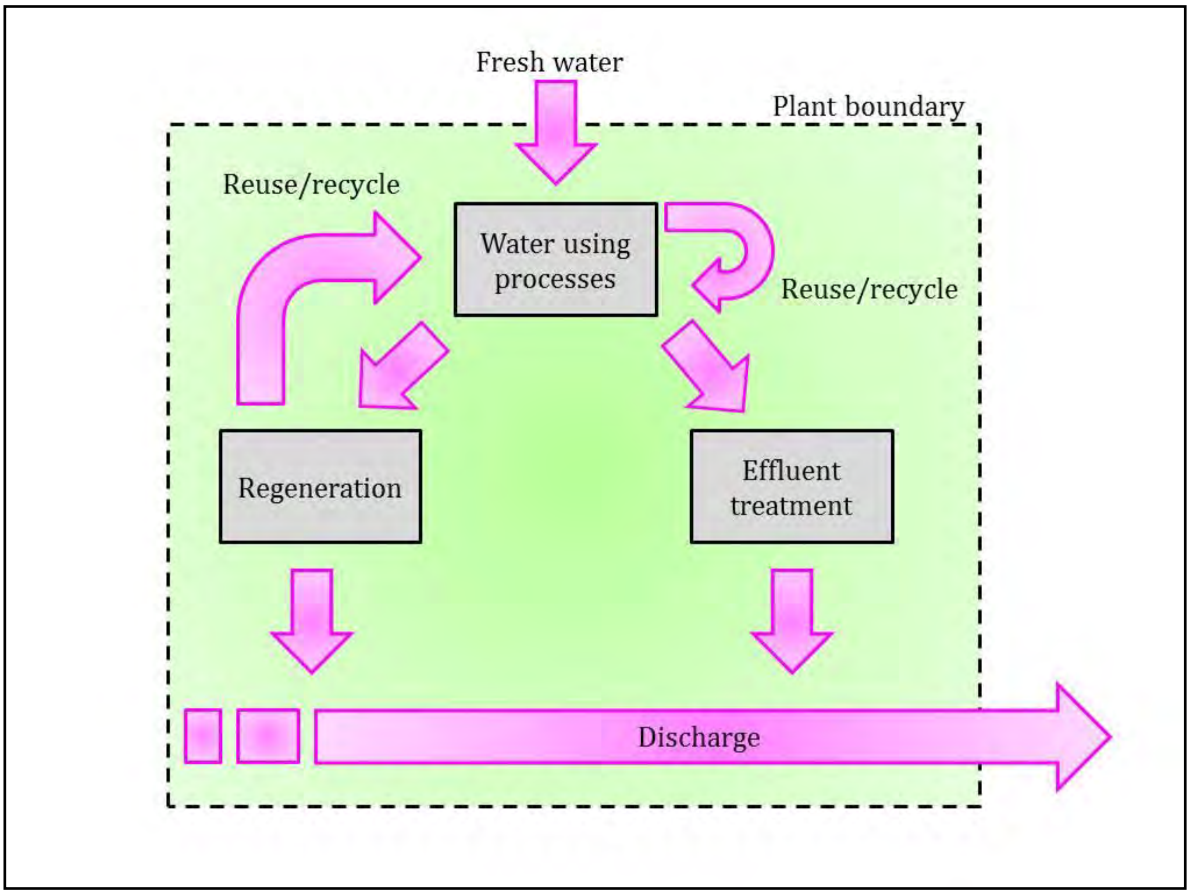

Figure 3-7: Overall framework of the total water network. Within the framework the overall elements interact with each other (Foo, 2009).

3.5.1 Targeting for fixed-load problems

The earliest method presented in this area is that of Kuo and Smith (1998). They combined the individual methods for reuse, recycle, regeneration and treatment and investigated the interaction between them.

However, no exact method has been developed to obtain the optimum water network which in its targeting process determines the minimum impurity load removal as well as minimum flow rates.

3.5.2 Targeting for fixed flow rate problems

The flow diagram below depicts the targeting procedure for the total water network proposed by Ng et al. (2007).

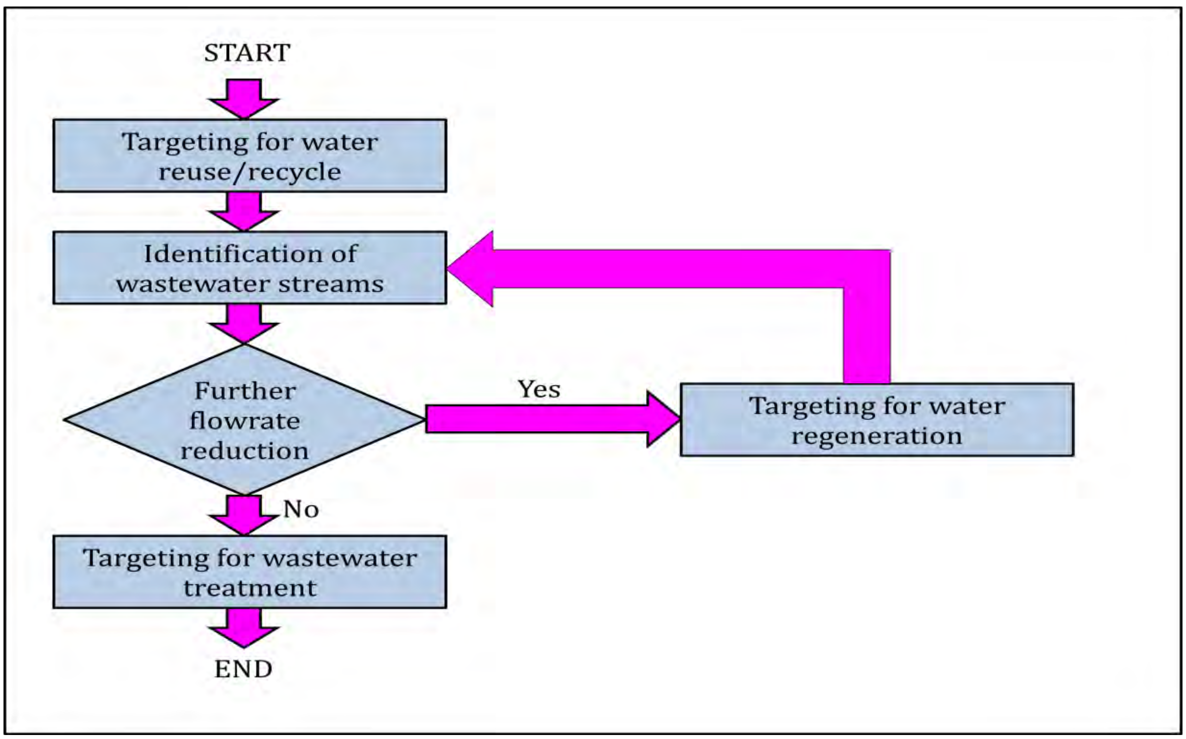

Figure 3-8: The over-all targeting procedure for total water network design proposed by Ng et al. (2007) (Foo, 2009).

This is a step-by-step method which ensures that the minimum flow is attained at each stage. The method also ensures lowest operating costs because it considers the removal of a minimum impurity load.

The limitation of this method is that it can only be applied to regeneration units of fixed C_{Rout} type and it cannot be applied if multiple treatment units are used.

The source composite curve method of Bandyopadhyay and Cormos (2008) can be applied to waste treatment systems. This method is simpler than that of Ng et al. (2008) because all flows are determined from one method i.e. the source composite curve. It cannot be used if different regeneration units with different C_{Rout} or reject ratio values are being used in a single system.

Ng et al. (2008) also presented generic automated targeting technique; the advantage of this technique is that many different objective functions can be built into the procedure. Different regeneration units with different outlet concentrations can be considered as well as multiple treatment systems. However it is designed to evaluate systems with fixed C_{Rout} or C_{Tout} types of regeneration unit and treatment units respectively i.e. it cannot be applied to the RR type of regeneration units.

One such method has been trademarked *WaterPinch* by Linnhoff and March and is available as a mathematical programming tool. The mathematical tool, involving integer non-linear programming algorithm allows the user to handle complex, multi-contaminant problems (Mansfield, 2005).

Bedard et al. (2001) list the following steps to be undertaken when approaching a water pinch problem:

- data gathering and formulation of mass balances by means of a simulation package.
- identification of the main contaminants and their maximum allowable concentration in the water streams, as well as other process constraints.
- apply pinch analysis using software to determine the minimum freshwater target and the design to achieve the target.
- verify the reuse scenarios proposed by the software by incorporating them into the mill simulation.

In this research study a more detailed inspection shall be done aside from that mentioned above including:

- the cause of the pinch
- methods to the overcome the pinch i.e. treatment of water or changing equipment?
- devise different up-grade trajectories and evaluate them

- consider the process, that is, will the proposed solution be realistically achievable in respect to the current process layout; and costs

3.6 Selecting an appropriate pinch analysis technique

Before selecting an appropriate method, the process must be first understood. **Chapter 2** details the process flow through the production process, Understanding was gained on the requirements, expectations and operating conditions of the various process units. This was needed in order to decide which method (numerical, graphical, and automated) would be better suited for the mill's operating conditions.

Therefore an extensive literature survey was conducted. All relevant information regarding this is detailed in **Chapter 1**.

3.6.1 Narrowing down the appropriate method

Pinch analysis was initially developed for energy recovery; the process integration between heat exchangers leads to greater energy usage efficiency. Due to the increase in environmental awareness, the need for corresponding methods for other material recovery led to various works on water pinch analysis based on the analogy between heat and mass transfer.

As discussed in **Chapter 1**, water using processes can be divided into *fixed load* (water flows are constant) or *fixed rate* problems (water flows vary). The former considers systems which use water as a mass separating agent e.g. in a scrubber where water is used to remove contaminants from a gas stream. Water is not a part of the process stream and its flow is assumed to be constant. Fixed (constant) load problems are considered to be mass transfer-based water-using processes. Here a certain (fixed) amount of impurity is removed from a process stream where water acts as mass separating agent. The load (amount of contaminant removed) is the primary concern and water gains or losses are considered negligible.

However, for some processes, the water flow into and out of a process is not constant. The concept of a sink and a source is developed to deal with these types of problems which are referred to as *fixed rate problems*. A *sink* refers to when water of a particular quality is required to be added to a process and a *source* refers to water which is removed from a process which has the potential for reuse, recycle, regeneration and a combination thereof.

Therefore pulp and papermaking processes are considered to be a fixed rate type of problem. Considering this, all works in **sections 3.2.1**, and **section 3.5.1**, cannot be applied.

Methods **3.2.2.1** and **3.2.2.2** were not selected because they are iterative and as pointed out by Hallale (2002), these methods do not identify the limiting pinch point in a multiple pinch problem. This will result in an inefficient placement of regeneration units, that is, due to the pinch point continuously shifting due to the iterative mature of the method, it will result in a greater number of regeneration units than is actually required.

Therefore Hallale (2002) developed the water surplus diagram which was the first method which identified the absolute minimum fresh water flowrate with its global pinch point. However it is an iterative process.

The material recovery pinch diagram, whilst eliminating the iterative steps of the water surplus diagram of Hallale (2002), still has a graphical representation. It is difficult to apply when the composite curves have very similar slopes, such as around the pinch point, which makes the pinch point difficult to identify. If the slopes are similar then the flowrates and contaminant concentrations of the sources and sinks around the pinch point are very similar, therefore identifying the pinch point may be difficult which can lead to inaccurate selection of regeneration units. Therefore the intervention selected will not be successful in reducing the water consumption. Hence the material recovery pinch diagram was not considered for application.

The algebraic method of Almutlaq et al. (2005) has not been extensively applied to the fixed rate type of problem such that conclusive results have been obtained to determine if the approach developed does indeed produce minimum water targets, as compared to other methods, and was therefore not considered.

Section 3.2.2.7 was not selected because the result is displayed graphically and the average concentration of the wastewater stream discharged from the network must be determined from the wastewater line and is not determined explicitly.

Various automated (computer programing based) techniques have been developed; according to Bedard (2001), if a pinch approach is being selected for application on such a scale that computer programming is required then it is best approached using computer software which is available for the system, such that all process operating parameters are considered in the analysis; therefore automated techniques were not considered.

Most of the fixed rate methods discussed were extended, aside from determining the minimum fresh water and wastewater flowrates, to also determine the minimum regeneration flowrate for the system.

Hallale (2002) pointed out that in order to attain absolute minimum flowrates, regeneration should occur across the pinch point.

The disadvantage of the source composite method of Bandyopadhyay and Cormos (2008) is that for systems where there is the discharge of wastewater from the system, the minimum regeneration flowrate cannot be determined. Wastewater treatment must be considered in the total water network in order for its application to be successful.

Ng et al. (2008) developed a mathematical optimisation based on the water cascade analysis. However it is relatively new and has not been extensively applied; it also cannot be applied to multiple fresh water sources or threshold problems.

The advantage of water cascade analysis and using the water cascade table is that it quickly yields the exact utility targets and the pinch location(s) without the iterative steps required by the water surplus diagram. The second advantage is that it clearly identifies the pinch-causing stream and hence the exact water allocation for the regions above and below the pinch to achieve the minimum water targets during the network design (Foo et. al., 2007). The water cascade analysis technique was also the first method to remove the iterative nature of the water surplus diagram of Hallale (2002) (Foo, 2009),

3.7 Conclusion

Considering the information and caparisons between the different water pinch methods available, as discussed in **section 3.6**, the best suited method for the system is the ultimate flowrate targeting technique with regeneration placement of Ng et al. (2009). An overview of this method will be discussed in detail in **Chapter 4**. The application of the method is detailed in **Chapter 6**.

Chapter 4 Ultimate flow rate targeting technique of Ng et al with regeneration placement (2009)

In **Chapter 3** it was determined that the most suitable water pinch analysis method for application to the tissue making process was the ultimate flowrate targeting technique of Ng et al. (2009). This section details the theory behind the method and discusses the various water targets which can be assessed through correct application of the method.

4.1 Reuse, recycle and regeneration

Significant work has been done to systematically address in-plant water *reuse/recycle, regeneration/treatment*. The term *reuse* means that the effluent produced in one unit is used in another unit but it will not re-enter the unit from which has left. *Recycle* however, allows this effluent to re-enter the unit from which it has been previously used. *Regeneration* refers to the partial or total upgrading of water purity using purification techniques (Ng et al, 2009). Within the context of the paper plant these purification techniques can be grouped into two categories i.e. those that are concentration driven and those which are pressure driven. Concentration driven processes include adsorption, ion exchange, steam stripping; and processes such as filtration and membrane separation fall into the pressure driven category.

Figure 4-1 illustrates various schemes for water reduction:

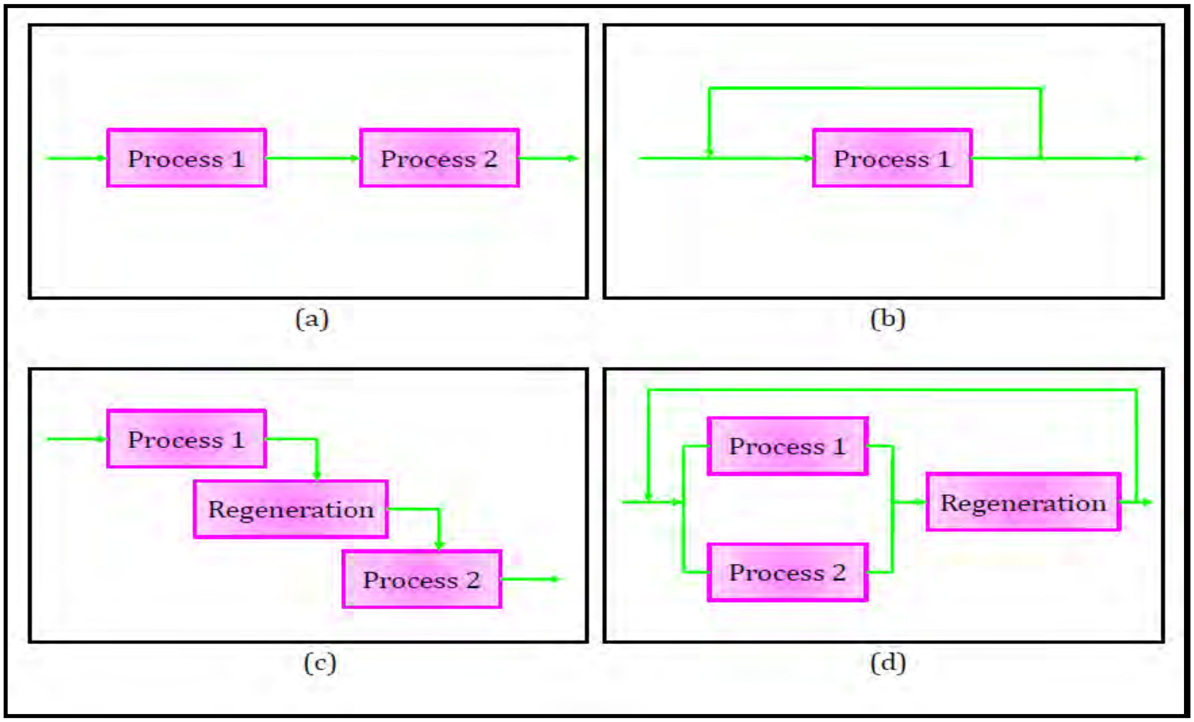

Figure 4-1: a) Reuse, b) Recycle, c) Regeneration-Reuse, d) Regeneration-Recycling

The procedure of obtaining an optimal water network has two stages:

1. Flow rate targeting: this aims to set the minimum fresh water and wastewater flow rates for a network based on concentration and flow rate restrictions
2. Network design: Matches are made between the water-producing and water-using processes, to achieve the minimum flow rates determined in the targeting stage

4.2 Flow rate targeting

Flow rate targeting refers to the procedure of determining the minimum fresh water and wastewater flowrates for a system. Various techniques exist. The technique which was followed will be discussed in detail in this section.

4.2.1 Ultimate flow rate targeting with regeneration placement

When undertaking the task of integrating process water streams, the problem must be identified as either a *constant load problem* or a *constant rate problem*.

Various graphical and numerical techniques have been developed to determine the minimum water targets. A numerical technique proposed by Ng et al. (2009) locates the minimum regeneration flowrate that achieves the ultimate fresh water and wastewater targets for both fixed load and fixed flow rate problems.

By intercepting a process stream to match the process constraint (e.g. limiting concentration of the water sink), the level of contaminant in the water sources are reduced and the regenerated water can either be reused in other water-using processes or recycled to the same process. This leads to further reduction of water flowrates in the network (Ng et. al., 2009).

Ng et al. (2009) have modified the numerical technique of water cascade analysis (Manan et al., 2004; Foo et al, 2006a), to produce the ultimate flowrate targeting technique. The ultimate flow rate targets, for a given quality of regenerated water, includes the lowest possible fresh water, wastewater and regeneration flowrates after water reuse/recycle has been maximised among all water using processes (Ng et al., 2009)

4.3 Water cascade analysis technique

Table 4-1 describes the water cascade analysis numerical method of Ng et al. (2009), that is, the water cascade analysis technique. An explanation of the table follows. A numerical example can be viewed in the original work of Ng et al. (2009)

Table 4-1: Water Cascade table for water flowrate targeting (Ng et al., 2007).

1 K	2 C_k	3 F_j	4 $\sum_j F_j$	5 F_i	6 $\sum_i F_i$	7 $(\sum_i F_i - \sum_j F_j)$	8 $F_{C,k}$	9 Δm_k	10 $Cum\Delta m_k$	11 $F_{FW,k}$
							F_{FW}			
K	C	F_{jc1} F_{jc2} . . . F_{jcm}	F_{jc1} + $F_{jc2} + \ldots + F_{jcm}$ = $(\sum_j F_j)_k$	F_{ic1} F_{ic2} . . . F_{icm}	$(\sum_i F_i)_k$	$(\sum_i F_i - \sum_j F_j)_k$				
							$F_{C,k}$	Δm_k		
k + 1	C_{k+1}		$(\sum_j F_j)_{k+1}$		$(\sum_i F_i)_{k+1}$	$(\sum_i F_i - \sum_j F_j)_{k+1}$			$Cum\Delta m_{k+1}$	$F_{FW,k+1}$
							$F_{C,k+1}$	Δm_{k+1}		
n – 2	C_{n-2}		$(\sum_j F_j)_{n-2}$		$(\sum_i F_i)_{n-2}$	$(\sum_i F_i - \sum_j F_j)_{n-2}$				
							$F_{C,n-2}$	Δm_{n-2}		
n – 1	C_{n-1}		$(\sum_j F_j)_{n-1}$		$(\sum_i F_i)_{n-1}$	$(\sum_i F_i - \sum_j F_j)_{n-1}$			$Cum\Delta m_{n-1}$	$F_{FW,n-1}$
							$F_{C,n-1} = F_{WW}$	Δm_{n-1}		
n	C_n								$Cum\Delta m_n$	$F_{FW,n}$

Table 4-1 summarises the procedure to be followed in carrying out a water cascade analysis for flowrate targeting in a water network. The procedure is as follows:

1. In column 1*(k)* and 2 *(C_k)* the concentrations (mass balance for sources and equipment specifications for sinks) are arranged in ascending order.
2. *j* represents a sink. Column 3 lists the sinks at concentration level *k*. The flowrates of these sinks are summed at their respective concentration levels in column 4.
3. *i* represents a source. The sources at concentration level k are listed in column 5. The flowrates of these sources are summed at their respective concentration levels in column 6.
4. In column 7, the net flow rate between the sources and sinks are determined for each concentration level *(k).* A positive net flow represents a surplus of water and a negative represents a deficit of water.
5. Next, the net water flowrate surplus/deficit is cascaded down the concentration levels to yield the cumulative surplus/deficit flowrates (Column 8). Initially a fresh water feed (F_{FW}) is assumed to be zero. This is done to facilitate the search for the minimum water flowrates and this zero flow will be replaced once the rigorous fresh water target is located (Ng et al., 2007)
6. In column 9, the impurity load is determined. This is calculated from the product of the cumulative flowrate *($F_{C,k}$)* and the concentration difference between two concentration levels i.e. C_{k+1} - C_k
7. These impurity loads calculated in column 9 are cascaded down in column 10 to produce the cumulative impurity load.
8. If a negative cumulative impurity load results in column 10, this means that an impurity load is transferred from a lower concentration to a higher concentration, which is not feasible. In this case, an interval feed water flowrate ($F_{FW,k}$) is determined in column 11. This is calculated from the following equation (Ng et al., 2007):

$$\mathbf{F_{FW,k} = \frac{Cum.\Delta m_k}{C_k - C_{FW}}}$$ **Equation 1**

Where:

$F_{FW,k}$ = interval feed water flowrate
$Cum.\Delta m_k$ = cumulative impurity load
C_k = concentration at level k
C_{FW} = fresh water concentration
C = concentration

k = concentration level

n = last concentration level, usually the effluent concentration

*Any set of consistent units can be used

The negative flows which result indicate that due to the initial assumption of zero fresh water, there is not enough fresh water to meet all water demands. Hence, some fresh water is required to be added. To obtain the minimum fresh water flow required the absolute value of the largest negative $F_{FW,k}$ will then replace the earlier assumed zero fresh water flow in column 8 and a new set of feasible flowrate cascade and hence load cascade are determined. This new fresh water flowrate represents the minimum fresh water flowrate of the network. The final row in column 8 (F_{WW}) represents the wastewater flowrate generated by the network. (Ng et al., 2007)

There will exist at a certain concentration and purity level k where $F_{FW,k}$ = 0. This concentration is referred to as the pinch.

The pinch is the most constrained point of the network that limits maximum water recovery (Foo et. al., 2004). It was stated by Hallale (2002) that the pinch will always occur at a source concentration and is the point where the source switches from being below a demand (deficit) to being above a demand (surplus).

A feasible water cascade is one in which there is a positive or zero $F_{FW,}k$ at each concentration level k and the feasible water cascade results in the minimum fresh water (F_{FW}) and wastewater (F_{WW}) for the process.

The advantage of water cascade analysis and using the water cascade table is that it quickly yields the exact utility targets and the pinch location(s) without the iterative steps required by the water surplus diagram. The first advantage of water cascade analysis is that both F_{FW} and F_{WW} are identified. With the water surplus diagram only F_{FW} is determined from a long iterative procedure.

The second advantage is that it clearly identifies the pinch-causing stream and hence the exact water allocation for the regions above and below the pinch to achieve the minimum water targets during the network design (Foo et. al., 2007).

4.4 Assessing options for process changes by the water cascade analysis technique

In order to reduce water targets, two possible changes can be made i.e. introduce water regeneration and/or equipment modifications.

Regeneration can occur:

- above the pinch - the water source(s) is partially treated to improve its purity
- across the pinch - regeneration consists of the treatment of water source(s) below the pinch to produce source(s) at a higher purity than the pinch purity
- below the pinch - for regeneration below the pinch, treatment results in a source of better purity but purity is still maintained below that of the pinch.

Regeneration above and across the pinch results in a reduction in both the fresh water flowrate and the wastewater flowrate.

Regeneration below the pinch results in reduction of the wastewater flowrate only; this occurs because the pinch causing stream (the bottleneck in the system) will not be alleviated, that is, the pinch point will still exist. Therefore the regenerated water can be reused in the system reducing the wastewater flowrate but due to the pinch point remaining, the fresh water consumption will still be high. Put simply, the wastewater is reduced due to regeneration, but because the pinch point still exists, which causes the higher fresh water usage, the fresh water requirement will be high.

For equipment modification, existing units can be modified, new units added to the system with existing units or a piece of equipment can be replaced by another more efficient unit.

4.5 Water regeneration targeting

The above outlined procedure of the water cascade analysis has been modified to target also for the minimum regeneration flow rate in the event of a required regeneration unit. Ng et al. (2009) provide detailed examples of how to apply the method in their original works.

A regeneration unit can operate as one of two types i.e. a unit which produces a fixed outlet concentration or a unit which removes a fixed fraction of the inlet impurity to the unit. The procedure followed uses the fixed outlet concentration model. This was assumed due the requirement of water of a certain minimum purity being required by particular processes at the mill, hence a fixed outlet concentration.

The first step of the targeting procedure calls for preliminary allocation of the water sinks and sources into their respective sub networks (Ng et al., 2009).

4.5.1 Preliminary allocation of water sinks and sources

There are two preliminary regions i.e. the Fresh Water Region (FWR) and the Regenerated Water Region (regenerated water region). The sources and sinks in the fresh water region are those which have a concentration lower than the concentration of the water stream leaving the regeneration unit. The sources and sinks in the regenerated water region are those which have concentrations higher than that of the regeneration unit.

It must be noted that the assumption made is that the water loss from the regeneration unit is negligible.

Two scenarios were considered:

- The total source flowrate is higher than that of the total sink flowrate in the regenerated water region (Ng et al., 2009)
- The total source flowrate is lower than that of the total sink flowrate in the regenerated water region.

4.5.1.1 Scenario 1

Here there is an excess of sources in the regenerated water region, therefore one or more of these sources can be re-allocated to the fresh water region. The source selected should be that of the highest concentration. If another source can be added to the fresh water region, it should be the one with the second highest concentration and so on.

Once this reallocation is done, the minimum regeneration flowrate in the regenerated water region is targeted using the water cascade analysis technique discussed.

From **Equation 1**, the feed water to the regenerated water region corresponds to regenerated water (fresh water region, regenerated water region) with a feed concentration of C_{RW} (i.e. $C_{FW} = C_{RW}$ in equation 1) (Ng et al., 2009).

Then the fresh water and wastewater flowrates of the overall network is determined by a separate water cascade analysis on the fresh water region (Ng et al., 2009). Since from these two separate water cascade analyses the minimum flowrates in each region are obtained, these are termed the *ultimate flowrate targets.* These flows represent the lowest possible fresh water, wastewater and regeneration flow rates for a given quality of regenerated water.

4.5.1.2 Scenario 2

When the sinks flowrate is greater than the source flowrate in the regenerated water region, the flow reallocated to the fresh water region, will be from the sink with the lowest concentration. The flow to be reallocated will be the difference between the total sink and total source flows. If after the first sink is reallocated, the required difference has still not been reallocated, the sink with the next lowest concentration is reallocated to the fresh water region and so on, until the required flow is met. The reason for this allocation procedure is so that the water sinks requiring higher quality water, such as fresh water, are found in the fresh water region. It will also have a concentration higher than the regeneration concentration and hence lead to reuse/recycle if water sources can be shifted from the regenerated water region. However, this will lead to a flow rate imbalance between the total sources and total sinks in the regenerated water region (Ng et al., 2009).

The balance between these flowrates is re-established by re-allocating an additional sink flowrate from the regenerated water region, which is equal to the flowrate of the additional water source. The amount to be re-allocated to the fresh water region, after the initial re-allocation of the sinks is determined from the following (Ng et al., 2009):

$$\mathbf{F_j C_j = F_{i,A}\left(C_{i,A} - C_{j,A}\right)} \qquad \textbf{Equation 2}$$

Where :

F_jC_j = additional load which can be accepted by the sink in the fresh water region
$F_{i,A}$ = additional source flow to be re-allocated to the fresh water region, which is also equal to the additional sink flow since these must be equal to avoid the flow imbalance in the regenerated region.
$C_{i,A}$ = Limiting concentration of the additional source to be allocated to the fresh water region
$C_{j,A}$ = Limiting concentration of the additional sink to be allocated to the fresh water region

*Any set of consistent units can be used

Following this procedure reduces the regeneration flowrate in the regenerated water region and ensures that the sinks in the fresh water region receive feed water at its maximum allowable concentration. The sinks chosen for the additional re-allocation must once again start from the lowest concentration, for the same reasons as the initial allocation.

The flow rates for the sources must be taken from the net positive flow rates (Column 5 on the water cascade analysis table), of the highest concentration level. The water source is selected from here because a net positive flow means that there is a surplus of water is available at that given concentration. Therefore, re-allocation of this to the fresh water region will have no effect on the water balance. Once all re-allocations of the sinks and sources are done, the water cascade analysis technique is used in the fresh water region and the regenerated water region to determine the ultimate flowrate targets.

An example of the application of the method can be viewed on the original referenced works of Ng et al. (2009) as the method was applied to the fixed rate type of problem (the same type of problem investigated in this research study).

4.6 Conclusion

The calculation procedure described in **section 4.3** was applied to tissue machine number one and tissue machine number two. The options for regeneration as discussed in **section 4.4** and **section 4.5** was also applied in the water pinch procedure. The application of the method is discussed in **Chapter 6, Chapter 7** and **Chapter 8**.

From **section 4.3** it was observed that the flowrates of the sources and sinks in the system as well as their associated contaminant concentration was required for the water cascade analysis procedure. The determination of these required system parameters is discussed in **Chapter 5** with application of the determined data in **Chapter 6**, **Chapter 7** and **Chapter 8**

Chapter 5 Material balances

As discussed in **Chapter 4**, in order to perform the pinch analysis, a verified material balance is required. This chapter details the steps taken and the scientific method followed in order to develop a consistent material balance for both tissue machine number one and tissue machine number two so that the pinch analysis method described in **Chapter 4** can be applied successfully and that the results obtained are accurate.

5.1 Preliminary work

From the literature survey it was determined that material flows through the tissue making process for both tissue machine one and tissue machine two were required. A mill visit was conducted to obtain necessary piping and instrumentation diagrams for both tissue machines. Time was also taken to walk the lines of the plant to understand the plant layout for each of the machines.

Using the detailed piping and instrumentation diagrams, process flow diagrams were drawn for each of the machines. These where then sent to the Project engineer at KCSA – Enstra (Mr Roets) for approval to ensure that the process flow diagrams were an accurate representation of the mill's processes as well as to determine the maximum allowable contaminant concentration which can be allowed to each unit; this was required because these were equipment constraints required to ensure that the equipment operates efficiently. Using the process flow diagrams and information from the piping and instrumentation diagrams, it was noted that all water and material flow rates and process flow information was not available to accurately represent the system.

Due to the large number of unknown variables as well as the large water flowrates which occurred in the process, physical sampling to determine all unknowns would be impractical hence alternate methods had to be considered. Initially it was considered to use a hand-held Doppler flow meter. Two-different types are available, one type is used flows where the water has a very low contaminant concentration (fresh water) and the other operates in ranges of much higher contaminant concentrations. However, these units are accurate only if the pipes are full and the system has very low vibrations, and this was not always the conditions of operation at the mill. From previous experience at the mill, the Doppler type flow meter proved to be inaccurate in determining the flowrates. Therefore a different approach was selected.

From material balance knowledge, values for unknown flows can be calculated, provided that equations relating the process flows and stream property data, in this case, the total suspended solids, can be developed.

Using the process flow diagrams, preliminary material balances were conducted around each unit for both tissue machines assuming that the species fractions in each stream could be obtained. The principles of material balances described in **section 5.1.1** were used to model each unit in the process from a mass balance perspective.

5.1.1 Material balances

In order to carry out material balances on a process, the process must first be classified correctly. A process can be identified as *batch, continuous* or *semibatch*.

> *Batch process: "The feed charged into a vessel at the beginning of the process and the vessel contents are removed sometime later. No mass crosses the system boundaries between the time the feed is charged and the time the product is removed," (Felder and Rousseau, 2000)*
>
> *Continuous process: "The inputs and outputs flow continuously throughout the duration of the process." (Felder and Rousseau, 2000)*
>
> *Semibatch process: "Any process that is neither batch nor continuous." (Felder and Rousseau, 2000)*

From the above, the mill's tissue making process was identified as a continuous process.

> *"If the values of all the variables in a process (i.e., all the temperatures, pressures, volumes, flow rates) do not change with time, except possibly for minor fluctuations about a constant mean value, the process is said to be operating at steady state. If any of the process variables change with time, transient or unsteady state is said to exist. By their nature, batch and semibatch processes are transient, whereas continuous processes are either steady state or transient.*
>
> *Continuous processes are usually run as close to steady state as possible; unsteady state conditions exist during the start-up of a process and following changes – intentional or*

otherwise - in process conditions. " (Felder and Rousseau, 2000)

Therefore the mill's tissue making process can be modelled as a continuous steady-state process.

5.1.1.1 General mass balance equation

Felder and Rousseau (2000) describe the generation mass balance as:

Input + generation – output – consumption = accumulation **Equation 3**

Where:

Input: enters through the system boundaries
Generation: produced within a system
Output: leaves through the system boundaries
Consumption: consumed within the system
Accumulation: build-up within a system

Units along the process line can be modelled by the general mass balance equation:

The following are rules which can be used to simplify the material balance equation;

- If the balance quantity is total mass, set generation = 0 and consumption = 0. Except in nuclear reactions, mass can neither be created nor destroyed. (Felder and Rousseau, 2000)
- If the balanced substance is a nonreactive species (neither a reactant nor a product), set generation = 0 and consumption = 0. (Felder and Rousseau, 2000)
- If a system is at steady state, set accumulation = 0, regardless of what is being balanced. By definition, in a steady-state system nothing can change with time, including the amount of the balanced quantity. (Felder and Rousseau, 2000)

5.1.1.2 Homogeneity of material balances

For material balances, balanced stream flow rates can be scaled up (final values are greater than the original values) or scaled down (final values are smaller than the original values) but the stream compositions must be the same. This allows for the calculation of flows based on a *basis* of a flow, and once determined all flows can be scaled to determine flows for a given stream flow rate or production rate.

> *"Since material balances can always be scaled, material balance calculations can be performed on the basis of any convenient set of stream amounts or flow rates and the results can afterward be scaled to any desired extent." (Felder and Rousseau, 2000)*

5.1.1.3 Mass balance model for units in the tissue manufacturing process

From the above the material balance theory in **section 5.1.1.1** and **section 5.1.1.2**, the equipment units found in the manufacturing process can be modelled as follows:

In + generation – accumulation = Out + consumption **Equation 4**

Since there are no reactions occurring, the generation and consumption terms fall away to produce

In – accumulation = Out **Equation 5**

If the system is at steady-state therefore the accumulation term equates to zero resulting in

In = Out **Equation 6**

Equation 6 is the mass balance model for all units in the process units depicted in **Figure** 2-3 and **Figure 2-4**. It must be noted that special relationships will exist between the inlet and outlet streams of separation units.

For each unit, a number of equations resulted with a large number of unknowns, in order to accurately describe the unit. This makes the system difficult to solve for. However, if the system is reduced to a set of *n* equations with *n* unknowns, then the system can be solved using Cramer's Rule. Cramer's rule is a mathematical matrix method which allows you to solve for a system of equations provided that the equations are independent and that the matrix is invertible; it is described in **Appendix B.**

5.2 Sampling period

A sampling period was implemented from November 2010 to January 2011. As mentioned in the previous section, preliminary material balances gave an indication of which streams should be tested. The sampling was required to determine the missing stream data requirements to produce a calibrated and verified material balance of the process flow for the production for each of the tissue machines. Raw data from the sampling period is available on **Appendix C** for both the tissue machines considered in the study.

The aim of undertaking the overall study was to determine if a calibrated and verified material balance of the mill's tissue making processes could be used to reduce the mill's specific water consumption on each of its tissue machines. Once the process flow diagrams (**Figure 2-3** and **Figure 2-4**) were drawn, through discussion with Mr Roets, it was determined that the total suspended solids in the water system was the limiting parameter in respect to re-use of water, therefore attention was given to this. The total suspended solids were limiting the total reuse of water because of the stringent water purity requirements for shower water; biological and chemical oxygen demand and cationic demand accumulation was not a problem faced by the mill in its production process because of existing control schemes. Outcomes of the discussion also included which units should be of primary concern and the maximum allowable contaminant concentration to each unit. This can be viewed in **Chapter 5, section 5.3.1** and **section 5.3.2** for tissue machine number one and tissue machine number two respectively. The importance of each unit with respect to the tissue making process is described in **Chapter 2**. Cationic demand has been included as a dependent variable to investigate how this property will vary once the system becomes more integrated.

The reason for the numerous sample points to be tested (**Appendix C**) was because all the water and stock streams were not monitored in detail on a daily basis. Firstly because every unit was not accessible for sampling and secondly, only certain streams were required to be monitored because if these are controlled correctly then downstream units and lines should be at the process conditions required for efficient operation.

Since stream property data were not being monitored regularly, there was not any historical mill data available for all the required streams of the material balance; therefore a rigorous sampling campaign had to be undertaken. The sampling was necessary because exact contaminant concentrations of the monitored water lines were needed to ensure an accurate representation of the processing systems and hence ensure an accurate pinch calculation. All data taken from the digital control system (DCS) were the set-points as these indicated the ideal operating conditions of the tissue machine and would be the desired steady-state values.

As previously mentioned, it was discussed that the total suspended solids of the water was important. Therefore concentration tests were performed (described in **Appendix A**); either the total suspended solids ($mg.\ell^{-1}$) or the consistency (%m/m) test was done on the sampled stream depending whether a water stream (total suspended solids test) or a stock stream (consistency test) was applied.

Three samples were taken of each stream investigated because this is the minimum number of samples that can be taken which can describe the distribution of data within reasonable accuracy. This was selected as a compromise between accuracy, the number of different sample points and the total time for analysis. Data on the cationic demand were obtained from the chemical companies currently performing the tests at the mill. Once all samples were gathered, statistical data analysis was undertaken. This is described further in **section 5.3**.

5.3 Statistical data analysis

The purpose of applying statistical analysis to data is to determine where the sources of variation or uncertainty in the measurements are, and, as a result of understanding the sources of variation/ uncertainty, how much (and with how much certainty) can be deduced from the data (Foxon, 2010).

Data analysis must meet the following criteria (Foxon, 2010):

- variability in data must be understood and quantified
- selection of data that supports conclusions must be appropriate and complete
- models (linear or non-linear) must be appropriate for the data and well fitting
- uncertainties in parameter estimates must be understood and quantified

If more samples are taken, the representation of the entire population will be more accurate; in this case the process system. However as previously mentioned, due to time constraints and numerous sample points, data gathering was limited. Statistical data analysis allows one to get a better understanding of data of an entire population based on a sample representative of the population. Therefore data statistical analysis was performed on all samples to give an indication of the spread of the data, that is, to see how the data varies across a unit as well as through the system. A normal distribution was assumed due to the data being dependent on a number of variables which were not being monitored as part of the study. The supporting theory for the normal distribution, mean, standard deviation and the confidence interval are available in **Appendix B.**

5.3.1 Tissue machine number one – data statistical analysis

As discussed in **section 5.2**, sampling was required in order to develop a consistent material balance and also to determine which data points affect the material balance more significantly. All data were obtained during steady-state operation of the machine.

From **Appendix D,** using the data for tissue machine number one (**Appendix C, section C.1**), it was determined that the streams in the **Table 5-1** below have a greater effect on the system due to greater standard deviation.

Table 5-1: Streams which have the most significant effect on the system

Section	Stream	Property	Relative standard deviation
Appendix D, **section D1**	Wire section	Total suspended solids	18.50
	Broke high density cleaner rejects	Total suspended solids	30.08
	Virgin high density cleaner rejects	Total suspended solids	30.08
	Dissolved air flotation unit clarified water	Total suspended solids	34.78
	Dissolved air flotation unit gravity strainer rejects	Total suspended solids	50.00
	Vacuum pump exit	Total suspended solids	100.0
	Virgin dump chest	Cationic demand	77.24
	Broke dump chest	Cationic demand	61.26
	Stock blender	Cationic demand	25.17
	Machine chest	Cationic demand	85.46
	Headbox	Cationic demand	79.47
	White-water	Cationic demand	79.79

5.3.2 Tissue machine number two – data statistical analysis

As discussed in **section 5.2**, sampling was required in order to develop a consistent material balance and also to determine which data points affect the material balance more significantly. All data were obtained during steady-state operation of the machine.

From **Appendix D**, **Section D.2**, using the data for tissue machine number two (**Appendix C, section C.2**) it was determined that streams in the **Table 5-2** below have a greater effect on the system due to greater standard deviation.

Table 5-2: Streams which have the most significant effect on the system

Table	Stream	Property	Relative standard deviation
Appendix D, section D2	Press to main vacuum separator	Total suspended solids	75.78
	Wire to single breast roll chamber	Total suspended solids	75.78
	Clarified water from save-all	Total suspended solids	33.46
	Shower water to save-all	Total suspended solids	33.46
	Main vacuum separator to seal pit	Total suspended solids	76.00
	Single breast roll chamber to seal pit	Total suspended solids	76.00
	Low-density cleaner rejects	Flowrate	32,10
	Long fibre chest	Cationic demand	44.59
	Short fibre chest	Cationic demand	58.92
	Save-all chest	Cationic demand	43.89
	Machine chest	Cationic demand	42.00
	Headbox	Cationic demand	79.02
	White-water	Cationic demand	79.85

5.3.3 Application of the data

The properties in **Table 5-1** and **Table 5-2** were varied in the hypothetical worst case operation system; instead of using maximum contaminant concentrations as (mean + 3×standard deviations), the upper limit of the confidence interval was used. This was because it gave a greater range of variation as compared to the interval of (mean ± 3×standard deviations). The concept behind this is that if the system works for normal operating conditions and a hypothetical worst case operating conditions then it should work for data values within this range. The cationic demand values all vary quite significantly therefore these data will all be varied when considering a new possible network configuration (**Chapter 10**).

The cationic demand varies considerably across the machine (**Chapter 10**). From **Chapter 1**, it is noted that "a good charge" is "a steady charge". The cationic demand should be regularly monitored and maintained at consistent levels rather than allowing it to reach a level where it begins to have a significant effect on retention, before action is taken to remedy the problem.

From the data analysis (**Appendix D**), it was also observed that the vacuum system under the wire and press were operated inconsistently and should be carefully monitored as it will have a significant effect on the pinch analysis and hence proposed network.

It was also noted that units which were monitored more closely e.g. virgin dump chest and broke dump chest for tissue machine number one and the DAF and long fibre chest for tissue machine number two, have smaller standard deviations because they were controlled more effectively.

In order to ensure that the new proposed system works efficiently, all significant parameters should be monitored and this, from the data, includes attention to the vacuum system and dissolved air flotation unit.

Using the data from **Appendix D** and by varying the parameters in **Table 5-1**and **Table 5-2,** for tissue machine number one and two respectively, with the material balances developed as described in **section 5.1.1.3**, the material balances represented by process flow diagrams **Figure 5-2** and **Figure 5-3** respectively, were determined. This is the first step in the water pinch analysis.

5.4 Material balances

Once all available data was gathered and analysed, material balances were reconstructed to incorporate these data points. From the data statistical analysis, mean values were used in balancing the system for 'normal' operating conditions. The upper limit of the confidence interval was used to examine a hypothetical worst case operation. The thinking was that if the new proposed system will operate efficiently under normal operation as well when operating conditions are not as desired (worst case) then it will work efficiently in the ranges between this. All considered data are available in **Appendix D, section D.1** for tissue machine number one and **Appendix D, section D.2** for tissue machine number two.

The Matlab code was developed to facilitate the application of Cramer's rule (**Appendix B**) and was used in association with Excel to calculate material balances for both the tissue machines. The models developed were input to Excel, data from Excel were entered to Matlab, output data from Matlab was once again entered into Excel. This process was iterated until the material balance converged, that is:

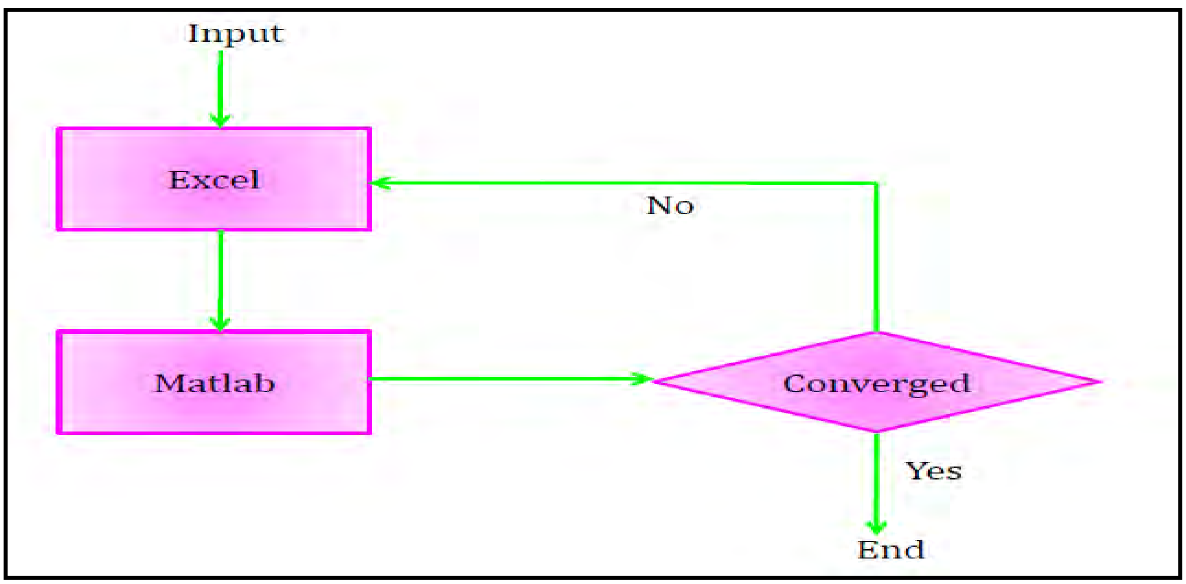

Figure 5-1: Iteration procedure for material balancing

Material balances were back-calculated using mean production rates corresponding to the duration during which the sampling was conducted. This was done in order to ensure that a correlation exists between production data and the production rate. Back calculations were based on a mean tissue production rate of 51.99 $ton.day^{-1}$ for tissue machine number one and 81.26 $ton.day^{-1}$ for tissue machine number two. This ensured consistency of the material balance. The data obtained from the calculation method were checked against process data which were recorded on the digital control system (**Appendix D**) this was also to investigate and confirm the consistency on the material balance.

The combination of Matlab and Excel was selected because Matlab quickly and accurately performs matrix calculations and eliminated the need for hand-based calculations and Excel outputs the data in a more user-friendly way than Matlab. Each equipment unit was reduced to a system of n independent equations with n unknowns to produce a $n \times n$ matrix. This was done for two reasons, for each unit, all streams were not required to be tested if Cramer's rule was applied and second, all sample points around the units were not accessible hence Cramer's rule allowed for the calculation of all necessary streams with minimal amount of data sampling.

The material balance determination was the first step in performing the pinch analysis. It was required to determine the flowrates of the sinks and sources with their respective contaminant concentrations so that the water cascade analysis technique of Ng et al. (2009) can be applied correctly.

When conducting the material balances, certain data properties were held constant so as to ensure that the system was represented accurately. This included:

- maximum contaminant concentrations into the unit so as to ensure that the system operates as desired
- vacuum seal water flow, for operational purposed
- dissolved air flotation unit feed-water flowrate due to the equipment design specifications

The remaining properties were varied through the data for normal operation and the hypothetical worst case operation.

The advantage of having a detailed material balance of the process was that it allowed the analysis to be done even if one was not physically present at the mill. One of the limitations of the project was the distance between the plant where sampling was conducted and the university where data analysis was performed. Therefore having an accurate material balance representation of the mill tissue making processes was essential and facilitated the analysis of the process system.

The results of the combined sampling period, statistical data analysis and material balancing are depicted in **Figure 5-2** and **Figure 5-3** and **Table 5-3** to **Table 5-10**.

The primary contaminant of concern was the total suspended solids as this was the limiting contaminant in terms of water reuse. The cationic demand was taken as a secondary parameter of significance in terms of process water reuse and closing the water networks.

5.4.1 Material balance results for tissue machine number one

The Matlab and Excel routines developed as described in **Chapter 5**, with data from **Appendix D** and **Table 5-1** to obtain all data in **Figure 5-2.**

5.4.1.1 Resulting process flow diagram

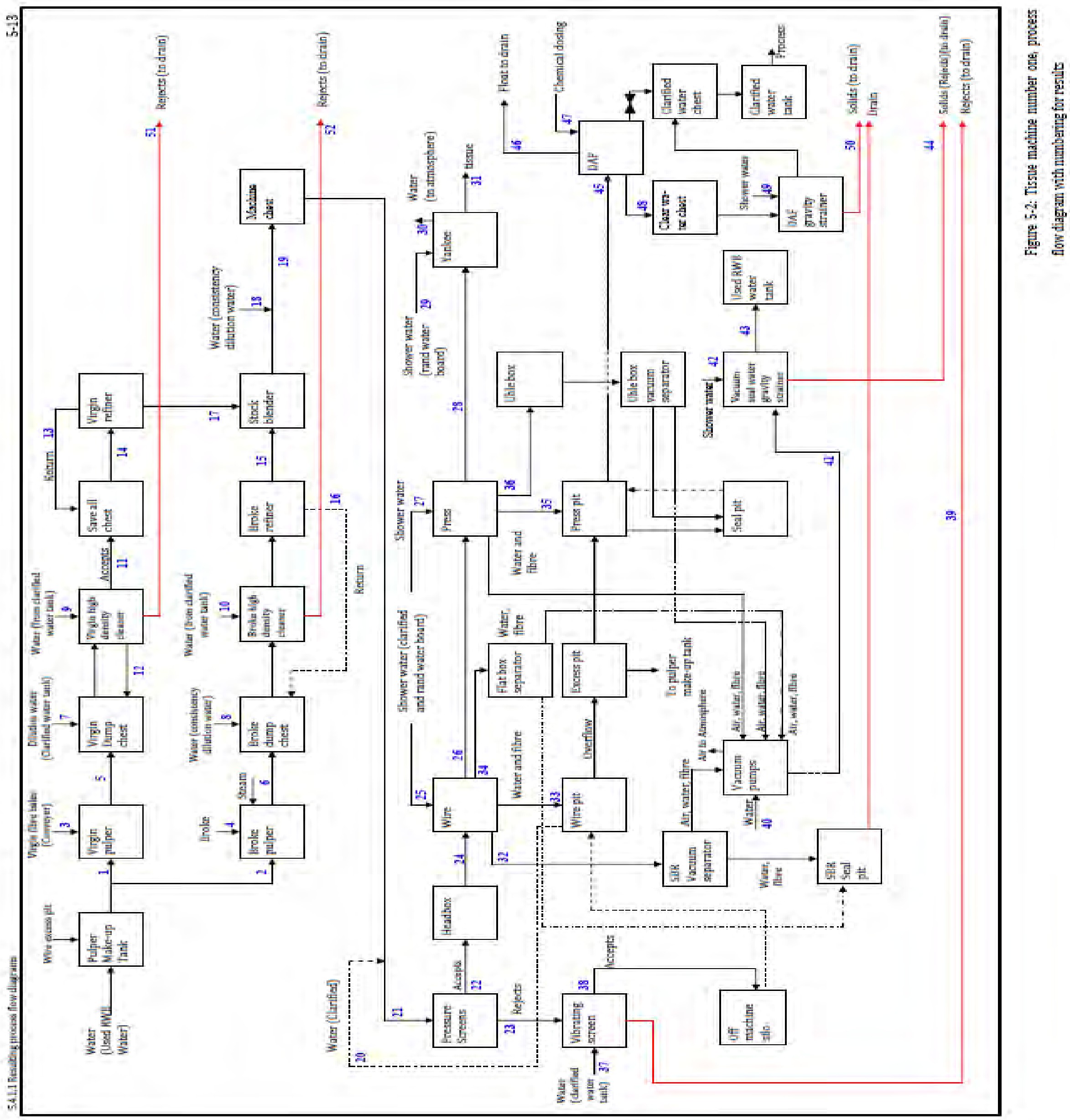

Figure 5-2: Tissue machine number one process flow diagram with numbering for results obtained from the material balancing process

5.4.1.2 Operating conditions

The results of the material balances performed across tissue machine number one (for normal operating conditions) are highlighted in **Table 5-3** and **Table 5-4**. The stream numbers are in reference to **Figure 5-2**.

Table 5-3: Material balance results for tissue machine number one, normal operating conditions

Stream number	Description	Flow (ℓ.min^{-1})	Consistency (%)	Total suspended solids (mg. ℓ^{-1})
1	Dilution water to virgin pulper	203.0		600.0
2	Dilution water to broke pulper	925.00		600.0
3	Virgin fibre bales	11.00 (kg.min^{-1})	96.50	
4	Broke	56.00 (kg.min^{-1})	96.50	
5	Virgin pulper to virgin dump chest	221.0	5.000	
6	Broke pulper to broke dump chest	981.0	5.000	
7	Dilution water to virgin dump chest	156.0		600.0
8	Dilution water to broke dump chest	290.0		600.0
9	Shower water to virgin high density cleaner	10.00		600.0
10	Shower water to broke high density cleaner	12.00		600.0
11	Virgin high density cleaner accepts to save-all chest	371.0	2.650	
12	Virgin high density cleaner return to virgin dump chest	6.000	2.650	
13	Virgin refiner return to save-all chest	737.0	2.650	
14	Save-all chest to virgin refiner	1108	2.650	
15	Broke refiner to stock blender	1266	3.700	
16	Broke refiner return to broke dump chest	156.0	3.700	
17	Virgin refiner to stock blender	371.0	2.650	
18	Dilution water to stock from stock blender	41.00		600.0
19	Inlet to the machine chest	1681	3.300	
20	Dilution water to fan pump	34960		600.0
21	From fan pump to pressure screens	36640	0.1800	
22	Pressure screen accepts to headbox	28180	0.1800	
23	Pressure screen rejects to vibrating screens	8463	0.2300	
24	Headbox to wire	28180	0.1800	

Table 5-4: Material balance results for tissue machine number one, normal operating conditions, continued

Stream number	Description	Flow (ℓ.min^{-1})	Consistency (%)	Total suspended solids (mg. ℓ^{-1})
25	Wire shower water	1100		100.0
26	Wire to press	175.0 (kg.min^{-1})	20.00	
27	Press shower water	660.0		30.00
28	Press to Yankee	81.00 (kg.min^{-1})	43.00	
29	Yankee shower water	235.0		0.0000
30	Water vapour to atmosphere	280.0		0.0000
31	Tissue	36.00(kg.min^{-1})	96.50	
32	Wire to SBR vacuum separator	182.0		1062
33	Wire to wire pit	24850		588.0
34	Wire to flatbox separator	4074		59.00
35	Press to press pit	514.0		881.0
36	Press to uhle box	240.0		59.00
37	Shower water to vibrating screen	16.00		
38	Vibrating screen accepts to wire pit	8448		1885
39	Vibrating screen rejects to drain	1.000		9385
40	Vacuum pump seal water	440.0		250.0
41	Water from vacuum pumps	1000		33.00
42	Shower water to vacuum seal water gravity strainer	6.000		100.0
43	Vacuum seal water gravity strainer accepts to used RWB water tank	1000		5.00
44	Vacuum seal water gravity strainer rejects to drain	1.000		9385
45	Water to DAF	2000		880.0
46	Dissolved air flotation unit float to drain	81.00	2.200	
47	Chemicals	40.00		0.0000
48	Water to clear water chest	1977		11.00
49	Dissolved air flotation unit gravity strainer shower water	11.00		5.00
50	Dissolved air flotation unit gravity strainer rejects to drain	6.000		9385
51	Virgin high density cleaner rejects to drain	8.000		115800
52	Broke high density cleaner rejects to drain	22.00		115800

5.4.1.3 Hypothetical worst case operation

In **section 5.3.3**, the use of the upper limit of the confidence interval for the worst case operating conditions material balances was discussed. The results of the material balances are highlighted in **Table 5-5** and **Table 5-6**. The stream numbers are in reference to **Figure 5-2**.

Table 5-5: Material balance results for tissue machine number one, hypothetical worst case operating conditions

Stream number	Description	Flow (ℓ.min^{-1})	Consistency (%)	Total suspended solids (mg. ℓ^{-1})
1	Dilution water to virgin pulper	207.0		600.0
2	Dilution water to broke pulper	925.0		600.0
3	Virgin fibre bales	11.00 (kg.min^{-1})	96.50	
4	Broke	56.00 (kg.min^{-1})	96.50	
5	Virgin pulper to virgin dump chest	219.0	5.000	
6	Broke pulper to broke dump chest	974.0	5.000	
7	Dilution water to virgin dump chest	159.0		600.0
8	Dilution water to broke dump chest	293.0		600.0
9	Shower water to virgin high density cleaner	12.00		600.0
10	Shower water to broke high density cleaner	9.000		600.0
11	Virgin high density cleaner accepts to save-all chest	371.0	2.650	
12	Virgin high density cleaner return to virgin dump chest		2.650	
13	Virgin refiner return to save-all chest	737.0	2.650	
14	Save-all chest to virgin refiner	1108	2.650	
15	Broke refiner to stock blender	1262	3.700	
16	Broke refiner return to broke dump chest	156.0	3.700	
17	Virgin refiner to stock blender	371.0	2.650	
18	Dilution water to stock from stock blender	41.00	600.0	
19	Inlet to the machine chest	1674	3.300	
20	Dilution water to fan pump	34960	600.0	
21	From fan pump to pressure screens	36640	0.1800	
22	Pressure screen accepts to headbox	28230	0.1800	
23	Pressure screen rejects to vibrating screens	8401	0.2300	
24	Headbox to wire	28230	0.1800	
25	Wire shower water	1100		100.0
26	Wire to press	175.0 (kg.min^{-1})	20.00	

Table 5-6: Material balance results for tissue machine number one, hypothetical worst case operating conditions, continued

Stream number	Description	Flow (ℓ.min^{-1})	Consistency (%)	Total suspended solids (mg. ℓ^{-1})
27	Press shower water	660.0		30.00
28	Press to Yankee	81.00 (kg.min^{-1})	43.00	
29	Yankee shower water	235.0		0.0000
30	Water vapour to atmosphere	264.0		0.0000
31	Tissue	36.00 (kg.min^{-1})	96.50	
32	Wire to SBR vacuum separator	405.0		1062
33	Wire to wire pit	23690		599.0
34	Wire to flatbox separator	5065		141.0
35	Press to press pit	507.0		1002
36	Press to uhle box	240.0		141.0
37	Shower water to vibrating screen	16.00		100.0
38	Vibrating screen accepts to wire pit	8381		1885
39	Vibrating screen rejects to drain	20.00		25470
40	Vacuum pump seal water	440.0		250.0
41	Water from vacuum pumps	1000		5.000
42	Shower water to vacuum seal water gravity strainer	6.000		100.0
43	Vacuum seal water gravity strainer accepts to used RWB water tank	1000		5.000
44	Vacuum seal water gravity strainer rejects to drain	1.000		9385
45	Water to dissolved air flotation unit	2000		1885
46	Dissolved air flotation unit float to drain	81.00	2.200	
47	Chemicals	40.00		0.0000
48	Water to clear water chest	1976		19.00
49	Dissolved air flotation unit gravity strainer shower water	4.000		5.000
50	Dissolved air flotation unit gravity strainer rejects to drain	13.00		9385
51	Virgin high density cleaner rejects to drain	8.000		268700
52	Broke high density cleaner rejects to drain	22.00		268700

5.4.2 Material balance results for tissue machine number two

The Matlab and Excel routines developed as described in **Chapter 5**, with data **Appendix D** and **Table 5-2,** were used to determine the process stream data for **Figure 5-3**.

5.4.2.1 Resulting process flow diagrams

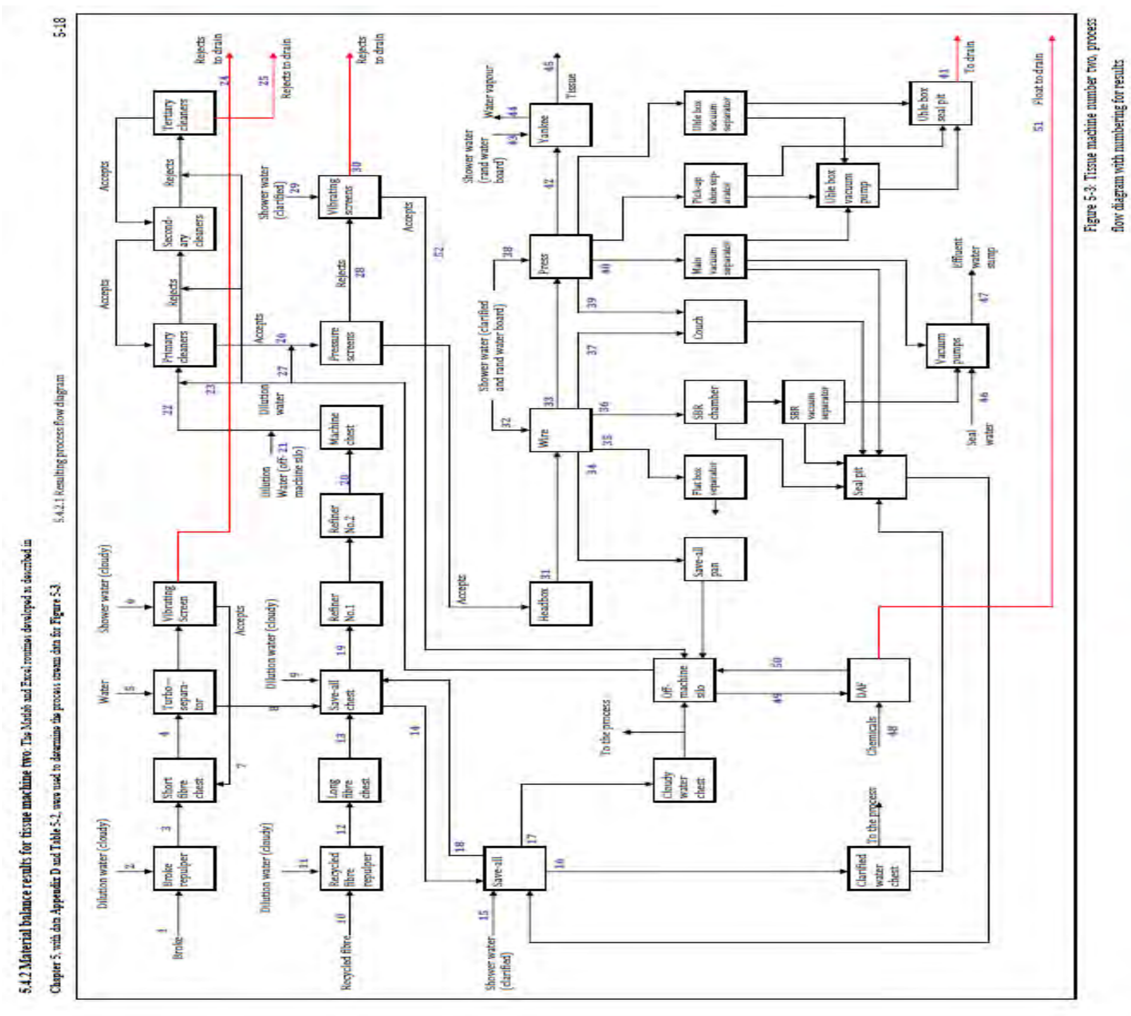

Figure 5-3: Tissue machine number two, process flow diagram with numbering for results obtained from the material balancing process

5.4.2.2 Operating conditions

The results of the material balances performed across tissue machine number two (for normal operating conditions) are highlighted in **Table 5-7** and **Table 5-8**. The stream numbers are in reference to **Figure 5-3.**

Table 5-7: Material balance results for tissue machine number two, normal operating conditions

Stream number	Description	Flow (ℓ.min^{-1})	Consistency (%)	Total suspended solids (mg. ℓ^{-1})
1	Broke	57.00(kg.min^{-1})	95.00	
2	Broke repulper dilution water	1197		400.0
3	From broke pulper to short fibre chest	1214	4.500	
4	Short fibre chest to turbo-separator	1239	4.360	
5	Water to turbo-separator	16.00		500.0
6	Shower water to turbo-separator vibrating screens	32.00		500.0
7	Turbo-separator vibrating screen accepts	24.00	1.43	
8	Turbo-separator accepts	1229	4.360	
9	Dilution water to save-all chest	240.0		800.0
10	Recycled fibre	39.00(kg.min^{-1})	95.00	
11	Recycled fibre repulper dilution water	804.0		400.0
12	From recycled fibre repulper to long fibre chest	843.0	4.470	
13	Long fibre chest to save-all chest	843.0	4.470	
14	Sweetening stock to save-all	300.0	4.360	
15	Save-all shower water	116.0		90.0
16	Water from save-all to clarified water chest	1467		89.0
17	Water from save-all to cloudy water chest	6329		868.0
18	Thickened stock from save-all to save-all chest	165.0	10.00	
19	Save-all chest to refiner No. 1	2177	4.360	
20	Refiner No. 2 to machine chest	2177	4.360	
21	Dilution water to machine chest stock	93.00		800.0
22	Stock to cleaners	2270	4.200	

Table 5-8: Material balance results for tissue machine number two, normal operating conditions, continued

Stream number	Description	Flow (ℓ.min^{-1})	Consistency (%)	Total suspended solids (mg. ℓ$^{-1}$)
23	Elutriation water to cleaners	26841		1200
24	Turbo-separator vibrating screen rejects	0.5000		101800
25	Cleaner rejects	71.00		33240
26	Cleaner accepts to pressure screens	28540	0.4200	
27	Water to pressure screens	27580		1200
28	Pressure screen rejects to vibrating screens	13310	0.7400	
29	Vibrating screens shower water	32.00		500.0
30	Vibrating screen rejects to drain	0.5000		99220
31	Headbox to wire	42730	0.2500	
	Wire shower water			
	SBR needle	333.0		0.0000
32	Rest	846.0		300.0
33	Wire to the press	269.0	20.00	
34	Wire to save-all pan	36490		723.0.
35	Wire to flatbox separator	847.0		1313
36	Wire to SBR chamber	333.0		6.000
37	Wire to couch pit	5970		828.0
38	Shower water to press			
	Flat-nip & PLU	270.0		15.00
	Uhle-box	28.00		300.0
	Press internals	270.0		0.0000
39	Press to couch pit	150.0		155.0
40	Press to main vacuum separator	480.0		6.000
41	Uhle box seal pit to drain	118.0		770.0
42	Press to Yankee	119.0	45.00	
43	Yankee shower water	150.0		0.0000
44	Water vapour to atmosphere	213.0		0.0000
45	Tissue	56.00(kg.min^{-1})	95.00	
46	Vacuum seal water	660.0		300.0
47	From vacuum pumps	1500		42.00
48	Dissolved air flotation unit chemical water	200.0		0.0000
49	Off-machine silo to dissolved air flotation unit	4000		723.0
50	Dissolved air flotation unit to off-machine silo	3954		70.00
51	Dissolved air flotation unit float to drain	265.0		43060
52	Vibrating screen accepts to off-machine silo	12820		2085

5.4.2.3 Hypothetical worst case operating conditions

In **section 5.3.3**, the use of the upper limit of the confidence interval for the worst case operating conditions material balances was discussed. The results of the material balances are highlighted in **Table 5-9** and **Table 5-10**. The stream numbers are in reference to **Figure** 5-3.

Table 5-9: Material balance results for tissue machine number two, hypothetical worst case operating conditions

Stream number	Description	Flow ($\ell.min^{-1}$)	Consistency (%)	Total suspended solids (mg. ℓ^{-1})
1	Broke	59.00(kg.min^{-1})	95.00	
2	Broke repulper dilution water	1197		400.0
3	From broke pulper to short fibre chest	1256	4.500	
4	Short fibre chest to turbo-separator	1283	4.360	
5	Water to turbo-separator			500.0
6	Shower water to turbo-separator vibrating screens	16.00		500.0
7	Turbo-separator vibrating screen accepts	27.00	1.430	
8	Turbo-separator accepts	1269	4.360	
9	Dilution water to save-all chest	241.0		800.0
10	Recycled fibre	39.00(kg.min^{-1})	95.00	
11	Recycled fibre repulper dilution water	830.0		400.0
12	From recycled fibre repulper to long fibre chest	869.0	4.470	
13	Long fibre chest to save-all chest	869.0	4.470	
14	Sweetening stock to save-all	593.0	4.360	
15	Save-all shower water	116.0		90.00
16	Water from save-all to clarified water chest	1706		95.00
17	Water from save-all to cloudy water chest	6329		870.0
18	Thickened stock from save-all to save-all chest	166.0	10.00	
19	Save-all chest to refiner No. 1	1952	4.360	
20	Refiner No. 2 to machine chest	1952	4.360	
21	Dilution water to machine chest stock	96.00		800.0
22	Stock to cleaners	2048	4.200	

Table 5-10: Material balance results for tissue machine number two, hypothetical worst case operating conditions, continued

Stream number	Description	Flow (ℓ.min^{-1})	Consistency (%)	Total suspended solids (mg. ℓ$^{-1}$)
23	Elutriation water to cleaners	26460		1200
24	Turbo-separator vibrating screen rejects	2.000		101800
25	Cleaner rejects	170.0		33240
26	Cleaner accepts to pressure screens	28340	0.420	
27	Water to pressure screens	27680		1200
28	Pressure screen rejects to vibrating screens	13280	0.7400	
29	Vibrating screens shower water	32.00		500.0
30	Vibrating screen rejects to drain	170.0		99220
31	Headbox to wire	42730	0.2500	
	Wire shower water			
	SBR needle	333.0		0.0000
32	Rest	846.0		300.0
33	Wire to the press		20.00	
34	Wire to save-all pan	36490		740.0
35	Wire to flatbox separator	847.0		1315
36	Wire to SBR chamber	333.0		23.00
37	Wire to couch pit	5970		1013
38	Shower water to press			
	Flat-nip & PLU	270.0		15.00
	Uhle-box	28.00		300.0
	Press internals	270.0		0.0000
39	Press to couch pit	150.0		155.0
40	Press to main vacuum separator	450.0		23.00
41	Uhle box seal pit to drain	119.0		770.0
42	Press to Yankee	119.0	45.00	
43	Yankee shower water	150.0		0.0000
44	Water vapour to atmosphere	213.0		0.0000
45	Tissue	56.00 (kg.min^{-1})	95.00	
46	Vacuum seal water	660.0		300.0
47	From vacuum pumps	1500		
48	Dissolved air flotation unit chemical water	200.0		0.0000
49	Off-machine silo to DAF	4000		740.0
50	Dissolved air flotation unit to off-machine silo	3937		85.00
51	Dissolved air flotation unit float to drain	263.0		43060
52	Vibrating screen accepts to off-machine silo	12860		2085

5.4.3 Conclusion

As expected more fresh water was required during the hypothetical worst case operation because due to the higher contaminant concentration of the process (white-) water, more fresh water was required to supply the demands (sinks) at their respective allowable contaminant concentrations. It was observed that there was less process water available from the system during worst case operating conditions because water was lost in larger amounts as rejects from the cleaners, screens and regeneration units. This will result in more fresh water being required for the hypothetical worst case operation to replenish the water lost from the system. This was observed in the material balances for both tissue machine number one and tissue machine number two.

Sample calculations for the material balances are detailed in **Appendix F**. The water flowrates into and out of the process were used in the ultimate flowrate targeting technique with regeneration placement (Ng et al., 2009) in **Chapter 6** and **Chapter 8** which follow.

In the process flow diagrams (**Figure 5-2** and **Figure 5-3**), all stream flowrates which were removed from the system through the drains were required to remain removed from the system in the analysis to ensure efficient operation of the process and to maintain product quality specifications; this was to ensure that there was no unwanted recirculation of contaminants, that is, contaminants were required to be purged from the system. Some of these streams being discharged to drain could be considered as possible sources but as per mill specification, they have been considered as sinks to account for the losses from the system which must be compensated for by the fresh water requirement.

5.5 Advantage of a detailed material balance

The preliminary work discussed could have been tackled in an alternate approach, that is, assumptions regarding mill operations could have been made in respect to operating flowrates, contaminant concentrations and equipment operation based on existing mill information. Using this assumed information, the pinch point could have been determined and then a sampling campaign could have been undertaken for only the streams around the pinch point because it is only these streams which will affect the minimum water targets. This would have reduced the amount of sampling which had to be done, leading to a shorter sampling period.

However it must be noted that due to the limitation of not being constantly present at the mill (mill located in Springs, Gauteng, whilst analysis was performed at UKZN), a detailed material balance was more useful as it allowed analysis of the mill's system to be conducted even while away from the mill. Therefore the extensive sampling period was necessary.

5.6 Conclusion

Using the material balance results obtained, the water pinch analysis was conducted on the tissue machines. The detailed nature of the material balances allowed for various pinch analyses to be conducted. These analyses will be discussed in **Chapter 6, Chapter 7** and **Chapter 8.**

It was important that the representation of the sources and sinks in terms of contaminant concentration and flowrate was accurate because these properties of the source and sink impacts on the pinch point determined; this must be considered when applying the pinch analysis methods.

Chapter 6 Initial pinch analysis

The pinch analysis method of Ng et al. (2009) discussed in **Chapter 4** was applied to tissue machine number one and to tissue machine number two to determine the pinch point for each of the machines in **Chapter 6**. This section describes the various water cascade analyses performed on each of the tissue machines with further analyses in **Chapter 8**.

This section outlines the techniques and procedures which were used in order to carry out a *water pinch* analysis on the tissue making process system as well as the equipment units considered. In order to perform the pinch analysis, material balances were conducted (**Chapter 5**); using these material balances the pinch analysis technique was applied in **Chapter 6** and **Chapter 8** followed the water network synthesis in **Chapter 9**.

In reference to **Chapter 2**, **section 2.2**, there was a need for continued improvement in water usage in both pulp and paper mills. This therefore indicates that there was a gap for inclusion of various new technologies to achieve this task. The application of such technologies is described in **Chapter 6** to **Chapter 9**.

6.1 Application of the pinch analysis to determine the pinch point on each of the tissue machines

In this chapter the pinch analysis was conducted as described by Ng et al (2007, 2009). An initial pinch analysis was performed to determine the pinch causing stream via the water cascade analysis. Thereafter, reallocations were done on the sources and sinks in the process in order to perform the ultimate flowrate targeting technique with regeneration placement (Ng et al. 2009). Various scenarios were considered to investigate the tissue making process system behaviour under varied conditions.

According to Ng et al (2009), regeneration should occur across the pinch point, that is, the stream which is identified as the pinch causing stream is where regeneration efforts should be focused. For determining the minimum regeneration flow rate, the system must be divided into the fresh water region and the regenerated water region. In the fresh water region, all sinks are to receive fresh water and in the regenerated water region, all sinks are to receive regenerated water and/or process water. Aside from this, two scenarios are also described by Ng et al (2009) where in the regenerated water region the source flows can either be (1) less than or (2) greater than the sink flows and these results in further reallocation procedures as described in **section 6.1.**

To take all of the above into account the following scenarios were investigated for each tissue machine for both normal operation and the hypothetical worst case operation:

a. Water cascade analysis to determine the pinch point

b. Confirm the global pinch point determination ability of the method by assuming the regeneration of the pinch stream. In doing this the pinch should shift to the effluent stream because this should be the stream which will now limit the total reuse of water in the system

c. Fresh water region process configuration where all streams with contaminant concentration below the regeneration concentration are found in the fresh water region

d. Regenerated water region process configuration where all streams with contaminant concentration above the regeneration concentration are found in the regenerated water region

e. Fresh water region process configuration where the reallocation procedure followed is such that the material flows in the fresh water region and regenerated water region are exactly balanced as in the ultimate flowrate targeting technique of Ng et al. (2009). This will result in sinks of $C_{sink} > C_{reg}$ present in the regenerated water region

f. Regenerated water region process configuration where the remaining sources and sinks after fresh water region process configuration from (e) has been performed will be present in this regenerated water region

Both normal and the hypothetical worst case operation were investigated to determine if the pinch point will shift under undesired process conditions, that is, to test the robustness of the method.

An additional comparison was made between (1) a system which assumed that the current regeneration was replaced by a new regeneration unit placed across the pinch point (2) a system where the current regeneration was considered in the system with the addition of an appropriate new regeneration unit placed across the pinch point. This was also done to investigate the robustness of the method – does it indeed identify a global pinch point? This was done so that the system recommended after the pinch analysis method was applied will work for all these varying conditions (**c** to **f** above) and to investigate the effect of the varied operating conditions on the fresh water consumption during undesired process conditions. Therefore considering all of the possible operating conditions and regeneration scenarios, the following was tested:

Table 6-1: The various systems investigated using the ultimate flowrate targeting technique of Ng et al (2009). (a) to (f) refer to points (a) to (f) above.

Tissue machine one				Tissue machine two			
Current regeneration replaced by the proposed regeneration unit		**Existing regeneration considered with addition of the proposed regeneration unit**		**Current regeneration replaced by the proposed regeneration unit**		**Existing regeneration considered with addition of the proposed regeneration unit**	
Operating conditions	Worst case operation	Operating conditions	Worst case operation	Operating conditions	Worst case operation	Operating conditions	Worst case operation
a b c d e f	a b c d e f	a b c d e f	a b c d e f	a b c d e f	a b c d e f	a b c d e f	a b c d e f

It is noted that according to Ng et al (2009), depending on which scenario occurs, mass flows between the sinks and sources should be balanced in the regenerated water region and the fresh water region, however with regards to plant operation and layout, this was unrealistic because some flows will not be able to be split because of the associated costs. It was also impractical to split the flow of a source to supply the demand if the split results in one flow being so low such that a very small diameter pipe results. Therefore when reallocations were performed, source and sink streams were shifted entirely, that is, stream splitting did not occur unless the stream splits were practical; the reallocations were conducted in this way and it was performed such that the source and sink flows in the fresh water region and regenerated water region were as close as possible to being evenly - balanced.

6.2 Initial pinch analysis results for tissue machine number one

As discussed, two different systems were considered, that is, in one system the current (existing) regeneration in the tissue making process was replaced by a new unit across the pinch point and the other system a system where the current regeneration was considered with a new regeneration unit placed across the pinch point. This section details the initial water cascade analysis performed for tissue number one and the results thereof. The calculations performed are those described in **Table** 6-1.

The initial pinch analysis indicates the pinch point. From this pinch point a suitable regeneration intervention can be selected (**Chapter 7**) and using the regeneration potential of the units, the ultimate flowrate targeting technique applied (**Chapter 8**). In this chapter the initial pinch point determined will be discussed.

6.2.1 Current (existing) regeneration of process water in the tissue making process was not considered in the pinch analysis

This system assumes that the dissolved air flotation unit(s) currently found in the system were not present, therefore only the material flowrates into and out of the equipment units were considered, therefore regeneration of any of the sources did not occur. The comparison between two different operating systems was considered to examine the robustness of the method and to determine if the water cascade analysis technique does indeed determine the global pinch of a multiple pinch problem as stipulated by Ng et al. (2007, 2009).

6.2.1.1 Normal operating conditions

The comparison between normal and worst case operating conditions was done to investigate:

1) the robustness of the method
2) determine the effect of the varied process conditions on the fresh water consumption

6.2.1.1 (a) Sources and sinks considered

Before the pinch analysis can be accurately applied, the sinks and sources in the system must first be clearly identified. These are indicated in **Table 6-2** and **Table 6-3**.

Table 6-2: Sink flowrates at allowable contaminant concentration determined for normal operating conditions on tissue machine number one (existing regeneration was not considered in the pinch analysis)

Sinks				
Stream	**Flow (ℓ.min^{-1})**	**C (mg. ℓ^{-1})**	**Stream number (Figure 5-2)**	**Demand (D)**
Yankee showers	235.0	0.0000	29	D1
Press showers	600.0	30.00	27	D2
Press showers	60.00	30.00	27	D3
Uhle box vacuum separator bottoms	240.0	59.00	36	D4
Wire showers	600.0	100.0	25	D5
Wire showers	500.0	100.0	25	D6
Vibrating screen shower	16.00	100.0	37	D7
Vacuum pumps seal water	440.0	250.0	40	D8
Fan pump dilution water	34960	600.0	20	D9
Broke pulper dilution water	925.0	600.0	2	D10
Broke dump chest dilution water	290.0	600.0	8	D11
Virgin Pulper dilution water	203.0	600.0	1	D12
Virgin dump chest dilution water	156.0	600.0	7	D13
Stock blender dilution water	41.00	600.0	18	D14
Broke high density screen shower water	12.00	600.0	10	D15
Virgin high density screen shower water	10.00	600.0	9	D16
Broke high density screen rejects	22.00	115800	52	D17
Virgin high density screen rejects	8.000	115800	51	D18
Vibrating screens rejects	15.00	254700	39	D19

Table 6-2 lists the sink flowrates for tissue machine number one in order of ascending contaminant concentration. The contaminant concentrations represent the maximum allowable concentration to the sink (demand) and are derived from equipment and process contaminant constraints. The fresh water make-up has been included with the Yankee water flowrate. The uhle-box vacuum separator bottoms could be considered as a water source, but as per mill specification, it had to be discharged to drain and was therefore considered as a sink (demand D4) to account for the water losses from the system. The same applies to the broke high-density cleaner rejects, the virgin high-density cleaner rejects and the vibrating screen rejects. It must be noted that all reject flowrates are an over-estimation because most rejects were removed periodically from the system, that is, every 20 to 30 min but it has been

considered here as a steady flowrate. All data have been extracted from **Figure 5-2** and **Table 5-3** and **Table 5-4**.

Table 6-3 lists all the source flowrates for tissue machine number one in order of ascending contaminant concentration. The contaminant concentrations are those determined from the sampling period.

Table 6-3: Source flowrates at respective contaminant concentration determined for normal operating conditions on tissue machine number one (existing regeneration was not considered in the pinch analysis)

Sources				
Stream	**Flow (ℓ.min^{-1})**	**C (mg. ℓ^{-1})**	**Stream number (Figure 5-2)**	**Source (S)**
Fresh water	To be determined by the pinch	0.0000		S1
Vacuum pumps	1000	33.00	41	S2
Flat box separator	4074	59.00	34	S3
Wire	24850	588.0	33	S4
Press	514.0	881.0	35	S5
SBR vacuum separator bottoms	182.0	1062	32	S6
Vibrating Screen accepts	8463	1885	38	S7

All flowrates at a given contaminant concentration must be combined for the purpose of applying the water cascade analysis technique. These are indicated in **Table 6-4** and these flowrates and contaminant concentrations were used in the water cascade analyses.

Table 6-4: Net source and sinks flows at respective contaminant concentrations

Demands		Sources	
Flow (ℓ.min^{-1})	**C (mg. ℓ$^{-1}$)**	**Flow (ℓ .min^{-1})**	**C (mg. ℓ$^{-1}$)**
234.0	0.0000	1000	33.00
660.0	30.00	4074	59.00
240.0	59.00	24850	588.0
1116	100.0	514.0	881.0
440.0	250.0	182.0	1062
36600	600.0	8463	1885
30.00	115800		
15.00	254700		

6.2.1.2 Hypothetical worst case operating conditions

As previously discussed, for the hypothetical worst case operation, the upper limits of the confidence interval for the streams which have a more significant effect on the pinch analysis were used in the material balance. Using these upper limits, the material balances were re-performed to get an indication of the process water requirements under these operating conditions. These results are depicted in **Figure 5-2** and **Table 5-5** and **Table 5-6**. All data requirements for the water cascade analysis which follows have been extracted from **Figure** 5-2.

6.2.1.2 (a) Source and sink streams considered

Following the same procedure as that during normal operating conditions, the source and sink streams where identified and listed in **Table 6-5** and **Table 6-6**.

Table 6-5: Sink flowrates at allowable contaminant concentration determined for hypothetical worst case operating conditions on tissue machine number one (existing regeneration was not considered in the pinch analysis)

Sinks				
Stream	**Flow (ℓ.min^{-1})**	**C (mg. ℓ$^{-1}$)**	**Stream number (Figure 5-2)**	**Demands (D)**
Yankee showers	235.0	0.0000	29	D1
Press showers	600.0	30.00	27	D2
Press showers	60.00	30.00	27	D3
Uhle box vacuum separator bottoms	240.0	141.0	36	D4
Wire showers	600.0	100.0	25	D5
Wire showers	500.0	100.0	25	D6
Vibrating screen shower	16.00	100.0	37	D7
Vacuum pumps seal water	440.0	250.0	40	D8
Fan pump dilution water	34960	600.0	20	D9
Broke pulper dilution water	925.0	600.0	2	D10
Broke dump chest dilution water	292.0	600.0	8	D11
Virgin Pulper dilution water	206.0	600.0	1	D12
Virgin dump chest dilution water	159.0	600.0	7	D13
Stock blender dilution water	42.00	600.0	18	D14
Broke high density screen shower water	12.00	600.0	10	D15
Virgin high density screen shower water	10.00	600.0	9	D16
Broke high density screen rejects	22.00	254700	52	D17
Virgin high density screen rejects	8.000	254700	51	D18
Vibrating screens rejects	20.00	268900	39	D19

Table 6-5 lists the sink flowrates for tissue machine number one in order of ascending contaminant concentration. The contaminant concentrations represent the maximum allowable concentration to the sink (demand) and are derived from equipment and process contaminant constraints. The fresh water make-up has been included with the Yankee shower water flowrate. The uhle-box vacuum separator bottoms could be considered as a water source but as per mill specification, it was required to be discharged to drain and was therefore considered as a sink (demand D4). The same applies to the broke high-density cleaner rejects, the virgin high-density cleaner rejects and the vibrating screen rejects. It must be noted that all reject flowrates are an overestimation as most rejects were removed periodically from the system, that is, every 20 to 30 min; they have been considered here as a constant flow.

Table 6-6 lists all the source flowrates for tissue machine number one in order of ascending contaminant concentrations. The contaminant concentrations are a combination of those determined from the sampling period and the upper limit of the confidence interval.

Table 6-6: Source flowrates at respective contaminant concentration determined for hypothetical worst case operating conditions on tissue machine number one (existing regeneration was not considered in the pinch analysis)

Sources				
Stream	**Flow (ℓ.min^{-1})**	**C (mg. ℓ$^{-1}$)**	**Stream number (Figure 5-2)**	**Source (S)**
Fresh water	To be determined by the pinch	0.0000		S1
Vacuum pumps	1000	33.00	41	S2
Flat box separator	5065	141.0	34	S3
Wire	23690	588.0	33	S4
Press	507.00	1003	35	S5
SBR vacuum separator bottoms	405.00	1062	32	S6
Vibrating Screen accepts	8401	1885	38	S7

All flowrates at a given contaminant concentration must be combined for the for the purpose of applying the water cascade analysis technique. These are indicated in **Table 6-7** and these flowrates and contaminant concentration were used in the water cascade analyses.

Table 6-7: Net source and sink flowrates at a given contaminant concentration

Demands		Sources	
Flow (ℓ.min^{-1})	**C (mg. ℓ$^{-1}$)**	**Flow (ℓ.min^{-1})**	**C (mg. ℓ$^{-1}$)**
234.0	0.0000	1000	33.00
660.0	30.00	5065	141.0
2400	141.0	23690	588.0
1116	100.0	507.0	1003
440.0	250.0	405.0	1062
36610	600.0	8401	1885
30.00	254700		
20.00	268900		

6.2.1.3 Results of ultimate flowrate targeting technique with regeneration placement for tissue machine number one

This section highlights the results obtained from the initial pinch analysis performed to determine the pinch causing stream by applying the ultimate flowrate targeting technique (Ng et al., 2009). The results obtained from the water cascade analysis for each of the operating conditions discussed in **section 6.2.1.1** and **section 6.2.1.2** was compared. The necessary data from **Appendix G, section G.1** is shown in **Figure 6-1** and **Figure 6-2**.

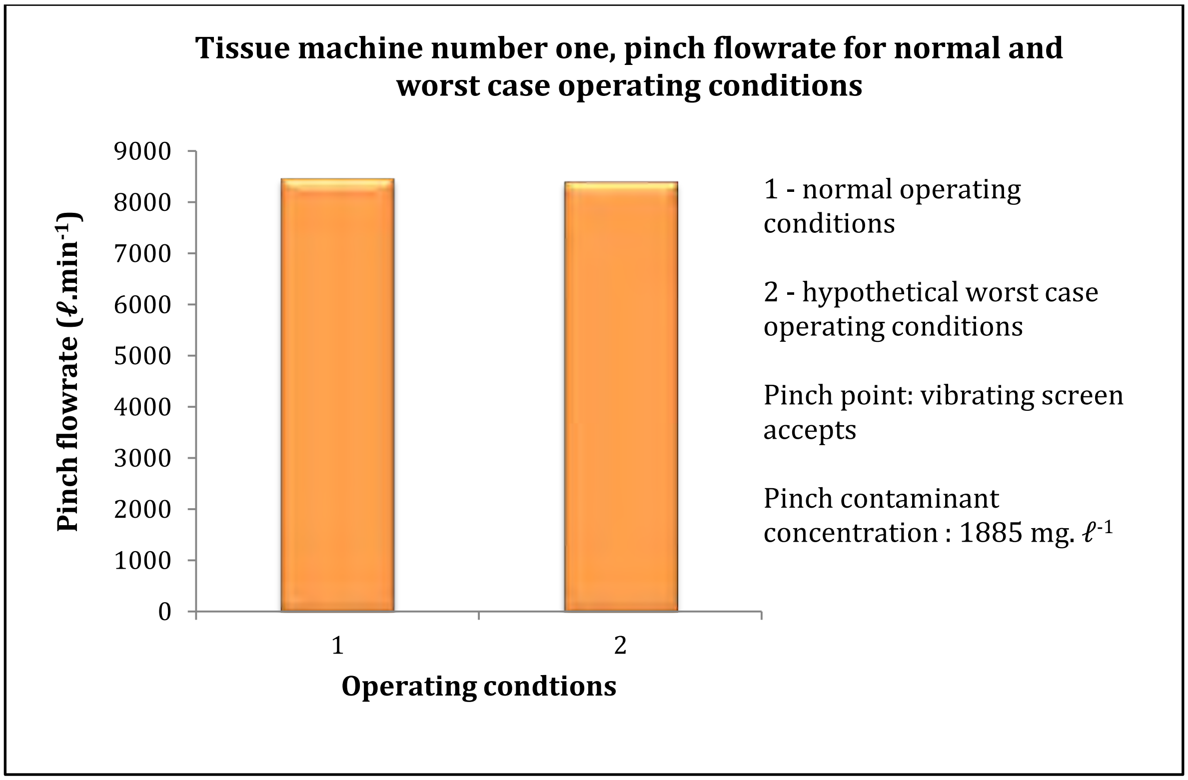

Figure 6-1: The vibrating screen accepts determined as the pinch point for both normal and worst case operating conditions on tissue machine number one (existing regeneration was not considered in the pinch analysis).

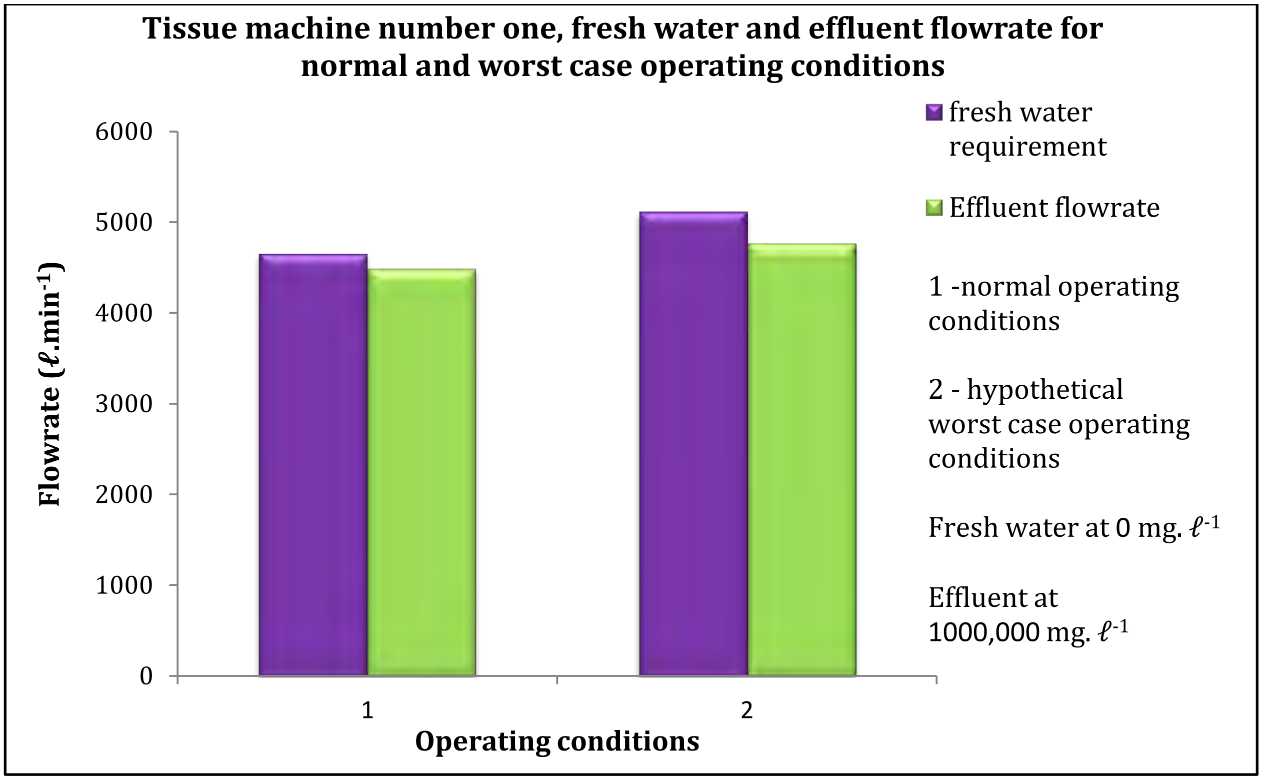

Figure 6-2: The fresh water and effluent water flowrate determined from the pinch analysis on tissue machine number one (both worst case and operating conditions) for the system where the existing regeneration was not considered in the pinch analysis.

6.2.1.4 Discussion of Water cascade analysis – operating and hypothetical worst case operation

The determination of the pinch point was necessary because it identified the stream which was limiting the reuse of water; using this, appropriate treatment can be selected and reallocations of the sources and sinks into the regenerated water region and fresh water region can be performed.

Figure 6-1 and **Figure 6-2** contains the results obtained from the initial water cascade analysis, for normal operating conditions as well as the hypothetical worst case operating conditions, as described by Ng et al. (2009) to determine the pinch point. The associated water cascade tables are available in **Appendix G, section G.1**. From these water cascade analyses it was determined that the pinch causing stream was the vibrating screen accepts at 1885 mg. ℓ^{-1} and 8463 ℓ.min^{-1} (235.0 kℓ. ton^{-1} tissue manufactured) for normal operation and 8401 ℓ.min^{-1} (230.0 kℓ.ton^{-1} tissue manufactured) for hypothetical worst case operation; the same pinch causing stream was identified for both normal and worst case operation. The flowrate of the pinch stream was lower under the worst case operation because if the system operates inefficiently it results in extra losses from other points in the system, resulting in less process water available for regeneration.

The minimum fresh water flowrate was 136.3 kℓ.ton^{-1} tissue manufactured for normal operation 139.9 kℓ.ton^{-1} tissue manufactured under worst case operation. There has been an increase in the fresh water required; this was expected because under the hypothetical worst case operation more fresh water would be required to compensate for the water at a poorer quality available to the system, so that all sinks (demands) can be supplied with water at their allowable contaminant concentrations. This increase in fresh water will have a corresponding increase in effluent flowrate (from the concept of material balances).

The minimum effluent flowrate under normal operation was 4483 ℓ.min^{-1} at 1000,000 mg. ℓ$^{-1}$ as compared to 4764 ℓ.min^{-1} at 1000,000 mg. ℓ$^{-1}$ for worst case operation. This shows that there will theoretically be more effluent removed from the system if the operating conditions are not at optimum; this will occur because more fresh water will have to be added to compensate for the poor quality process water available to the system under worst case operation (refer to paragraph above). 1000,000 mg.ℓ$^{-1}$ was used for the effluent concentration because this was the maximum allowable effluent concentration as stipulated by Ng et al. (2009). The effluent concentration was considered as 1000,000 mg. ℓ$^{-1}$ to ensure maximum uptake of contaminants by the equipment units as well as attempting to send a low-flow, highly-concentrated stream to effluent treatment such that little further treatment will be required because of the effluent already being highly concentrated.

The difference in the fresh water flowrate and effluent flowrate was due to water losses from the system through the drying process as well as through the various reject streams in the process.

In the case of both normal and worst case operating conditions the required fresh water flowrate was very close to the effluent flowrate. This correlates with work done by Ng et al. (2009) because what was added to the system was removed from the system (if no recycle, reuse or regeneration was considered and only the pinch point was determined). It was observed that the effluent flowrate was very high, this was because the initial analysis assumed that the pinch stream was not regenerated, that is, fresh water was continuously being replenished into the system and water was continuously removed from the system as effluent rather than being regenerated so that cascading and recycling could occur. Determining the pinch point was the first step in a series of targeting procedures. It identifies the stream about which the efforts should be focused.

According to Hallale (2002) the pinch should correspond to a source, the pinch causing (vibrating screen accepts) stream identified, was a source. Therefore the method was accurate in determining the pinch point for a given system. The method was also accurate in determining the global pinch point under varying operating conditions, that is, the same pinch point was identified for the operating and worst case operating conditions. This was important because the pinch point should not shift if operating conditions vary because this will render proposed treatment systems ineffective.

The most common units used for regeneration are the dissolved air flotation or save-all type. These can be applied to regenerate the pinch causing stream identified. Therefore the dissolved air flotation could be used to regenerate the vibrating screen accepts rather than the water from the off-machine silo.

From literature the pinch point will vary depending on the operation of a respective tissue machine and the contaminant concentrations of the process (white-) water. However, the pinch causing stream will always correspond to a source stream.

6.2.2 Current (existing) regeneration of process water in the tissue making process was considered in the pinch analysis

A comparison was then made between the system in section 6.2.1 and the system where the existing regeneration was considered in conjunction with an new regeneration unit. In this system all existing regeneration of the process water was considered in the pinch analysis, that is, the dissolved air filtration unit water source has been included in the water cascade analysis. This section details all calculations described in **Table** 6-1 for both the normal operating conditions and the hypothetical worst case operation. The results here will be compared to that of the system in **section 6.2.1** to determine which will be the more cost effective option to implement in order to bring about a reduction in the fresh water consumption. This analysis will also give insight as to whether the current regeneration scheme on tissue machine number one is effective or whether it can be improved upon.

6.2.2.1 Normal operating conditions

The comparison between operating and worst case operation was done to investigate two aspects:

1. the robustness of the method
2. whether the pinch point determined for this system was the same as that determined for the system where none of the existing regeneration was considered (**section 6.2.1.1 (a)**)

6.2.2.1(a) Source and sink streams considered

Before the pinch analysis can be performed, the sources and sinks in the system must be clearly identified. The source and sinks flowrates for tissue machine number one are indicated in **Table 6-8** and **Table 6-9.**

Table 6-8: Sink flowrates at the allowable contaminant concentrations determined for tissue machine number one for normal operating conditions for the system where the existing regeneration was considered

Sinks				
Stream	**Flow (ℓ.min^{-1})**	**C (mg. ℓ^{-1})**	**Stream number (Figure 5-2)**	**Demand (D)**
Yankee showers	235.0	0.0000	29	D1
DAF chemical dilution water	40.00	0.0000	47	D2
DAF gravity strainer shower	11.00	5.0000	49	D3
Press showers	600.0	30.00	27	D4
Press showers	60.00	30.00	27	D5
Uhle box vacuum separator bottoms	240.0	59.00	36	D6
Wire showers	600.0	100.0	25	D7
Wire showers	500.0	100.0	25	D8
DAF gravity strainer rejects	6.000	100.0	50	D9
Vacuum seal water gravity strainer shower	6.000	100.0	42	D10
Vacuum pump seal water	440.0	250.0	40	D11
Fan pump dilution water	34960	600.0	20	D12
Broke pulper dilution water	924.0	600.0	2	D13
Broke dump chest dilution water	290.0	600.0	8	D14
Virgin pulper dilution water	203.0	600.0	1	D15
Virgin dump chest dilution water	156.0	600.0	7	D16
Stock blender dilution water	41.00	600.0	18	D17
Vibrating screen shower water	16.00	600.0	37	D18
Broke high density cleaner shower water	12.00	600.0	10	D19
Virgin high density cleaner shower water	9.000	600.0	9	D20
Vacuum seal water gravity strainer reject	1.000	9385	44	D21
Virgin high density cleaner rejects	8.000	115800	51	D22
Broke high density cleaner rejects	22.00	115800	52	D23
Vibrating Screens rejects	15.00	254700	39	D24

Table 6-8 lists the sink flowrates for tissue machine number one in order of ascending contaminant concentration. The contaminant concentrations represent the maximum allowable concentration to the sink (demand) and are derived from equipment and process contaminant constraints. The uhle-box separator bottoms could be considered as a water source but as per mill specification it has to be discharged to drain and was therefore considered as a sink (demand D6) to account for water losses from the system. This stream

could be regenerated but it was necessary to consider this purge from the system to avoid the accumulation of stickies and other contaminants. Similarly, the vacuum seal water gravity strainer rejects, virgin high-density cleaner rejects, broke high-density cleaner rejects and the vibrating screen rejects were considered as sinks.

All reject flowrates were an over-estimation because most rejects were removed periodically from the system, that is, every 20 to 30 min; they are considered here as a steady flowrate. All data have been extracted from **Figure 5-2**.

Table 6-9 lists all the source flowrates in ascending contaminant concentration. The contaminant concentrations are those determined from the sampling period (**Chapter 5**, **section 5.2**)

Table 6-9: Source flowrates at their respective contaminant concentrations determined for tissue machine number one for normal operating conditions for the system where the existing regeneration was considered

	Sources			
Streams	**Flow (ℓ. min^{-1})**	**C (mg. ℓ^{-1})**	**Stream number (Figure 5-2)**	**Sources (S)**
Fresh water	To be determined by the pinch	0.0000		S1
Vacuum pump gravity strainer	1000	5.000	43	S2
DAF	1977	11.00	48	S3
Flat box separator	4074	59.00	34	S4
Wire	24850	588.0	33	S5
Press	514.0	881.0	35	S6
SBR vacuum separator bottoms	183.0	1062	32	S7
Vibrating Screen accepts	6462	1885	38	S8

By comparing **Table 6-8** with that of the system where none of the existing regeneration was considered (**Table 6-2**), there was a greater fresh water requirement for the system where existing regeneration of the process water was considered (Yankee and dissolved air flotation requirements). This was because the regeneration unit (dissolved air flotation) which has been included in the analysis has an added fresh water requirement due to the fresh water required for the chemical dosing.

All flowrates at a given contaminant concentration must be combined for the purpose of carrying out the water cascade analysis. These are indicated in **Table 6-10.** The 5 mg. ℓ$^{-1}$ demand from **Table 6-8** has been included with the 0 mg. ℓ$^{-1}$ demand in **Table 6-10**.

Table 6-10: Net source and sink flowrates at respective contaminant concentrations

Demands		Sources	
Flow (ℓ.min^{-1})	**C (mg. ℓ$^{-1}$)**	**Flow (ℓ.min^{-1})**	**C (mg. ℓ$^{-1}$)**
286.0	0.0000	1000	5.000
660.0	30.00	1977	11.00
240.0	59.00	4074	59.00
1112	100.0	24850	588.0
440.0	250.0	514.0	881.0
36610	600.0	183.0	1062
8.000	9385	6462	1885
22.00	115800		
15.00	254700		

The above flowrates were used in the water cascade analysis. These flowrates will be used in the water cascades which follow in **section 6.3** and in the various water cascades considered will be discussed in **Chapter 8**.

6.2.2.2 Hypothetical worst case operating conditions

A discussed in Chapter 5, the upper limit of the confidence interval of the material balances were used for the worst case operating conditions pinch analysis; the water flowrates are obtained from **Figure 5-2**, **Table 5-5** and **Table 5-6.**

This system was investigated to determine if the varied operating conditions resulted in a shifting of the pinch point.

6.2.2.3(a) Source and sink streams considered

The source and sink streams considered in the water cascade analysis for tissue machine number one for the hypothetical worst case operation are detailed in **Table 6-11** and **Table** 6-12.

Table 6-11: Sink flowrates at the allowable contaminant concentrations determined for tissue machine number one for worst case operating conditions for the system where the existing regeneration was considered

Sinks				
Stream	**Flow (ℓ.min^{-1})**	**C (mg. ℓ$^{-1}$)**	**Stream number (Figure 5-2)**	**Demands (D)**
Yankee	235.0	0.0000	29	D1
DAF chemical dilution water	40.00	0.0000	47	D2
DAF gravity strainer shower	11.0	5.000	49	D3
Press	600.0	30.00	27	D4
Press	60.00	30.00	27	D5
Wire	600.0	100.0	5	D6
Wire	500.0	100.0	25	D7
DAF gravity strainer rejects	13.00	100.0	50	D8
Uhle box vacuum separator bottoms	240.0	141.0	36	D9
Vacuum seal water gravity strainer shower	6.000	100.0	42	D10
Vacuum pumps	440.0	250.0	40	D11
Fan pump	34960	600.0	20	D12
Broke pulper	924.0	600.0	2	D13
Broke dump chest	293.0	600.0	8	D14
Virgin pulper	207.0	600.0	1	D15
Virgin dump chest	159.0	600.0	7	D16
Stock blender	41.00	600.0	18	D17
Vibrating screen shower	16.00	600.0	37	D18
Virgin high density cleaner shower	12.00	600.0	10	D19
Broke high density cleaner shower	9.00	600.0	9	D20
Vacuum seal water gravity strainer reject	1.000	9385	44	D21
Vibrating Screens rejects	20.00	254700	39	D22
Broke high density cleaner rejects	22.00	268700	52	D23
Virgin high density cleaner rejects	8.000	268700	51	D24

Table 6-11 lists the sink flowrates in order of ascending contaminant concentration; the contaminant concentrations represent the maximum allowable concentration to the sink (demand) and are derived from equipment and process contaminant constraints. All streams required to be discharged to drain (as discussed in **section 6.2.2.1**) are considered as sinks, to account for water losses from the system.

Table 6-12: Source flowrates at their respective contaminant concentrations determined for tissue machine number one for worst case operating conditions for the system where the existing regeneration was considered

Sources				
Streams	**Flow (ℓ.min^{-1})**	**C (mg. ℓ^{-1})**	**Stream number (Figure 5-2)**	**Source (S)**
Fresh water	To be determined by pinch	0.0000		S1
Vacuum pump gravity strainer	1000	5.000	41	S2
DAF	1985	19.00	48	S3
Flat box separator	5065	141.0	34	S4
Wire	23690	588.0	33	S5
Press	507.0	1002	35	S6
SBR vacuum separator bottoms	405.0	1062	32	S7
Vibrating Screen accepts	6401	1885	38	S8

Table 6-12 lists all source flowrates in order of ascending contaminant concentrations. The contaminant concentrations are a combination of those obtained from sampling and the upper limits of the confidence interval.

Due to inclusion of the regeneration units, the fresh water requirement was greater in comparison to **Table 6-7** because additional fresh water was required for the chemical dosing at the dissolved air flotation unit. All flowrates at the respective contaminant concentration must be summed for the purpose of conducting the water cascade analysis. These are indicated in **Table 6-13**.

Table 6-13: Net source and sink flowrates at respective contaminant concentrations

Demands		Sources	
Flow (ℓ.min^{-1})	**C (mg. ℓ$^{-1}$)**	**Flow (ℓ.min^{-1})**	**C (mg. ℓ$^{-1}$)**
286.0	0.0000	1000	5.000
660.0	30.00	1985	19.00
1113	100.0	5065	141.0
240.0	141.0	23690	588.0
440.0	250.0	507.0	1002
36600	600.0	405.0	1062
1.000	9385	6401	1885
20.00	254700		
30.00	268700		

From **Table 6-13** it was noted that there was a reduced total source flowrate because of the undesired process conditions. The flowrates and contaminant concentrations in **Table** 6-13 were used in the water cascade analysis. The 5 mg. ℓ$^{-1}$ demand was included in the 0 mg. ℓ$^{-1}$ requirement. The various water cascades as described in **Table 6-1** are discussed in the **section 6.3**, **Chapter 7** and **Chapter 8.**

6.2.2.3 Results - ultimate flowrate targeting technique with regeneration placement (Ng et al., 2009)

This section highlights the results obtained from the initial pinch analysis to determine the pinch causing stream. The results obtained from the water cascade analysis for each of the operating conditions discussed in **section 6.2.2.1** and **section 6.2.2.1** was compared. The necessary data from **Appendix G, section G.1** is shown in **Figure 6-3** and **Figure 6-4.**

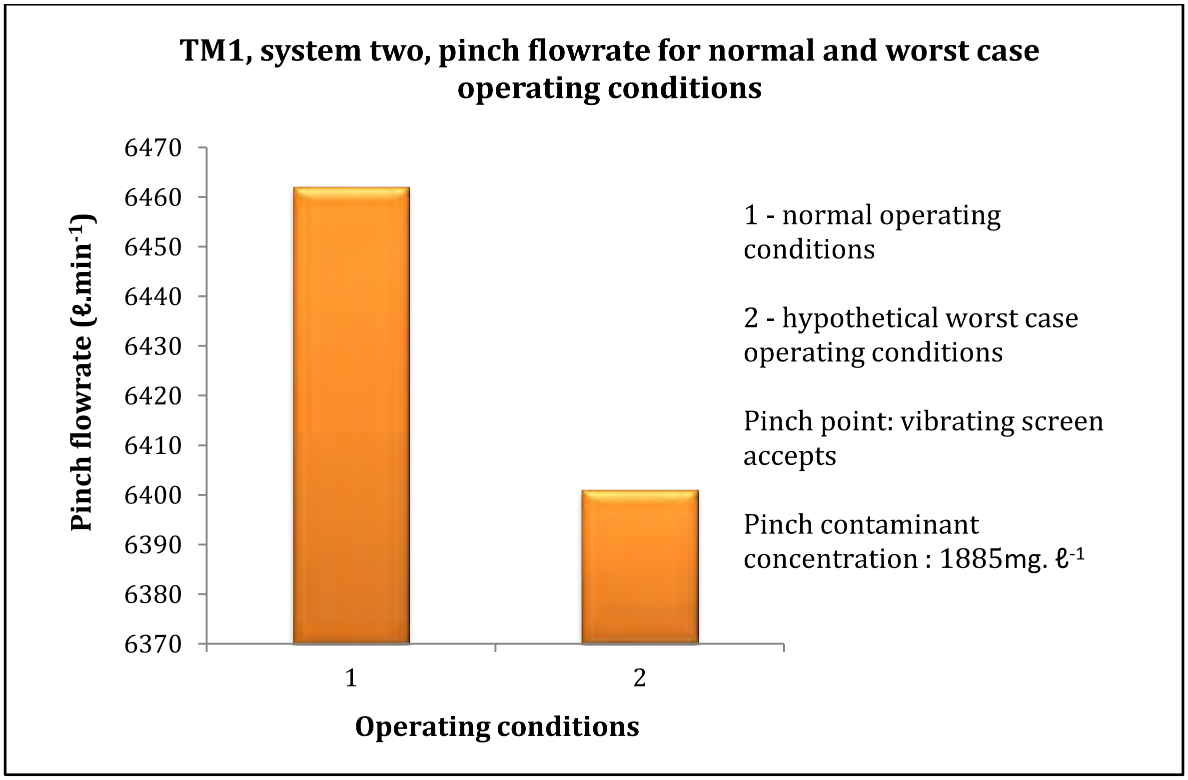

Figure 6-3: The vibrating screen accepts determined as the pinch point for both normal and worst case operating conditions on tissue machine number one for the system where existing regeneration was considered in the pinch analysis.

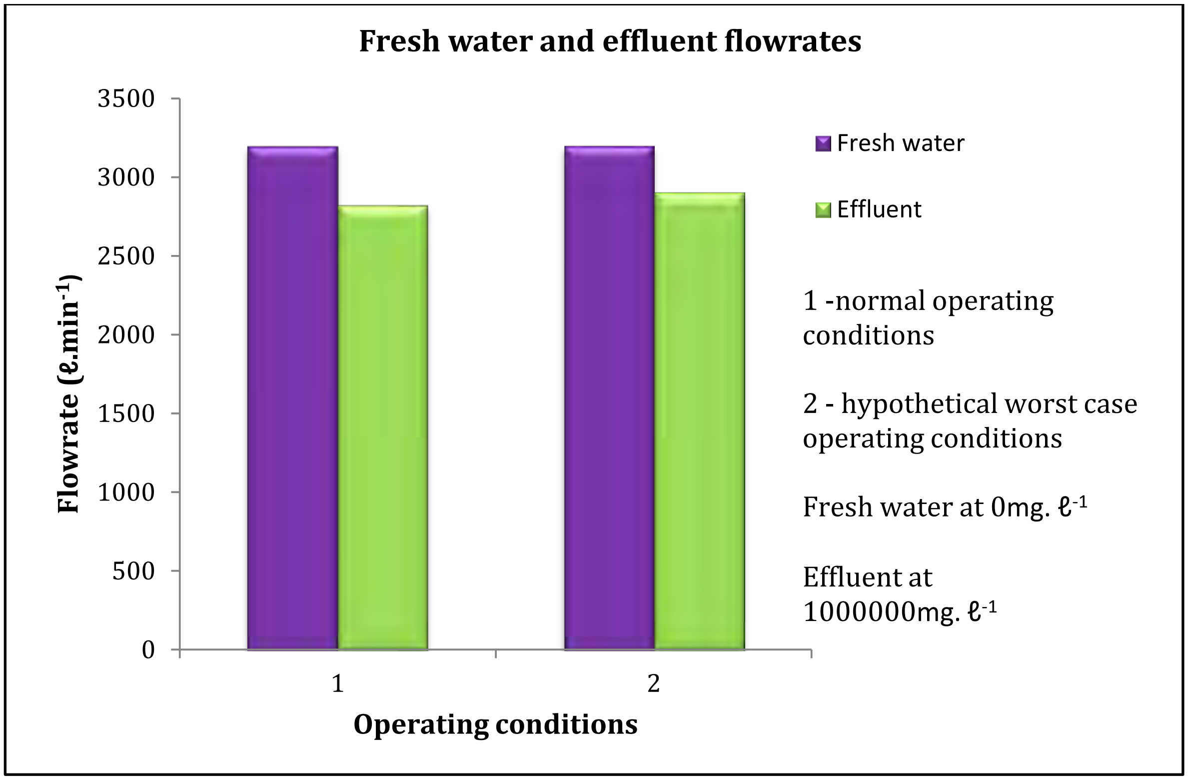

Figure 6-4: The fresh water and effluent water flowrate determined from the pinch analysis on tissue machine number one (both worst case and operating conditions) for the system where the existing regeneration was considered in the pinch analysis.

6.2.2.4 Discussion of Water cascade analysis – operating and hypothetical worst case operation

In this chapter, various water pinch analyses were performed on two different water systems on tissue machine one, that is, one system in which the existing regeneration was considered in the pinch analysis and the other where the regeneration was not considered in the pinch analysis as well as considering a range of operating conditions through the consideration of normal and worst case operation. This was done to verify that the method of Ng et al. (2009) did indeed accurately define the global pinch point of a multiple pinch problem; if it did not then the pinch would shift to different points in each system. The discussion of the results obtained from these analyses follows and describes the process of arriving at the conclusion as to whether the method was indeed accurate in identifying the global pinch point for the system.

Figure 6-3 and **Figure 6-4** contain the results obtained from the water cascade analyses in **Appendix G**, **section G.1**, these are the initial water cascade analysis performed to determine the pinch causing stream. As previously discussed, the pinch point is required as it is where regeneration efforts should be focussed and it is the first step in determining correct regeneration placement.

The pinch causing stream was identified as the vibrating screen rejects for both normal and worst case operating conditions by the water cascade analysis. This was the same pinch causing stream as for the system where none of the existing regeneration was considered (**section 6.2.1**) and for the system where the process water regeneration was considered. The vibrating screen accepts flowrate was less for the system in which the existing regeneration of the process water considered because of the flowrate of process water to the dissolved air flotation unit for regeneration. From **Figure 6-3**, due to the undesirable process conditions, the pinch causing stream had a lower flowrate (and hence there was a lower source flowrate available for regeneration) for the hypothetical worst case operating conditions. The flowrate of the pinch stream was lower under the worst case operation because there will be less of the source available if the system operates inefficiently resulting in extra losses from other points in the system.

Comparing **Figure 6-2** and **Figure 6-4** the minimum fresh water for the system where existing regeneration of the process water considered, has increased due to the inclusion of the regeneration unit, with a corresponding increase in the effluent water flowrate. Both the fresh water and the effluent flowrates increased under worst case operation. This was expected because under the hypothetical worst case operation more fresh water was required to compensate for the water at a poorer quality which was available to the system, in order to ensure that all sinks (demands) could be met at the allowable contaminant concentrations. More effluent was produced because less water was reused in the system due the constraints in respect to the maximum allowable contaminant concentration to the sink (demand) and the increased fresh water usage.

The effluent contaminant concentration was fixed at 1000,000 mg. ℓ^{-1} because the method aims at reducing flowrates by supplying demands at the maximum allowable contaminant concentration. This was the maximum allowable effluent concentration as stipulated by Ng et al. (2009). The water cascade analysis was performed in this way to ensure maximum taking-up of the contaminant by the units as well as attempting to send a low-flow, high contaminant concentration stream to effluent treatment such that little further treatment will be required because of the effluent already being already being highly concentrated which will promote easier clarification at the effluent treatment plant.

The minimum fresh water and effluent flowrates were very similar; this correlates with work done by Ng et al. (2009) because the water being added to the system was removed from the system. The difference in the fresh water flowrate and effluent flowrate was due to water losses from the system through the drying process as well as through the various reject streams in the process.

These flowrates are very large because this water cascade analysis assumed that the pinch stream was not regenerated, that is, fresh water was continuously replenished in the system and water was continuously removed as effluent from the process rather than being regenerated.

The initial pinch analysis was the first step in a series of targeting procedures. It identifies the stream about which regeneration efforts should be focussed.

According to Hallale (2002) the pinch should correspond to a source, the pinch causing stream identified was a source (**Table 6-3** and **Table 6-9**).

Considering that the same pinch point was determined under varying operating conditions (normal and worst case operation) and for two different process water systems (one where re current regeneration was considered and the other where it was not considered in the analysis), this indicates that the method was accurate in determining the global pinch point of a multiple pinch problem.

This aspect is very important as the solution for reducing the fresh water consumption will depend on this pinch point; if it shifts as the process properties vary, then it will render the proposed treatment systems ineffective.

6.3 Discussion of initial pinch analysis results obtained for tissue machine number two

The pinch analysis procedure describe in **section 6.2** for tissue machine number one was applied to tissue machine number two. This section will highlight the results obtained from the analyses for both normal and worst case operating conditions for the system where (1) current regeneration in the tissue making process was not considered and (2) for the system where existing regeneration of the process water was considered, for tissue machine number two. The results tables and figures for both normal and worst case operating conditions are available in **Appendix H.**

6.3.1 Initial pinch analysis for tissue machine number two

The various operating conditions and process configurations were investigated to verify:

1) the robustness of the method
2) determine the effect of the varied process conditions on the fresh water consumption
3) whether the pinch point determined for all considered system was the same

The results were obtained from the water cascade analyses tables in **Appendix G**, **section G.2**.

6.3.1.1 Pinch analysis results

In this section only the results will be highlighted because the procedure followed was the same as described in **section 6.2**. The full discussion of the results obtained for tissue machine number two is detailed in **Appendix G, section G.2** and **Appendix H**.

6.3.1.1(a) Current regeneration in the tissue making process was not considered in the pinch analysis

It was determined that for the system where current regeneration was not considered in the pinch analysis, the pinch point was the combined flowrate from the main vacuum separator and the single breast roll chamber at 6 mg. ℓ^{-1} and 23 mg. ℓ^{-1} for normal and worst case operation respectively (**Appendix H, Figure H.1**). The contaminant concentration of the pinch point was higher under worst case operation as expected because the sources will have a higher contaminant concentration under worst case operation. The effluent flowrate for this system was similar for both normal and worst case operation (3.182 kℓ.ton^{-1} tissue manufactured and 3.130 kℓ.ton^{-1} tissue manufactured for normal and worst case operation respectively). The effluent flowrate for normal operation was higher that of worst case operation because during worst case operation water was lost to a greater extent through the rejects from the screens.

The fresh water requirement was greater for the worst case operation (18.31 $m^3.ton^{-1}$ tissue manufactured as compared to 16.67 $k\ell.ton^{-1}$ tissue manufactured for normal operating conditions) (**Appendix H, Figure H.2**) This was expected because under the hypothetical worst case operation more fresh water would be required to compensate for the water at a poorer quality available to the system, so that all sinks (demands) can be supplied with water at their allowable contaminant concentrations. The fresh water flowrate was very high because the water cascade analysis assumed that regeneration did not occur; this should be the minimum fresh water consumption for the system. This was the first step in a series of targeting procedures. It identifies the stream about which regeneration efforts should be focused.

The effluent flowrate was less than the fresh water flowrate into the system because water was lost from the system through the drying of the product which accounts for this difference. This trend was similar to that displayed by tissue machine number one for both normal and worst case operation. The effluent contaminant concentration was fixed at 1000,000 mg. ℓ^{-1} because the method aimed at reducing flowrates by supplying demands the maximum allowable contaminant concentration. This was the maximum allowable effluent concentration as stipulated by Ng et al. (2009). The water cascade analysis was performed in this way to ensure maximum taking-up of the contaminant by the units as well as attempting to send a low-flow, highly concentrated stream to effluent treatment such that little further treatment will be required because of it already being highly concentrated.

According to Hallale (2002) the pinch should correspond to a source, and from **Figure 5-3** and **Table 5-7** to **Table 5-10**. The pinch causing stream was a source. Therefore the method was accurate in determining the pinch point for a given system.

This was the first step in a series of targeting procedures. It identifies the stream around which regeneration efforts should be focused. The method was also accurate in determining the global pinch point under varying operating conditions, that is, the pinch point did not shift under the varying operating conditions for the system where the current regeneration in the tissue making process was not considered, the same pinch point was identified for both normal and worst case operating conditions. This was important because we do not want the pinch point to shift if operating conditions vary because this will render the proposed treatment systems ineffective.

6.3.1.1(b) Current regeneration in the tissue making process considered in the pinch analysis

The initial pinch analysis was performed with the intention of determining the pinch point as this is where regeneration efforts should be focused, this section highlights the results obtained from these analyses. The system with the current regeneration in the tissue making process was investigated using the pinch analysis for a comparison to the system in **section 6.3.1.1(a).** In **section 6.3.1.1(b)** (**and Appendix G, section G.2**)all existing regeneration was considered in the pinch analysis, that is, the dissolved air flotation unit and save-all has been included in the analysis as compared to the system where none of the existing regeneration was considered (**section 6.3.1.1(a)**). This section will detail the results obtained from the calculations described in (**Table 6-1**) for both the normal operating conditions and the hypothetical worst case operating conditions. The results here will be compared to the results in descried in **section 6.3.1.1(a)** to determine which would be a more cost effective option to implement to bring about a reduction in water usage. The water cascade tables and figures can be observed in **Appendix G, section G.2** and **Appendix H**, **section H.2.**

From **Appendix G, section G.2** (**Table G-28**, page G-23) the pinch point determined was the water removed from the system via the vacuum pumps, this is displayed graphically in **Figure H-3** for both normal and worst case operating conditions. **Figure H-3** indicates the pinch point flowrate, contaminant concentration and stream name as determined from water cascade analysis.

The pinch causing stream identified was the water from the vacuum pumps, in both the normal and worst case operating conditions. In the previous system (**section 6.3.1.1(a)**), the pinch point was identified as the water from the main vacuum separator and the single breast roll chamber. However in **section 6.3.1.1(b),** these streams do not exist because in this system, these flowrates empty into the seal pit from which it is sent to the save-all for regeneration (**Figure 2-4**). Therefore the water from the save-all replaces these as a source. The difference between these two systems on tissue machine number two will allow for a comparison as what can be done to the current system to bring about reductions in the fresh water consumption without making unnecessary changes to the current system. It is very different from tissue machine one where the vibrating screen accepts exists as a source in both the **section 6.2.1** and **section 6.2.2**. For tissue machine two, section **6.3.1.1(a)** and section **6.3.1.1(b)** are very different due to the way the streams are connected.

Comparing **Figure H-2** with **Figure H-4**, the fresh water requirement was greater for **section 6.3** as compared to **section 6.2**, that is, the current regeneration scheme at the mill uses more water than the system considering an alternate regeneration scheme where regeneration will only occur across the pinch point.

This occurred because in the existing regeneration scheme the regeneration units included in the pinch analysis have associated fresh water consumption, for example, the dissolved air flotation unit required fresh water input for chemical dosing.

The effluent flowrate was also greater for **section 6.3** as compared to **section 6.2**; this corresponds to the greater fresh water input from the material balance perspective.

The fresh water consumption was greater for worst case operation than normal operation (**Figure H-2** and **Figure H-4**). This was because in order to ensure that the sinks (demands) are supplied with water at the allowable contaminant concentration, more fresh water will be required to compensate for the poorer water quality available to the sinks (demands) under the hypothetical worst case operating conditions.

The effluent flowrate decreased for worst case operation compared to normal operation because more water was lost through the rejects from the system. The effluent contaminant concentration was fixed at 1000,000 mg. ℓ^{-1} because the method of Ng et al. (2009) aims at reducing flowrates by supplying demands with water at the maximum allowable contaminant concentration. 1000,000 mg.ℓ^{-1} was the maximum allowable effluent concentration as stipulated by Ng et al. (2009) and is considered as 1000,000 mg. ℓ^{-1} to ensure maximum taking-up of contaminants by the units as well as attempting to send a low flowrate, highly concentrated stream to effluent treatment such that little further treatment of the effluent stream will be required because the solids are already concentrated.

The minimum fresh water and effluent flowrates were similar; this correlates with work done by Ng et al. (2009) because the water added to the system was removed from the system. The effluent flowrate was lower than that of the fresh water because some water was lost via evaporation in the drying process and was not recovered in the process

The fresh water and effluent flowrates are very large because the pinch point was not regenerated indicating that the regeneration units were not appropriately placed,

The initial pinch analysis was the first step in a series of targeting procedures. It identified the stream about which regeneration efforts should be focussed.

The pinch point has once again been identified as a source (**Table 6-6**) which corresponds to the literature of Hallale (2002). The water cascade analysis was therefore accurate in determining the pinch point for a given system.

The method was also accurate in determining the global pinch point under varying operating conditions (same pinch point identified under normal and worst case operating conditions). This was important because we do not want the pinch point to shift if operating conditions vary because this will render proposed treatment systems ineffective.

6.4 Comparison between initial pinch analysis of tissue machine number one and tissue machine number two

This section highlights the pinch point determined from the initial pinch analysis for tissue machine number one and number two. The difference in pinch points between the machines results from the difference in water purity constraints for each of the machines (as described in **Chapter 2**). This indicates that he pinch point was sensitive to the differences in contaminant concentrations allowed to the process units (sinks). The more relaxed the purity requirements, the lower the regeneration flowrate required; also if the purity requirements are relaxed it will result in the higher purity sinks being the limitation in process water recycle because it will require higher purity water than the process water available and hence fresh water will have to be used to supply the sink. The pinch point determined for each of the tissue machines is described in **Table 6-14.**

Table 6-14: Pinch point determined for tissue machine number one and number two

	Tissue machine number one	Tissue machine number two
Pinch point	Vibrating screen accepts	Main vacuum separator and single breast roll/vacuum pumps
Pinch flowrate	8401 ℓ.min^{-1}	783 ℓ.min^{-1}/1500 ℓ.min^{-1}
Pinch contaminant concentration	1885 mg.ℓ$^{-1}$	6 mg.ℓ$^{-1}$/42 mg.ℓ$^{-1}$

The pinch point for tissue machine one was at a higher flowrate and contaminant concentration because of the stringent water quality requirements on tissue machine number one as compared to tissue machine number two, that is, because the sinks on tissue machine one have stringent water purities, the lower quality process water cannot be used to meet the higher flow requirements for the sinks. This resulted in a large regeneration flowrate required was indicated by the pinch point.

On tissue machine number two, water at a poorer quality can be used in the system because of the less stringent water quality requirements on tissue machine number two (**Chapter 2**); hence the process water limiting the reuse in the system was the water of highest quality available from the process, that is, the process water could be used in the system foe all sinks except the fresh water sinks. Therefore regeneration will be required to supply the higher purity sinks.

The implications of these different pinch points are that different degrees of regeneration will be required for each of the tissue machines in order to reduce the specific water consumption. The various regeneration schemes will be discussed in **Chapter 7**.

Chapter 7 Intervention

From the previous section, it was determined that the pinch point for tissue machine number one was the vibrating screen accepts at 1885 mg. ℓ^{-1} and that of tissue machine two was the combined flowrate from the main vacuum separator and single breast roll chamber at 6 mg. ℓ^{-1} to 23 mg. ℓ^{-1} for the system where none of the existing regeneration was considered and the water from the vacuum pumps at 42 mg. ℓ^{-1} to 50 mg. ℓ^{-1} for the system where existing regeneration was considered. Therefore a solids-liquid separation unit was required. Considering the different degrees of regeneration needed, two different regeneration units would be required for the two tissue machines. Necessary regeneration unit outlet concentrations are required before the source-sink reallocation procedure described by Ng et al. (2009) can be performed.

The following procedure was used to determine the degree of regeneration required:

3. Use water cascade analysis to determine up to which regeneration concentration will have a significant effect on the pinch point
4. Investigate various regeneration units capable of achieving the regeneration concentration determined in (1)
5. Apply regeneration concentration in the method of Ng et al. (2009)

This section details the procedure followed in order to determine the suitable regeneration units for each of the tissue machines.

7.1 Regeneration units

Once the required regeneration duty was determined, a suitable regeneration unit was required to be selected. Various treatment and reuse options are available and the most suitable option was selected. Physical, chemical and biological methods can be combined in treatment systems.

It must be noted that design of selected unit should be carried out by a specialist in the field. With regards to testing, testing should be done on a pilot-plant scale rather than on a laboratory scale because operation does not always correspond to predictions made from theory (Svarovsky, 1997).

Solid-liquid separation processes purpose is to achieve one of the following (Svarovsky, 1997):

1. recovering the valuable solids (the liquid being discarded);
2. recovering the liquid (the solids being discarded);
3. recovering both the liquid and the solid;
4. recovering neither (but for example to prevent water pollution).

Filtration can be defined as the process or removing solid particles from a fluid (liquid or gas) by forcing the fluid through a porous medium through which a solid particle cannot pass (Allhands, 2011).

Metcalf and Eddy (1991) provide an extensive review of which separating process should be applied depending on the contaminants to be removed from the system. A summary of the treatment types discussed are available in **Appendix I.**

From the processes described in **Appendix I,** only those relevant to the study shall be discussed in the sections which follow. For details on the other processes, reference can be made to the original text by Metcalf and Eddy (1991).

Granular filtration medium, chemical precipitation and grit removal are described in detail by Metcalf and Eddy (1991). Bar-racks are described by Nemerow and Dasgupta (1991). Details of operation, types and troubleshooting of horizontal filters and centrifuges can be found in the text by Schweitzer (1997). Due to the contaminant particle size-range of the systems under consideration, these processes will be ineffective and therefore these types of regeneration units are not considered in the study. Only those applicable to the study are highlighted in the sections which follow. Details on flocculation and removal of colloids can be viewed in **Appendix I** and are not discussed in this chapter.

7.1.1 Flotation

Casey (1999) defines flotation *…as a process in which suspensions, the particle phase of which has a specific gravity less than that of the suspending medium, are clarified by allowing the suspended material to float to the surface where it is removed by skimming…*

The details of the flotation process are available in **Appendix I. T**he advantages and disadvantages of the flotation process are highlighted in **Table 7-1**.

Nemerow and Dasgupta (1991) describe the following advantages and disadvantages in using flotation as a wastewater treatment process:

Table 7-1: Advantages and disadvantages of flotation units (Nemerow and Dasgupta, 1991)

Advantages	Disadvantages
1. Grease and light solids rising to the top and grit and heavy solids settling to the bottom are all removed in one unit	1. The additional equipment required results in higher operating costs
2. High overflow rates and short detention periods mean smaller tank sizes, resulting in decreased space requirements and possible savings in construction costs	2. Flotation units generally do not give as effective treatment as gravity-settling units although the efficiency varies with waste
3. Odour nuisances are minimised because of the short detention periods and, in pressure and aeration type units, because of the presence of dissolved oxygen in the effluent	3.The pressure type has high power requirements, which increase operating costs
4. Thicker scum and sludge are obtained, in many cases, from a flotation unit than from gravity settling and skimming	4.The vacuum type requires a relatively expensive airtight structure capable of withstanding a pressure of 30.48kPa; any leakage to the atmosphere will adversely affect performance
	5. More skilled maintenance is required for a flotation unit than for a gravity-settling unit

Casey (1997) also describes similar advantages and disadvantages.

7.1.2 Screens

Nemerow and Dasgupta (1991) consider two main types of screens, that is, the rotary, self-cleaning, gravity-type units and the circular, overhead-fed, vibrating units. These are discussed in **Appendix I.**

These types of screens are further differentiated into coarse screens, fine screens and rotary drum screens. The details of these screening processes, the equipment design and their associated applicability to removal of contaminants from the system are described in **Appendix I**.

7.1.3 Filtration

Filtration operations refers to systems in which pores or holes exists as the filter medium, the order of magnitude of the pores or holes being between the order of 10^2 to 10^4 nm.

Schweitzer (1997) describes three broad categories of filtration, that is, cake filtration, depth filtration and surface filtration. For the study, continuous filtration units are highlighted; these can be of the drum or disk filter type. The details of these filters are available in **Appendix H**.

According to Schweitzer (1997) the disk filter gives the lowest cost per unit area as compared to other continuous units. This is subject to the use of mild steel, cast iron or similar materials of construction. It is also the preferred unit if a large filtration area is required with a limited floor space available.

It should be used as a dewatering device and not for the recovery of dissolved solids. The disc filters are commonly used in the pulp and paper industry as thickening devices called *save-alls*; thickened stock (concentrated solids) is mixed either with bypassed feed slurry or sent to storage (Schweitzer, 1997).

One of the advantages of the unit is the ease with which damaged sectors can be replaced. It may be possible to do this without isolating the unit. The level of submergence will have to be determined depending on the slurry being filtered.

7.1.4 Membrane processes

… Membrane filtration includes a broad range of separation processes from filtration and ultrafiltration to reverse osmosis… (Eckenfelder, 2000). The efficiency of this type filtration depends on the difference in size of the particle to be removed and the pore size. (Eckenfelder, 2000)

Whilst membrane technology is very recent (< 50 years old), its proven use in municipal wastewater treatment has accelerated its use in other industries such as the process industries. The attractiveness of membranes is due to its ability to produce specific separations at ambient conditions, with no phase change. Membrane processes are more cost effective than conventional methods such as rotary vacuum cleaners or filter presses (Niro Inc., 2011)

The various membrane filtration processes are distinguished by the size of the molecules which can be retained. **Figure 7-1** is a general guide for the classification of the various processes:

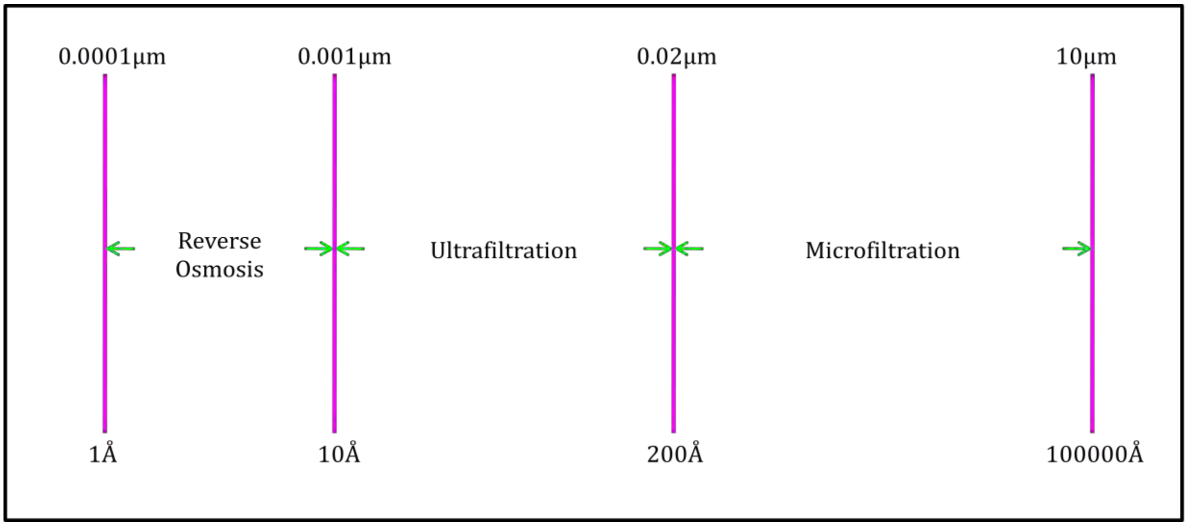

Figure 7-1: Definition of pressure-driven membrane processes based on the smallest particle (molecule) retained (Schweitzer, 1997).

The following membrane processes exist (Niro Inc., Filtration Division, 2011):

- microfiltration (MF) – is a low pressure means of separating large molecular weight suspended or colloidal compounds from dissolved solids
- ultrafiltration (UF) – is a selective separation step used to both concentrate and purify medium to high molecular weight components
- nanofiltration (NF) – is a unique filtration process in-between UF and reverse osmosis designed to achieve highly specific separation of low molecular weight compounds
- reverse osmosis (RO) – is a high pressure, energy-efficient means of de-watering process streams, concentration of low molecular weight compounds

Of these, only microfiltration shall be discussed. The remaining membrane processes are described in **Appendix I**. The application of each process depends on the contaminants in stream to be treated and the desired quantity of contaminant to be removed.

7.1.4.1 Microfiltration and ultrafiltration

From the above processes, microfiltration should be employed to remove macromolecules. Microfiltration, ultrafiltration and reverse osmosis are pressure driven membrane filtration processes and should not be confused with dialysis or electrodialysis in which driving forces such as concentration and electrical gradients are made use of (Schweitzer, 1997).

Microfiltration is a continuation of conventional filtration processes. It is used to remove particles less than a micron in size. Microfiltration is a low-pressure cross flow membrane process for separating colloidal and suspended particles in the range of 0.05μm to 10μm.

Microfiltration and ultrafiltration are both physical separation processes based on a pressure gradient. Contaminants are removed based on the pore diameter of the membranes. MF and UF remove dissolved substances from the water to a lesser extent than nanofiltration and reverse osmosis (Lenntech water treatment solution, 2011).

The pore size on microfiltration membranes ranges between 0.1 μm to 10 μm. They are used in various water treatment systems provided that the contaminant particle size > 0.1 mm need to be removed (Lenntech water treatment solution, 2011).

Microfiltration units have been successfully applied in the following industries (Lenntech water treatment solution, 2011):

- cold sterilisation of pharmaceuticals and beverages
- clearing of fruit juices, wines and beer
- biological wastewater treatment
- effluent treatment
- separation of oil/water emulsions
- pretreatment before nanofiltration

Ultrafiltration is used mainly for removal of viruses. Membrane pore size is between 0.001μm and 0.1 μm. It is commonly applied in the following industries (Lenntech water treatment solution, 2011):

- dairy
- food
- textile

- metal

The type of membrane filtration process to be used will depend on the contaminant particle-size range. **Figure 7-2** indicates the type of membrane filtration process to be used depending on the contaminants to be removed:

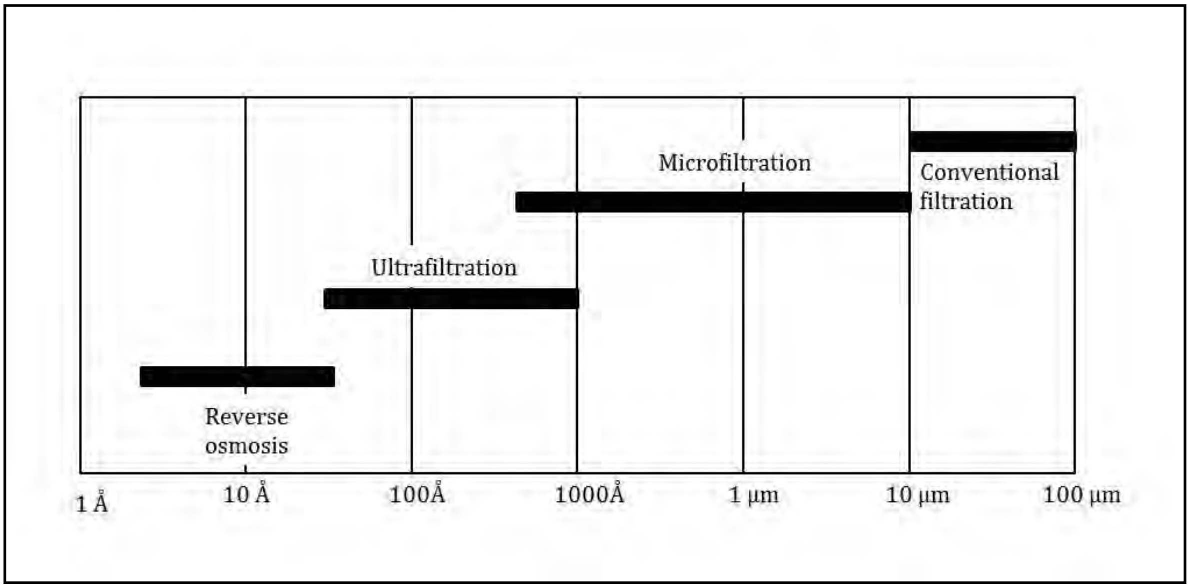

Figure 7-2: Membrane processes and pore size (Eckenfelder, 2000).

Table 7-2 below indicates the type of membrane separation process which will occur depending on the respective particle size of the contaminants.

Table 7-2: Membrane processes (Eckenfelder, 2000)

Material to be removed	Approximate size, nm	Process
Ion removal	1-20	Diffusion or reverse osmosis
Removal of organics in true solution	5-200	Diffusion
Removal of organics: subcolliodal - not in true molecular dispersion	200-10000	Pore flow
Removal of colloidal and particulate matter	75000	Pore flow

Table 7-3 below taken from Eckenfelder (2000) provides an indication of the appropriate water treatment operations depending on the contaminant to be removed.

Table 7-3: Membrane separation technologies for wastewater treatment (Eckenfelder, 2000)

Feature	Micro-filtration	Ultra-Filtration	Nano-filtration	Reverse osmosis	Per-vaporation
Suspended solids removal	Excellent	Impractical	Impractical	Impractical	N/A
Dissolved organic removal	N/A	Excellent	Excellent	Excellent	Good
VOC removal	N/A	Poor	Fair	Fair-good	Excellent
Dissolved inorganic removal	N/A	N/A	Good	Very good	N/A
Osmotic pressure effects	None	Minor	Significant	High	None
Concentration capabilities	Up to 5% total solids	Up to 50% total organics	Up to 15%	Up to 15%	N/A
Permeate quality	Excellent	Excellent	Good	Excellent	Excellent
Energy requirements	1-3 bars	3-7bars	5-10bars	15-70bars	<25% of distillation
Capital costs ($/GPD)	0.15-1.5	0.15-1.85	0.15-1.5	0.15-1.5	1.85-4.00
Operating cost ($/1000ℓ feed rate)	0.15-1.10	0.15-0.80	0.20-0.80	0.25-0.80	0.80-1.30

Membranes are currently being applied widely in the paper industry. A Guangdang paper company in China is using ultrafiltration to produce 65000 $k\ell.d^{-1}$ of water for their boilers. The membranes used can remove suspended solids, micro-organisms and viruses by physical means.

An olive industry in California became the first in the food industry to use membrane filtration as a primary unit operation in a zero-discharge treatment facility. A study was done at the plant into a feasible process which would purify the process and wastewater for reuse as well as concentrate the waste solids to be sold as animal feed. This process was also aimed at eliminating other treatment processes currently in operation. In the process, ultrafiltration was used to remove suspended solids and other large molecular weight components. Reverse osmosis was then used to purify the water and to remove dissolved components. The purified water is sent to storage tanks for reuse for all water operations. The membrane process can be controlled to meet desired operation under varying wastewater requirements. It was determined from the study that spiral-wound membrane configurations offer a more cost effective capital and operating cost for systems aimed at this type of water treatment (Niro Inc., Filtration Technologies, 2011). This type of system has been successfully applied to the following industries aside from many others (Niro Inc., Filtration Technologies, 2011):

- process water reclamation
- paper additives
- kraft black liquor
- spent sulphite liquor
- paper/textile dyes

The membrane life depends on the constituency of the feed. If the feed contains undesirable contaminants such as bacteria, fungi and phenols and is also subjected to fluctuating temperatures and pH conditions the membrane life can be drastically shortened. The usual life span of a membrane is up two years with some loss in flux efficiency. (Eckenfelder, 2000)

The power requirements of membranes are associated with the system pumping capacity and the operational pressure of the membrane. The power values range from 2.400 to 4.500 kWh.m^{-3}. The lower limit of this range takes into account any possible energy recovery from the solution.

Pulp mill effluents have been treated by reverse osmosis at a pressure of 4137 kPa. Waste streams were concentrated up to 100,000 mg.ℓ^{-1} total solids. The flux was found to be a function of total solids level and varied from 0.08000 to 0.6100 kℓ.d^{-1}m^{-2}. Reverse osmosis will not be described in detail as they are usually employed for very high quality water treatment operations. Eckenfelder (2000) described the principles, capabilities and operating requirements for reverse osmosis.

7.1.5 Petax™ filtration system

The Petax™ system is becoming increasingly popular as a way to achieve continuous circulation of white-water with simultaneous capturing fibres and colloidal material. The Petax™ system also aids in higher paper machine efficiency and runnability. It is currently successfully applied in various paper making plants in Asia*… A paper and board producer in Thailand has now installed four units and has ordered another three. The recycled white-water regenerated by this system can be reused for a wide range of functions, and does not clog equipment such as showers… Koepenick (2011)*

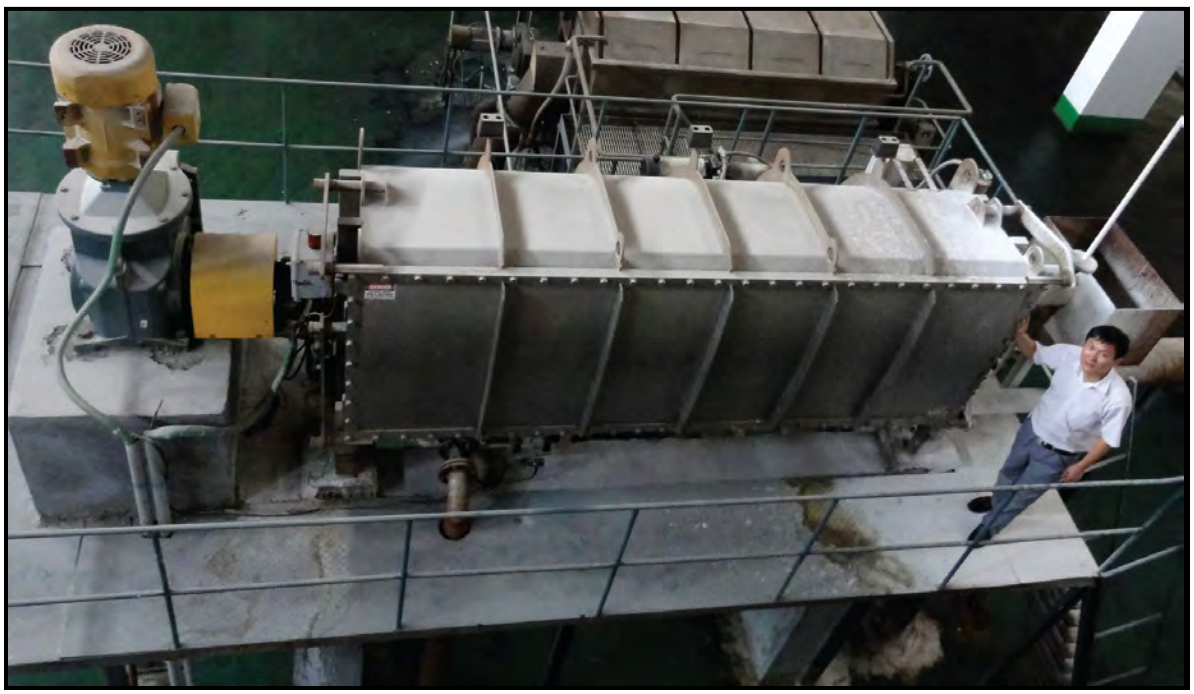

Figure 7-3: The Petax™ filtration system (McGowan, 2002)

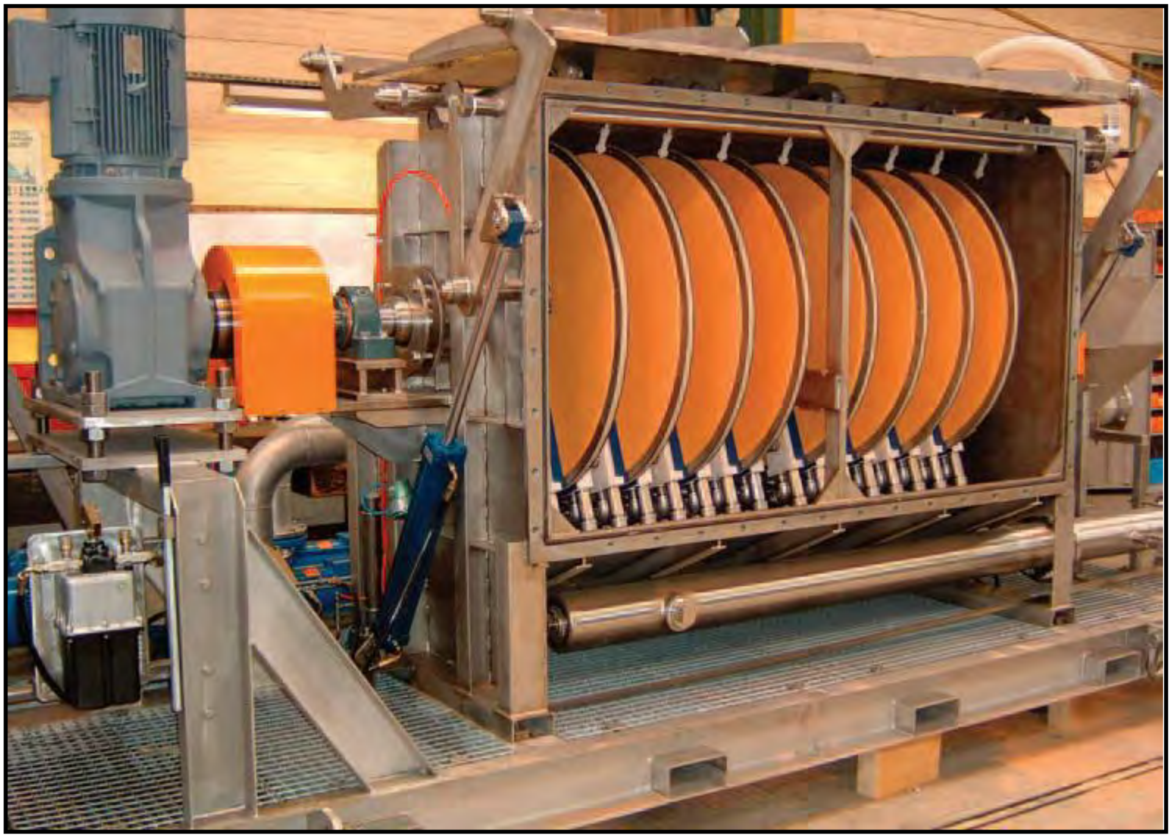

Figure 7-4: Internals of the Petax™ filtration system (McGowan, 2002)

Ecore Tissue in Australia applied the system and it allowed the reuse of process water without compromising water quality in the manufacturing process.

The system benefits include:

- reduction in fresh water usage and effluent treatment costs
- energy saving due to reclaiming and reuse of process water
- shower nozzle plugging is minimised

An Australian paper company wanted to reduce the fresh water consumption and effluent discharge without adversely affecting the process or production. The regenerated water is used for:

- high pressure showers at the wire
- seal water
- chemical dilution

The mill has not experienced any adverse effects in machine runnability since the Petax™ unit has been installed nor has there been a reduction in efficiency of wire and cleaning showers (Koepenick, 2006).

The Storo Enso Uetersen paper mill achieved similar results. It is one of the most closed mills with respect to water use and with the application of the Petax™; it allowed a further reduction in fresh water consumption by 30 % (McGowan, 2002).

In various trials conducted in Europe, the Petax™ unit displayed a 80 % to 98 % removal-efficiency in:

- tissue
- newsprint
- corrugated medium and
- linerboard mills

The thickened solids after regeneration are typically sent back to the couch pit. McGowan (2002) highlights the following advantages of the system:

- removal efficiencies are much higher than compared to gravity strainers
- no sweetening stock is required
- no associated chemical costs
- it occupies a third of the floor space of a DAF designed to treat the same capacity
- Petax™ system has higher removal efficiencies than DAFs

The Petax™ system now allows the reuse of process water in critical applications such as wire and felt cleaning showers. It removes most of the particles without the use of:

- precoat
- flocculants
- sweetening stock
- vacuum drop leg

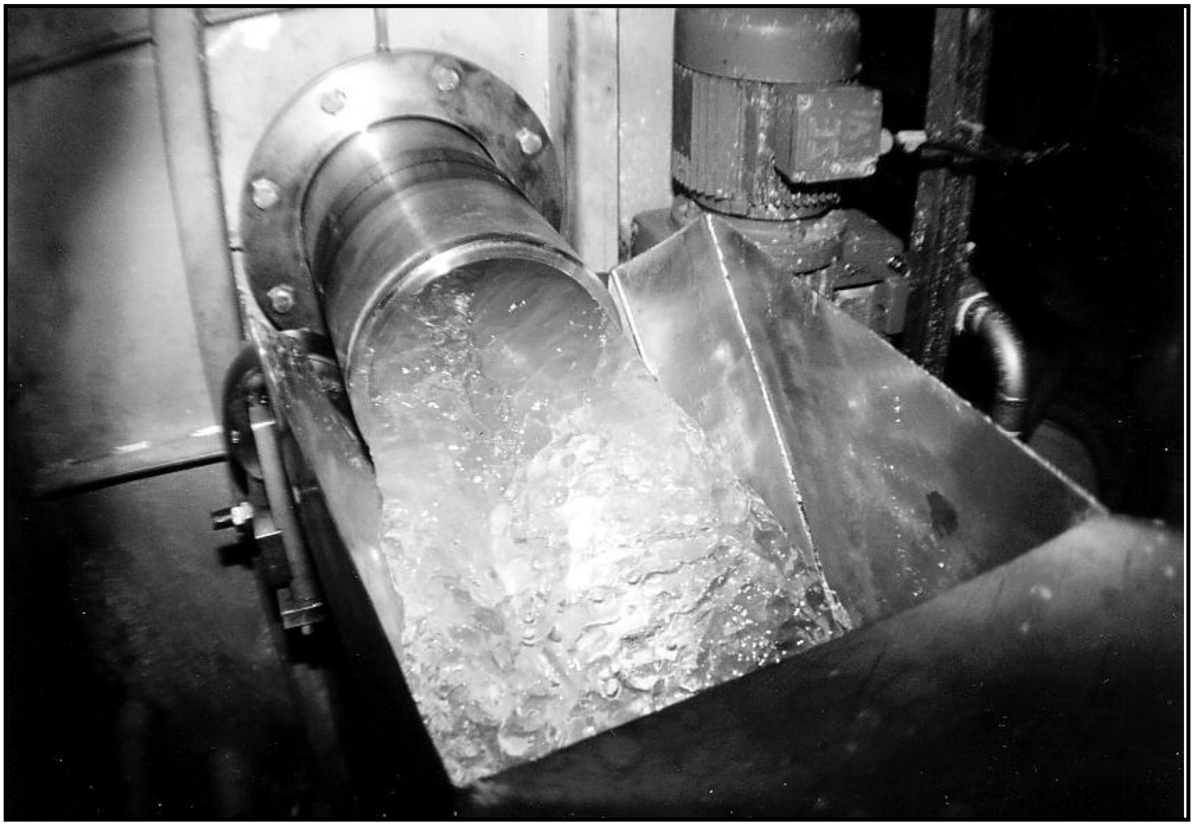

Figure 7-5: Petax™ unit filtrate quality (McGowan, 2002)

Table 7-4: efficiency of the Petax™ unit for various paper grades (McGowan, 2002)

Grade	Water source	Inlet (mg.ℓ$^{-1}$)	Outlet (mg.ℓ$^{-1}$)	Efficiency (%)
Newsprint	Save-all clear leg	82.00	2.000	97.60
Tissue	Dissolved air flotation clarifier clear	50-1700	0-10	>97.00
Fine paper	Save-all clear leg	87.00	10.00	88.50
Fine paper	Wire pit	1260	115.0	90.80
Kraft packaging 10% Recycle 90% Kraft	Flat box water	142.0	10.00	93.00
Packaging board 100% Recycle	DAF clarifier clear	260.0	13.00	95.00
Packaging board 100% Recycle	DAF clarifier feed	340.0	34.00	90.00

7.1.6 Application of units in industry

Various regeneration units have been applied to the pulp and paper industry. This section highlights the traditional approaches taken to process water regeneration and reuse.

7.1.6.1 Paper- mill wastes

Figure 7-6 is a simplified process flow diagram of the paper/tissue making process. It gives an idea of the water utilisation and waste in the process.

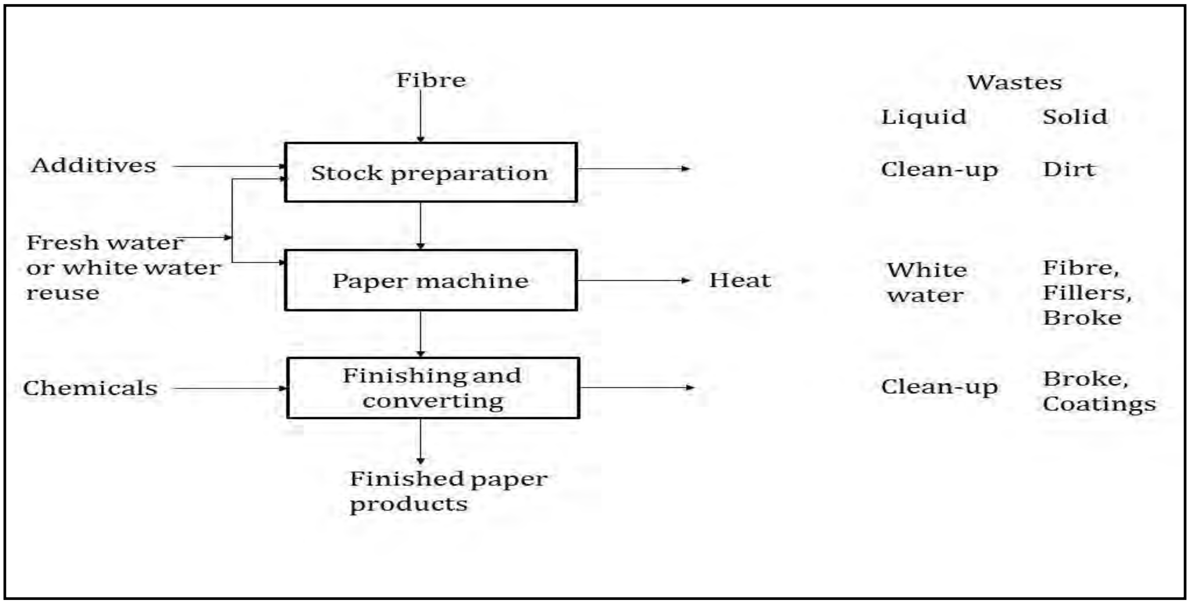

Figure 7-6: Simplified diagram of the paper/tissue making process with associated process requirements and waste generated

> *"The main sources of waste at the pulp mills are digester liquors and the chief sources at the paper mills are the beaters and paper machines. Fibre losses generally average 3 % or less. In so-called 'closed-systems', where white-water is recirculated and reused, it is possible to reduce fibre losses to 0.1 %." Nemerow and Dasgupta (1991)*

Treatment of paper-mill wastes:

Emphasis is placed on recovery rather than treatment, treatment being the last option. Recovery process used save-alls; save-alls serve a dual purpose i.e. waste treatment measure and conservation measure to recover fibres and fillers (Nemerow and Dasgupta, 1991).

Three main types of save-alls are used:

- filtration
- sedimentation
- flotation

> *…Filtration devises are usually some variation of a revolving, cylindrical, perforated screen or filter that removes the suspended solids in the form of a mat, which is subsequently scraped off the drum and returned to the papermaking stock system. Conical or other sedimentation tanks are also often used to separate the suspended matter by difference in specific gravity…Nemerow and Dasgupta (1991)*

Both fibre and other solids are removed by flotation. The particles form a *mat* at the surface of the tank which is removed by a scraper-conveyer. Flotation is an efficient method for certain fibre which have natural tendency to float in suspension, being buoyed up by minute bubbles of air dissolved in the fibrous waste (Nemerow and Dasgupta, 1991)

When the correct save-all is applied, recovery can be greater than 95 %. Recirculation of the clarified white-water does cause some slime growth on the paper/tissue machine. This is combated with appropriate application of organic mercuriles, pH and temperature control and chlorination.

Sedimentation and flotation are achieved by use of save-alls. They are used for fibre recovery and white-water clarification. Due to increased fibre recovery, the effluent from the machines has reduced pollution strength.

Sedimentation is usually the final treatment step of paper/tissue mill effluents. Unlike save-alls, these are not used within the mill's process i.e. not considered as part of the mill's process equipment.

7.2 Extent of regeneration required

It is important to determine the degree of regeneration required because if it is required to regenerate to a very low regeneration concentration, then a greater amount of work will be required to be performed by the regeneration units, therefore, only what regeneration is necessary should be performed. By investigating the effect of various regeneration concentrations on the fresh water required, one can determine the degree to which the process water needs to be treated i.e. how big a difference does a lower regeneration concentration make on the fresh water consumption? The pinch analysis can be used to determine this degree of regeneration required as described in **Figure 7-7**.

Before a regeneration concentration can be selected, it needs to be determined which regeneration concentration would reduce the fresh water consumption sufficiently with the least possible regeneration. Therefore various regeneration concentrations were investigated (**Appendix G**). The resulting fresh water flowrates with corresponding regeneration concentration is displayed in **Figure 7-7** below.

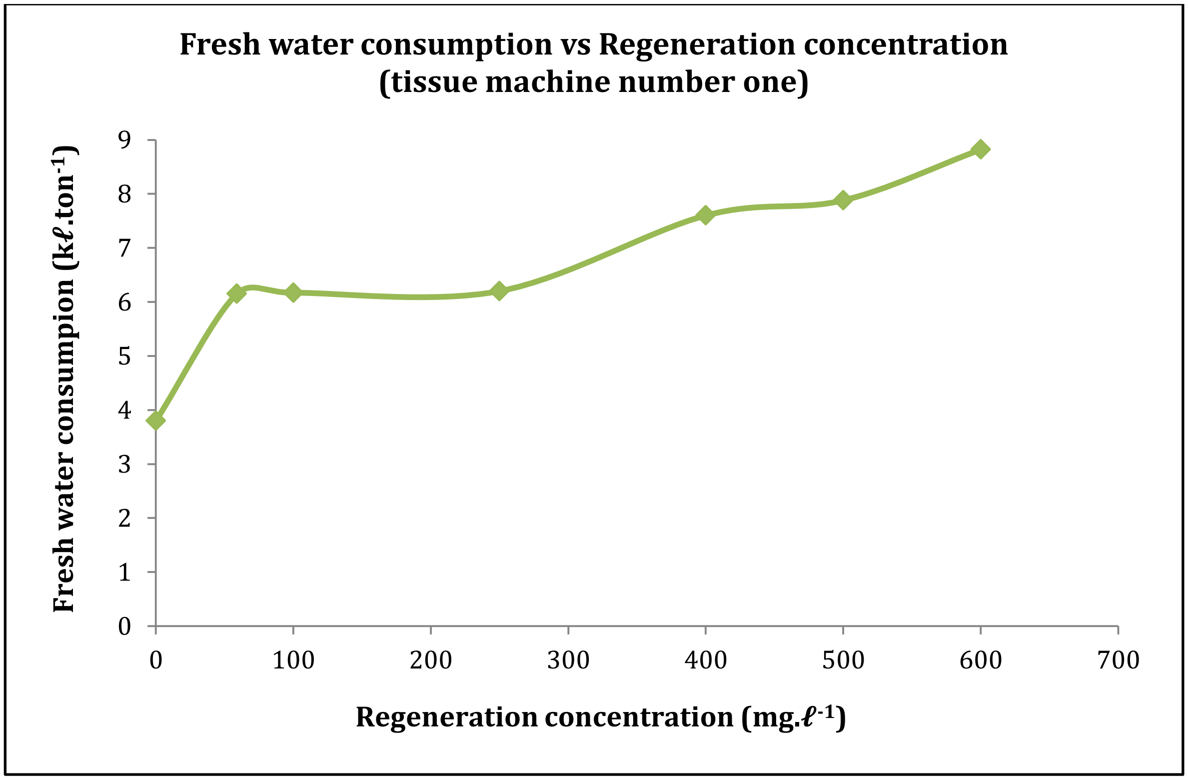

Figure 7-7: Specific water consumption with corresponding regeneration concentration for tissue machine number one

Figure 7-7 was obtained by applying the water cascade analysis technique with the various assumed regeneration concentrations and determining the effect on the fresh water consumption. The fresh water consumption for each of these regeneration concentrations are plotted in **Figure 7-7**. From **Figure 7-7** it is noted that, for tissue machine number one, below a regeneration concentration of 300 mg.ℓ^{-1} the fresh water consumption does not vary significantly. Therefore regeneration efforts should be focused to any total suspended solids below 300 mg.ℓ^{-1}, that is, there is no need to regenerate to concentrations much lower than

300 mg.ℓ^{-1} because the fresh water consumption will not be reduced significantly below a regeneration concentration of 300 mg.ℓ^{-1}.

In **Chapter 6** it was determined that the pinch point for tissue machine number two had a contaminant concentration of 6 mg.ℓ^{-1}. Therefore to reduce the contaminants in the process water to a level where it can be reused, for tissue machine number two a membrane unit would be required because as described in **section 7.1**, the conventional solid-liquid separation equipment are not capable of reducing the contaminants below 20 mg.ℓ^{-1}. Therefore, for tissue machine number two, regeneration of the pinch point to a total suspended solids content of 0 mg.ℓ^{-1} would be required to reduce the specific water consumption.

7.3 Selected units

In order to perform the ultimate flowrate targeting technique, the appropriate regeneration concentration needs to be determined. The effect of different regeneration concentrations was investigated by performing water cascade analyses assuming an available regenerated water source at varied regeneration concentrations. These water cascade analysis tables are available in **Appendix G**. This was done to obtain an indication of the range of regeneration concentrations which would be feasible; because depending on the regeneration needs, the appropriate unit can be selected.

Various regeneration equipment units were investigated and are detailed in **section 7.1** and **Appendix I**. The purpose of the regeneration unit needs to be clearly defined, in the case of this project; water clarification is the deciding factor.

Metcalf and Eddy (1991) describe various contaminant separation methods. These are described briefly in **Appendix I.** From these methods only those which are applicable for removal of suspended solids are considered for this system.

Table 7-5: Selection of appropriate regeneration units

Water treatment method	Applicability to the research study
Sedimentation	• usually used for primary treatment of wastewater • purpose is to produce a highly concentrated sludge • should only be considered for industrial wastewater sludge if the water has a high concentration of suspended solids • this will not be a suitable choice for this system, considering the rheology of pulp fibre suspensions • usually the final treatment step of paper mill effluents • not considered as part of the mill's process equipment
Flotation	• used when the surface gravity of the particle is less than the suspending medium or very close to that of the suspending medium • gas bubbles are employed to artificially reduce the specific gravity of the suspended solids • The advantages of this unit as well as disadvantages are described in **Table 7-1**
Granular filtration medium and chemical precipitation	• used predominantly for potable water and municipal water treatment respectively • therefore not suitable for application to this system
Screens	• viable option as it efficiently and economically reduce suspended solids to acceptable/desired levels • considerable BOD is also removed in the screening process • various fine screens exist; these are described in section **Appendix I**.
Grit chambers	• used for removal of gravel, sand, cinders and other heavy metals • therefore not applicable to this system

Table 7-6: Selection of appropriate regeneration units continued

Water treatment method	Applicability to the research study

Filtration mechanisms	• viable option if the correct unit is applied
	• continuous filters are considered
	• these are drum, disk and horizontal types (discussed in **section 7.1**)
	• disk filters are most appropriate
	  ▪ provide a large filtration area with limited floor space
	  ▪ can be used as thickening devices e.g. save-alls, for recovery of fibres
	  ▪ advantage is the ease with which damaged can be replaced, may be possible to replace without isolating the unit

Centrifuges	• disadvantage is that the effectiveness of the unit depends on the feed slurry concentration • feed slurry must be at a minimum of 40% for most applications • therefore not suitable for application in this system
Cartridge filtration	• able to operate at current contaminant concentrations • are limited to low flowrates • cannot accommodate the flow requirement for the mill's regeneration requirement • therefore are not considered
Gravity strainers	• lack efficiency in removing particles smaller than 45μm • fibres much smaller than this (**Table 7-8**) • therefore not considered
Sand filters	• plug excessively • have high maintenance when used in fine filtration applications • therefore not considered

Table 7-7: Selection of appropriate regeneration units continued

Water treatment method	Applicability to the research study
DAF	• considered the most promising for removal of fine suspended solids • can remove fines, fillers and fibres • disadvantage ▪ there is no physical barrier for separation therefore the clarified liquid can have both large and small particles (McGowan, 2011) ▪ requires continuous flocculent addition ▪ require a large area for installation and operation ▪ flocculants remain in the system after treatment which can result in formation problems ▪ flocculants also retain contaminants on the machine fabrics, resulting in difficulty in cleaning the fabric and the fabric will therefore have to be replaced more frequently ▪ very sensitive to process upsets

Considering the above information from **Table 7-5** to **Table 7-7**, the Petax™ fine filtration system from Kadant has been selected as a suitable regeneration nit to applied to tissue machine number one. It has been successfully applied to a tissue mill in the Negev desert with increasing popularity in application (**section 7.1.5**). These units are capable of processing up to 240.0 kℓ.h^{-1} with a feed suspended solids content in the range of 100 mg.ℓ$^{-1}$ to 2000 mg.ℓ$^{-1}$ (Kadant, 2011). The filtrate is less than 20 mg.ℓ$^{-1}$ and is achieved without the addition of chemical flocculants, fibre sweetening stock or precoats.

> *...In additions to the reduction in fresh water consumption, the reduction of fines in circulation can result in a decrease of COD from the paper machine of up to 40 %... Kadant, 2011*

Dissolved air flotation units can provide the same clarifying potential as the Petax™, but the Petax™ is more cost effective. Its operating cost is about one-fifth that of the DAF operating cost (McGowan, 2002).

McGowan (2002) describes the following advantages of the Petax™ fine filtration system:

- reduced mill operating costs
- lower fresh water consumption
- lengthened machine fabric life
- minimising sewage disposal costs

This system has been successfully applied in Austria for the past 4 years.

Membrane processes are quickly becoming an attractive process equipment choice with regards to the regeneration of process water. Food and textile industries have successfully implemented microfiltration and ultrafiltration units which have allowed total reuse of process water. It has been discussed by GEA Process Engineering Inc. (2011) that microfiltration units provide a more cost effective solution compared to conventional clarifiers.

Microfiltration units are aimed at operating in particle size ranges between 0.02μm to 10μm. **Table 7-8** describes various pulp fibre dimensions:

Table 7-8: Properties of North American pulpwoods (Smook, 1992):

Species	Fibre length (mm)	Fibre diameter (μm)
Southern region		
Longleaf pine	4.9	35-45
Shortleaf pine	4.6	35-45
Loblolly pine	3.5	35-45
Slash pine	4.6	35-45
Northern region		
Black spruce	3.5	25-30
White spruce	3.3	25-30
Jack pine	3.5	28-40
Balsam fir	3.5	30-40
Northwest region		
Douglas-Fir	3.9	35-45
Western Hemlock	4.2	30-40
Redwood	6.1	50-65
Red Cedar	3.5	30-40
Harwood		
Aspen	1.04	10-27
Birch	1.85	20-36
Beech	1.20	16-22
Oaks	1.40	14-22
Red gum	1.70	20-40

The mill uses a combination of southern and northern pine and eucalyptus as its virgin fibre source therefore the fibre length and diameters will be similar to that of softwoods and hardwoods described in **Table 7-8**. Recycled-fibre dimensions will be smaller than that of the softwood species because due to repeated processing, it results in shortening of the fibres.

In reference to **Figure 7-1**, **Table 7-3** and **Table 7-8**, microfiltration provides an attractive option for regeneration. Therefore a microfiltration unit will be able to produce the desired clarification of the process water.

All details of successful operation in other industries as well as in the paper industries are detailed in **section 7.1.4**.

7.4 Conclusion

The degree of regeneration required was discussed in **section 7.2**. It was determined by using various water cascade analyses that a fine-filtration unit would be required for tissue machine number one (**Figure 7-7**) and a microfiltration unit would be required for tissue machine number two. Considering all available information regarding regeneration unit capabilities required for each of the tissue machines and the pinch points determined in **Chapter 6**, the regeneration units assumed to be applied in the process for the purpose of the water cascade analysis were the Petax™ for tissue machine number one and a microfiltration membrane for tissue machine number two. The regeneration duties were required in order to apply appropriate source-sink reallocations into the fresh water region and regenerated water region in order to apply the ultimate flowrate targeting technique. The calculations described in **Table 6-1** were then conducted on tissue machine number one and tissue machine number two assuming the application of the new regeneration units; the results thereof will be discussed in detail in **Chapter 8.**

Chapter 8 Application of the ultimate flowrate targeting technique with the selected regeneration units

In this section, the regeneration units selected in **Chapter 7** were assumed to be applied to each of the tissue machines. This was done because the regeneration unit outlet concentration was required for appropriate reallocations into the fresh water region and regenerated water region as described by Ng et al. (2009) (**Chapter 4**) in order to perform the ultimate flowrate targeting technique. The pinch points for tissue machine one and tissue machine two were determined in **Chapter 6** and the comparisons of results and associated discussion are presented in **Table 6-14**. The data from **Table 6-14** as well as the conclusions drawn from **Figure 7-7** were used to perform the ultimate flowrate targeting technique of Ng et al. (2009) to determine the minimum water usages for each of the tissue machines. The results of the targeting procedure for tissue machine number one and tissue machine number two are discussed in this chapter.

8.1 Tissue machine number one

Various regeneration units were surveyed (**Chapter 7**) and the appropriate unit was selected as the Petax™ fine filtration system. Whilst the Petax™ has the capability to achieve regeneration concentrations well below 20 mg.ℓ^{-1} (**Table 7-4**), 20 mg.ℓ^{-1} was selected as the exit concentration (regeneration concentration) of the regeneration unit. According to Ng et al. (2009), regeneration must occur across or above the pinch in order for there to be a reduction in fresh water consumption. Therefore the pinch stream, that is, the vibrating screen accepts was selected as the stream to be regenerated. Using this, the ability of the method to determine the global pinch point was investigated for the system where current regeneration was considered in the pinch analysis and for the system which does not consider current regeneration but includes an alternate regeneration scheme.

8.1.1 Current regeneration replaced by the Petax™ unit placed at the pinch point

As previously mentioned, the system where none of the existing regeneration was considered examines the operation of tissue machine one without any regeneration units present, therefore the only regeneration was that of the new unit being considered, the Petax™ unit. In this section, the pinch analysis results considering the Petax™ regeneration unit are discussed. The initial pinch results presented in **Chapter 6** were used to determine the stream to be regenerated. This chapter highlights the results obtained by applying the ultimate flowrate targeting technique with the Petax™ regeneration unit.

8.1.1.1 Confirming the ability of the ultimate flowrate targeting technique to determine the global pinch point of a multiple pinch point problem

In **Chapter 6** the pinch point for tissue machine number one was determined to be the vibrating screen accepts for both the normal and worst case operating conditions. The next step in the pinch analysis was to confirm if the pinch point determined by the pinch analysis method was indeed the global pinch point or was it a local pinch point. According to Ng et al. (2009), this method is accurate in determining a global pinch point for a multiple pinch problem without iterative calculations.

The entire pinch stream, the vibrating screen accepts, was assumed to be regenerated to determine if the global pinch point has been identified. Therefore assuming that a Petax™ unit was present as the regeneration unit in the system and that it produces a process water source at 20 mg.ℓ^{-1} and removing vibrating screen accepts as a source (because this will be regenerated by the Petax™), the water cascade analysis was re-performed on tissue machine number one. The results from the water cascade analyses are available in **Table 8-1** and **Table 8-2** and **Figure 8-1** to **Figure 8-3**; data from these tables have been extracted from **Appendix G**.

Table 8-1: Confirming the global pinch point on tissue machine number one under normal operating conditions for the system where current regeneration replaced by the Petax™ unit.

Results from the water cascade analysis – Confirming global pinch	
Pinch causing streams	Effluent to drain
Pinch flow rate	13.83 ℓ.min^{-1} (0.3800 kℓ.ton^{-1} tissue manufactured)
Pinch concentration	1000,000 mg.ℓ^{-1}
Minimum fresh water required	275.2 ℓ.min^{-1} (7.530 kℓ.ton^{-1} tissue manufactured)
Current fresh water usage – Minimum fresh water usage	13.47 kℓ.ton^{-1} tissue manufactured

According to Ng et al. (2009), the stream selected for regeneration should be, but does not necessarily have to be, the pinch causing stream but that the regeneration must occur across or above the pinch point and that the flowrate to be regenerated to be taken from a net surplus at a given concentration level. This occurred for this pinch point and therefore the selection of the pinch point for regeneration was appropriate. It was assumed that the entire stream was regenerated; the result was that the pinch point shifts to the effluent stream. This was expected as the effluent stream should now limit the reuse of water in the system because it was required to be discharged to drain. Both the fresh water and effluent flowrates have been reduced. Therefore this method was accurate in determining the global pinch point in a multiple pinch system. If the water cascade analysis was not accurate in determining the global pinch point of a multiple pinch problem then when the regeneration of the initial pinch stream was assumed, the pinch point would shift to another source and not the effluent stream. This is a quick step in verifying if the initial water cascade has been performed correctly. If it has not, then the pinch point will shift to another source rather than the effluent stream. Therefore one can rectify any faults before continuing with the pinch analysis.

The same concept was also applied to the hypothetical worst case operation; results from the water cascade analysis are presented in **Table 8-2**. Following the calculation procedure applied for normal operating conditions, for worst case operation, the pinch shifted to the effluent stream (as it did for the normal operating conditions); therefore the water cascade analysis was accurate, once again, in determining the global pinch point of a multiple pinch point problem. There was an increase in the fresh water flowrate for the worst case operation, as compared to normal operating conditions. This was expected because more fresh water will be required to compensate for the poorer quality process water available to the system (as described in **Chapter 6**). Both the fresh water and effluent flowrates have been reduced as compared to **Figure 6-2.**

Table 8-2: Confirming the global pinch point on tissue machine number one under worst case operating conditions for the system where current regeneration replaced by the Petax™ unit.

Results from the water cascade analysis – Confirming global pinch	
Pinch causing streams	Effluent to drain
Pinch flow rate	19.51 ℓ.min^{-1} (0.5400 kℓ.ton^{-1} tissue manufactured)
Pinch concentration	1000,000 mg.ℓ^{-1}
Minimum fresh water required	298.3 ℓ.min^{-1} (8.160 kℓ.ton^{-1} tissue manufactured)
Current fresh water usage – Minimum fresh water usage	12.84 kℓ.ton^{-1} tissue manufactured

8.1.1.2 Reallocations of sinks and sources into the fresh water region and the regenerated water region to obtain minimum fresh water, regenerated water, and effluent flowrates

Two different types of reallocations were conducted, that is, the first reallocation (fresh water region 1 and regenerated water region 1) considered the reallocation procedure of Ng et al. (2009); aside from this, another reallocation (fresh water region 2 and regenerated water region 2) were investigated to determine if the reallocation procedure of Ng et al. (2009) does indeed result in the minimum water targets for fresh water, regenerated water and effluent flowrates.

For the fresh water region 1-regenerated water region 1 reallocation, all sources and sinks below the regenerated source concentration are found in the fresh water region and those above, in the regenerated water region. Sinks in the fresh water region recieved fresh water and those in the regenerated water received regenerated and process water; it was just the split between the fresh water region and the regenerated water region at the regeneration concentration with no further shifting.

For the fresh water region 2- regenerated water region 2 reallocation, sources and sinks are reallocated in the fresh water region such that sources and sinks are balanced irrespective of whether fresh water was required by the sink in the fresh water region, that is, streams in the fresh water region can be supplied by a combination of process and fresh water.

The sources and sinks were kept together (as described in **section 6.1**) to avoid unrealistic matching of streams. This means that in the method of Ng et al. (2009) was applied in the reallocation however if in terms of the material balance, only a portion of a particular source had to be shifted into various regions, the source was shifted entirely. This was done because in the mill, practically it is ideal to keep the various sources as a single flow rather than splitting the flow. This was due to the cost implications associated with splitting the various sources.

The comparison between these reallocations was used to give an indication as to which targets should be used to develop a water network to achieve the minimum targets.

The results of the various reallocations are represented in **Figure 8-1** to **Figure 8-2**. The corresponding water cascade tables are available in **Appendix G.**

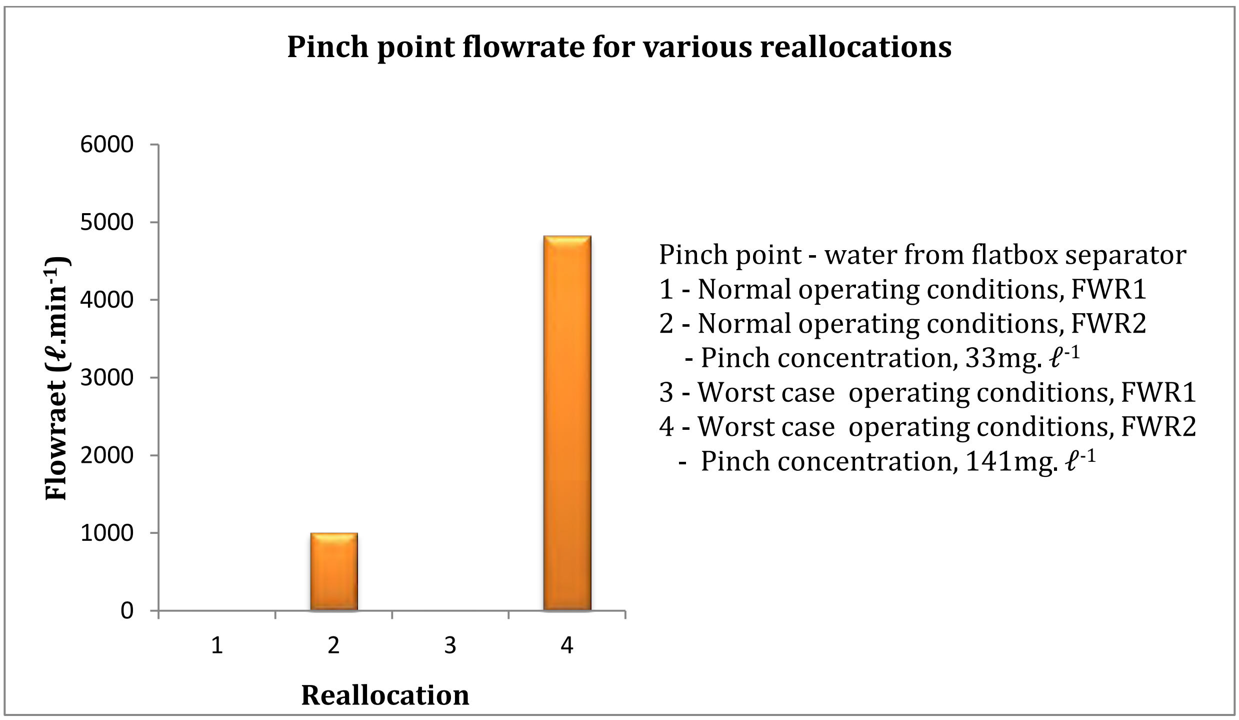

Figure 8-1: Pinch point flowrate in fresh water region depending on the reallocation of sources and sinks in the region for both normal and worst case operation

From **Figure 8-1** it is observed that a pinch point occurs for the second reallocation (fresh water region 2) in the fresh water region for both the operating and worst case operating conditions. The reallocation into the fresh water region and the regenerated water region was only to determine minimum fresh water, regenerated water and effluent flowrates and should not result in another pinch point in either of these regions. Therefore the first reallocation (fresh water region 1) as described by Ng et al. (2009) was the correct reallocation procedure to determine minimum water targets.

The next comparison was made between the fresh water flowrate for each of the reallocations.

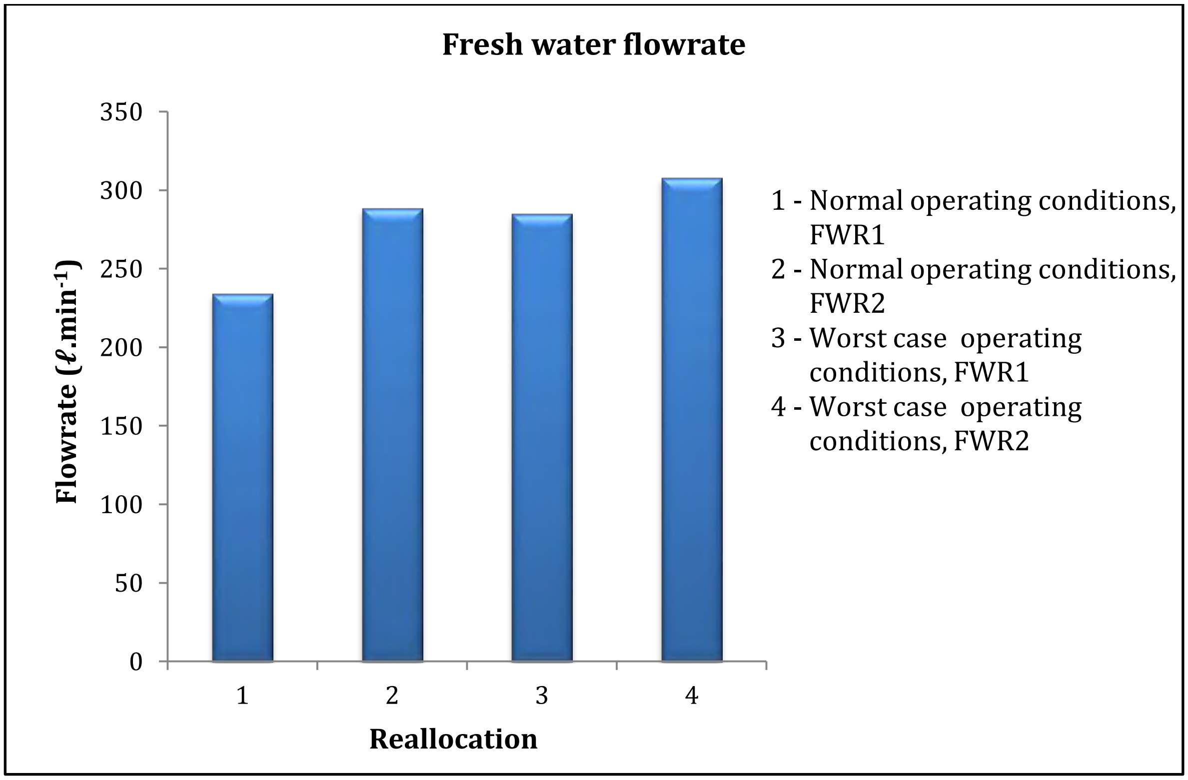

Figure 8-2: The fresh water flowrate for the fresh water regions for both operating and worst case operation

Comparing the fresh water requirement between each reallocation and between normal and worst case operating conditions, it is observed from **Figure** 8-2 that the fresh water requirement was lower for the initial reallocation, that is, fresh water region 1, for both normal and worst case operation (this was the reallocation procedure as described by Ng et al., 2009). The fresh water requirement was higher for fresh water region 2 indicating that this reallocation of the sources and sinks was not an efficient reallocation. The fresh water required under worst case operation was greater than that required for normal operation. The fresh water requirement was also higher for fresh water region 2 because in this reallocation there were more demands in fresh water region 2 as compared to fresh water region 1, therefore more fresh water was required to meet the demands at the acceptable contaminant concentration. All fresh water region and regenerated water region water cascade tables are available in **Appendix G.**

Whilst there was an excess of a sources in the regenerated water region 1 by 84 $\ell.min^{-1}$ it was not practical to shift the sources into fresh water region 1 because there was no demand for the source to satisfy; also further reallocation would be inefficient because streams which do not need fresh water would be catered for by an increased fresh water consumption.

The fresh water requirement for fresh water region 2 (worst case operation) was higher than that of fresh water region 1 (worst case operation) as well as the corresponding fresh water region 2 for normal operating conditions. This was because, as previously discussed, more fresh water will be required to compensate for the poorer quality process water (higher level of contaminants) available to the system. The fresh water requirement was also higher because in this reallocation of fresh water region 2, there are more demands in fresh water region 2 as compared to fresh water region 1, therefore a greater quantity of fresh water was required to meet the demands at the acceptable contaminant concentration (**Chapter 2**) in fresh water region 2.

Under normal operating conditions, there was a 23 % increase in fresh water requirement if the reallocation of fresh water region 2 was used.

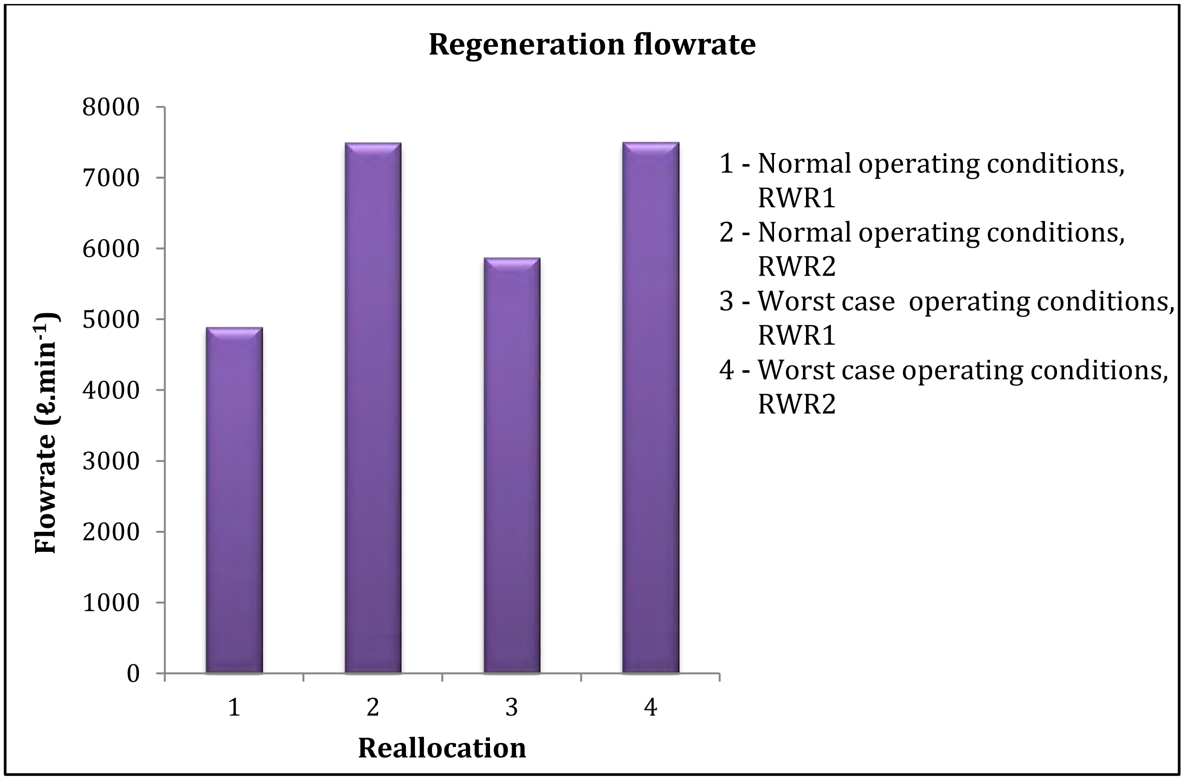

Figure 8-3: The regenerated water flowrate for the regenerated water regions for both operating and worst case operation

In comparison to regenerated water region 1 (normal and worst case operation) there was an increase in the minimum regeneration flowrate for regenerated water region 2 (normal and worst case operation). This occurred because in the second reallocation, sources which were previously available in the regenerated water region were shifted to the fresh water region, resulting in less sources available in regenerated water region 2 to meet the demand flowrates in regenerated water region two; thus a higher regenerated water flowrate was required to meet the sink flowrates at the acceptable contaminant concentrations (**Chapter 2**).

The regeneration flowrate required increased for the hypothetical worst case operating conditions as expected because more regenerated water was required to mitigate the adverse effect of the poorer quality process water produced by the system.

A larger number of regeneration units will be required for regenerated water region 2 (normal and worst case operation) because of the higher regeneration flowrate required in regenerated water region 2 as compared to regenerated water region 1 (for normal and worst case operation).

The disadvantage of this method is that when it determines the minimum regeneration flowrate it does not take into account which stream will be regenerated to meet this minimum regeneration target. It therefore results in an inaccurate representation of the effluent flowrate. If this method is applied elsewhere, careful note must be taken to keep that in mind.

A comparison was done between the effluent water produced from the system for each of the different reallocations under normal operating conditions und worst case operating conditions. The results from the water cascade analyses are presented in **Figure 8-4**.

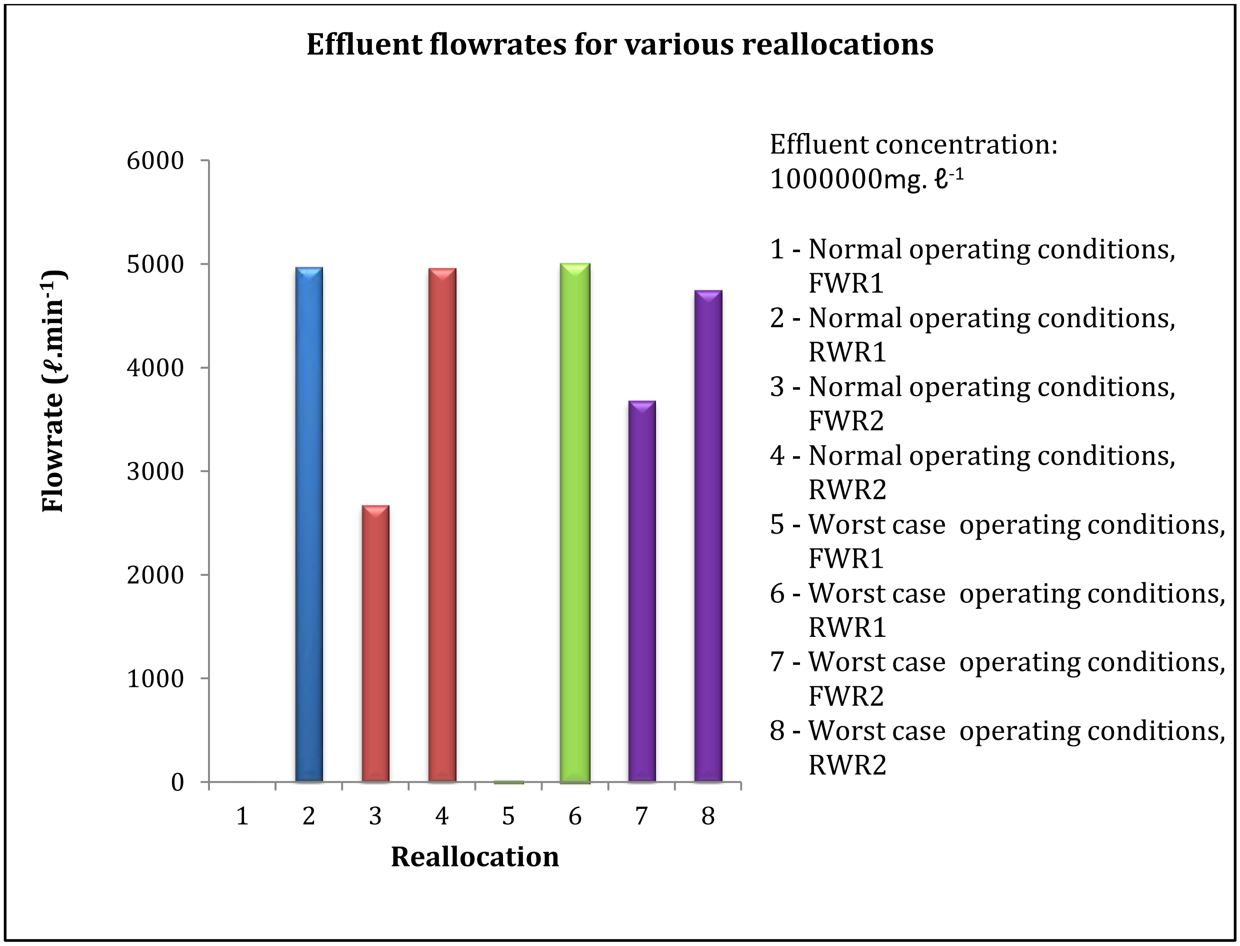

Figure 8-4: Effluent flowrate depending on the reallocation of the sources and sinks in the fresh water region and regenerated water region

It was observed from **Figure 8-4** (the water cascade tables are available in **Appendix G**) that for the reallocation procedure of Ng et al. (2009), the effluent flowrate from the fresh water region (fresh water region 1) was negligible for both normal and worst case operation. However, the effluent flowrate for fresh water region 2 for both normal and worst case operation was higher than that of fresh water region 1. The effluent flow in fresh water region 1 (both normal and worst case operation) was very small because just enough fresh water was supplied to meet the fresh water demand.

The effluent flowrate from regenerated water region 1 for normal and worst case operation are similar, with the effluent from regenerated water region 1 for the worst case operation being slightly lower than that of the normal operation; this was because water was lost in greater amounts elsewhere in the system during worst case operation, such as excess rejects from the system, due to the inefficient operation. The same applied for the effluent from regenerated water region 2 for worst case operation in reference to regenerated water region 2 for normal operation.

The effluent flowrate, under all operating conditions and reallocations, appears to be high and appears to not correlate from the material balance perspective but this was because (1) the method assumes that a source will not be used to meet a demand which has an allowable concentration lower than that of the source and therefore will be sent to effluent treatment and (2), the method does not remove the regenerated flowrate from the stream being regenerated which results in an unrealistic representation of the effluent flowrate.

Comparing the combined effluent flowrates of the fresh water region and regenerated water region, it was observed that the lower effluent flowrate was obtained for the reallocation procedure of Ng et al. (2009) (fresh water region 1 and regenerated water region 1). Therefore it does indeed produce the minimum target for effluent flowrate.

Comparing the combined effluent flow from fresh water region 1 and regenerated water region 1 with that of fresh water region 2 and regenerated water region 2, for both normal and worst case operation, the effluent flowrate was lower for the first reallocation system. This shows that the reallocation procedure of Ng et al. (2009) is accurate in determining the minimum fresh water, effluent and regeneration flowrates.

8.1.1.3 Conclusion

This section highlights the ability of the ultimate flowrate targeting technique (Ng et al., 2009) to determine the minimum fresh water, regenerated water and effluent flowrates for a particular process system. Considering the lower fresh water, regenerated water and effluent flowrate for fresh water region 1 and regenerated water region 1, this reallocation scenario was considered for the water network synthesis. Therefore the targets obtained for fresh water region 1 and regenerated water region 1 were used for the water network synthesis. The water networks developed to meet the water targets are described in **Chapter 9**.

8.1.2 Current (existing) regeneration of process water in the tissue making process was considered with the Petax™ regeneration unit placed at the pinch point

A comparison between a new system and the current was required in order to confirm that regeneration unit selected will operate under the varied conditions and to determine which system (current or new) would be the most effective to reduce the specific water consumption. The comparison between the two systems will determine whether it will be feasible to remove existing regeneration and replace it with a new unit placed at the pinch point or to leave the system with the current regeneration scheme. As explained in **section 6.2.2**, this section discusses the water pinch analysis for the system which includes existing regeneration units in the system, that is, the dissolved air flotation was included in the pinch analysis together with the Petax™ regeneration unit.

8.1.2.1 Confirming the ability of the ultimate flowrate targeting technique to determine the global pinch point of a multiple pinch point problem

For the purpose of the pinch analysis, as for **section 8.1.1**, the entire pinch causing stream, that is, the vibrating screen accepts was assumed to be regenerated to determine if the global pinch point has indeed been identified. Therefore assuming that a Petax™ unit was in the system and produced a regenerated water source at 20 mg.ℓ^{-1} and removing vibrating screen accepts as a source, the water cascade analysis was re-performed. The results are available in **Table 8-3** and **Table 8-4** and **Figure 8-5 to Figure 8-7**; data from these tables have been extracted from **Appendix G, section G.1**.

It was determined in **Chapter 6** that the pinch point for the existing regeneration scheme of the process water was also the vibrating screen accepts (as determined for the **section 8.1.1**). It was required to confirm that the pinch point determined was the global pinch point for a multiple pinch problem. According to Ng et al. (2009), this method is accurate in determining a global pinch point without iterative calculations.

The regeneration concentration of the Petax™ unit was assumed to be 20 mg.ℓ^{-1} for reasons previously discussed in **section 7.2** and **section 7.3**. Regeneration must occur across or above the pinch point in order for there to be a reduction in fresh water consumption as well as a reduction in the effluent flowrate and the regeneration flowrate. Therefore the pinch point was assumed to be regenerated. Using this, the ability of the method to determine a global pinch point was investigated for both normal and worst case operation (as in **section 8.1.1**).

Assuming that the pinch point was regenerated, the water cascade analysis was re-performed for both normal and worst case operating conditions, the results of which are available in **Table 8-4** and **Table 8-5**, all data has been extracted from **Appendix G**.

Table 8-3: Confirming the global pinch point on tissue machine number one under normal operating conditions for the system where the existing regeneration scheme of the process water with the Petax™ was considered

Results from the water cascade analysis – Confirming global pinch	
Pinch causing streams	Effluent to drain
Pinch flow rate	13.87 ℓ.min^{-1} (0.3800 kℓ.ton^{-1} tissue manufactured)
Pinch concentration	1000,000 mg.ℓ$^{-1}$
Minimum fresh water required	361.9 ℓ.min^{-1} (8.676 kℓ.ton^{-1} tissue manufactured)
Current fresh water usage – Minimum fresh water usage	12.32 kℓ.ton^{-1} tissue manufactured

Table 8-4: Confirming the global pinch point on tissue machine number one under worst case operating conditions for the system where the existing regeneration scheme of the process water with the Petax™ was considered

Results from the water cascade analysis – Confirming global pinch	
Pinch causing streams	Effluent to drain
Pinch flow rate	19.83 ℓ.min^{-1} (0.5400 kℓ.ton^{-1} tissue manufactured)
Pinch concentration	1000,000 mg.ℓ$^{-1}$
Minimum fresh water required	364.5 ℓ.min^{-1} (8.748 kℓ.ton^{-1} tissue manufactured)
Current fresh water usage – Minimum fresh water usage	12.25 kℓ.ton^{-1} tissue manufactured

The entire vibrating screen accepts flowrate was assumed to be regenerated. The result was that the pinch point shifted. This was expected as the effluent stream should now limit the reuse of water in the system because it was required to be discharged to drain.

Both the fresh water and effluent flowrates have been reduced (for both the normal and worst case operating conditions). Therefore the method was accurate in determining the global pinch point in a multiple pinch point system. The fresh water requirement and the effluent flowrate were greater under worst case operation; this was expected because more fresh water will be required to meet the demands at the allowed contaminant concentrations because the sources available have a higher contaminant concentration under worst case operation. The effluent flowrate was greater because more water cannot be used because it had a high contaminant concentration and would be required to be discharged to effluent treatment.

Whilst in the practical application, the entire pinch stream will not be regenerated, assuming the regeneration of the entire stream allows the confirmation of the global pinch point determination of the method of Ng et al. (2009). This is a quick verification of whether the initial water cascade has been performed correctly. If it has not been performed correctly then the pinch point will shift to another source after the initial pinch point has been treated rather than shifting to the effluent stream. This can be corrected before continuing with the pinch analysis.

8.1.2.2 Reallocations of sinks and sources into the fresh water region and the regenerated water region to obtain minimum fresh water, regenerated water, and effluent flowrates

The procedure followed in **section 8.1.1.2** was applied to this system where existing regeneration units together with the Petax™ fine filtration unit were considered in the pinch analysis.

The same reallocation procedure described for fresh water region 1 – regenerated water region 1 and fresh water region 2 – regenerated water region 2, as described in **section 8.1.1.2**, was applied. Fresh water region 1 – regenerated water region 1 applies to the reallocation procedure of Ng et al. (2009).

The comparison between these reallocations was used to give an indication as to which targets should be used to develop a water networks (**Chapter 9**) to achieve the minimum targets. It gives an indication of how the water networks at the mill should be configured in comparison to the current configuration.

The water cascade analysis was re-performed for the fresh water region and regenerated water region. The results of which are presented in **Figure 8-5** to **Figure 8-8**.

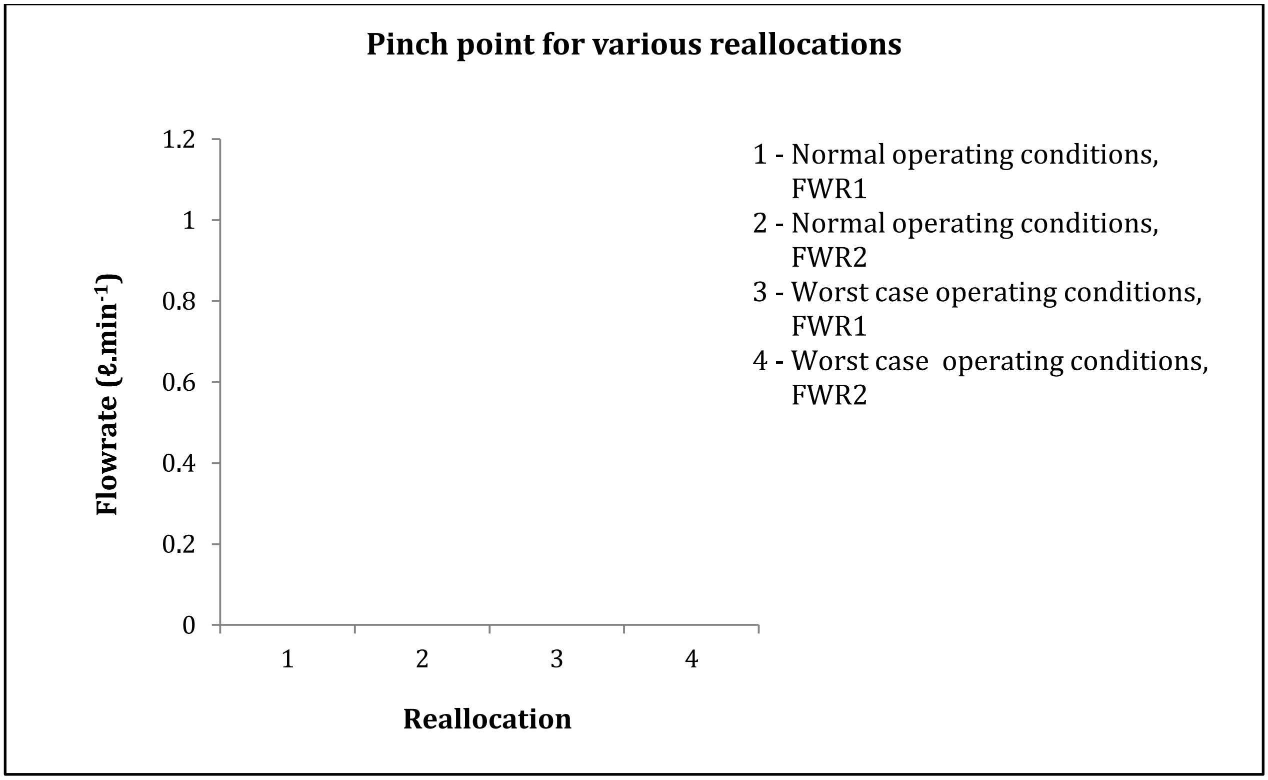

Figure 8-5: Pinch point flowrate in fresh water region depending on the reallocation of sources and sinks in the fresh water region

For the system where none of the existing regeneration was considered, a pinch point was observed in fresh water region 2 at the water leaving the flat-box separator (**Figure 8-1**). This did not occur in the existing regeneration scheme (**Figure 8-5**) because the dissolved air flotation unit regenerated water was now considered as a source in fresh water region 2 which meets the demands in the fresh water region 2. The dissolved air flotation unit source was reallocated to the fresh water region because regeneration was considered across the pinch point at the vibrating screens, therefore a regeneration concentration of 20 mg.ℓ^{-1} was assumed and the dissolved air flotation unit source had a lower contaminant concentration than 20 mg.ℓ^{-1} (**Table 6-9**).

The next comparison was made between the fresh water flowrate for each of the reallocations.

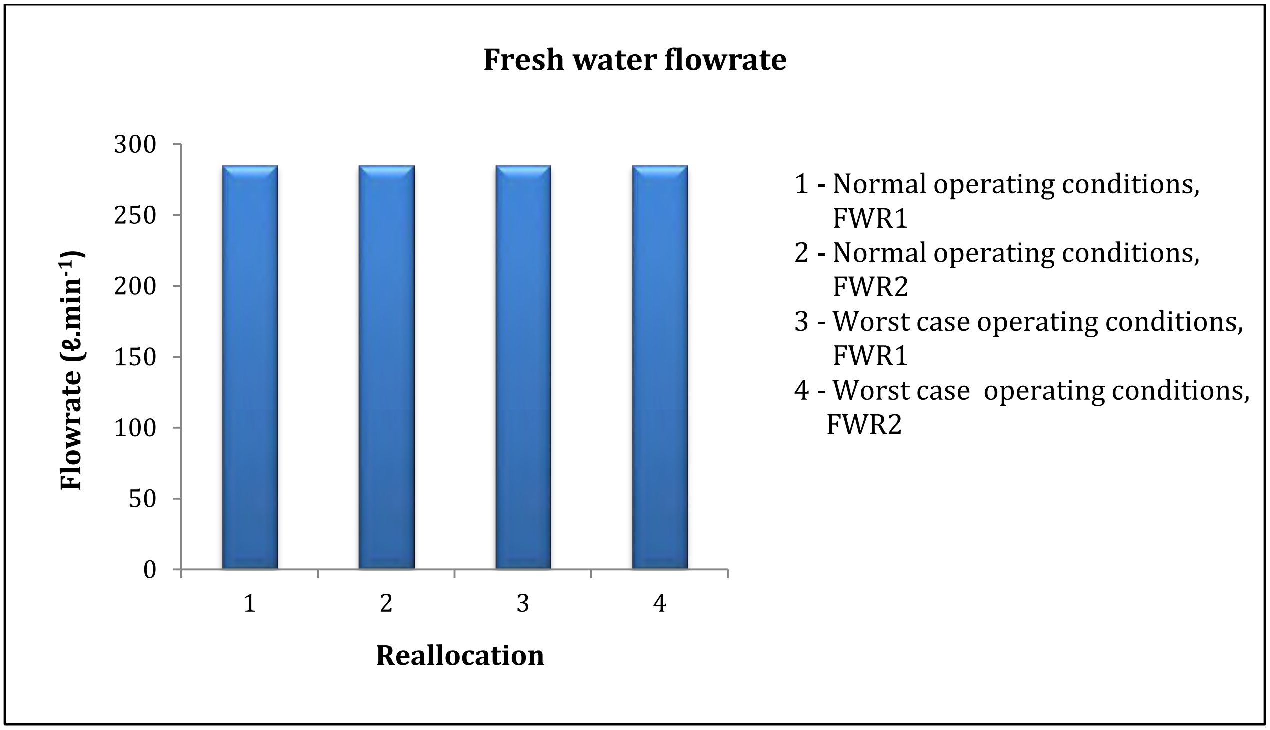

Figure 8-6: The fresh water flowrate for the fresh water regions for both operating and worst case operation

Comparing the fresh water requirement for the existing regeneration scheme for the process water considered (**Figure 8-6**) with that of the system where the regeneration scheme was replaced with the Petax™ unit (**Figure 8-2**); the fresh water requirement was greater for the existing regeneration scheme of the process water with the Petax™ unit added for normal operating conditions. This was because there was a greater fresh water requirement because of the inclusion of the regeneration unit, that is, fresh water was required for the dissolved air flotation unit chemical dosing as well as to account for losses from the system due to evaporation at the Yankee and rejects from the system.

The fresh water requirement remained unchanged for the various reallocations because the dissolve air flotation unit source was included in the fresh water region, therefore fresh water was required only to meet the 0 mg. ℓ^{-1} demands and for fresh water make-up, the rest of the demands are provided for by the water source from the dissolved air flotation unit. Because of the inclusion of regeneration units there was an excess of sources in the fresh water region available to meet the sink flowrate requirements. This resulted in the high effluent flowrate in fresh water region 2 (**Figure 8-8**), in practice these sources will not be sent to effluent but will be reused in the system in regenerated water region 2.

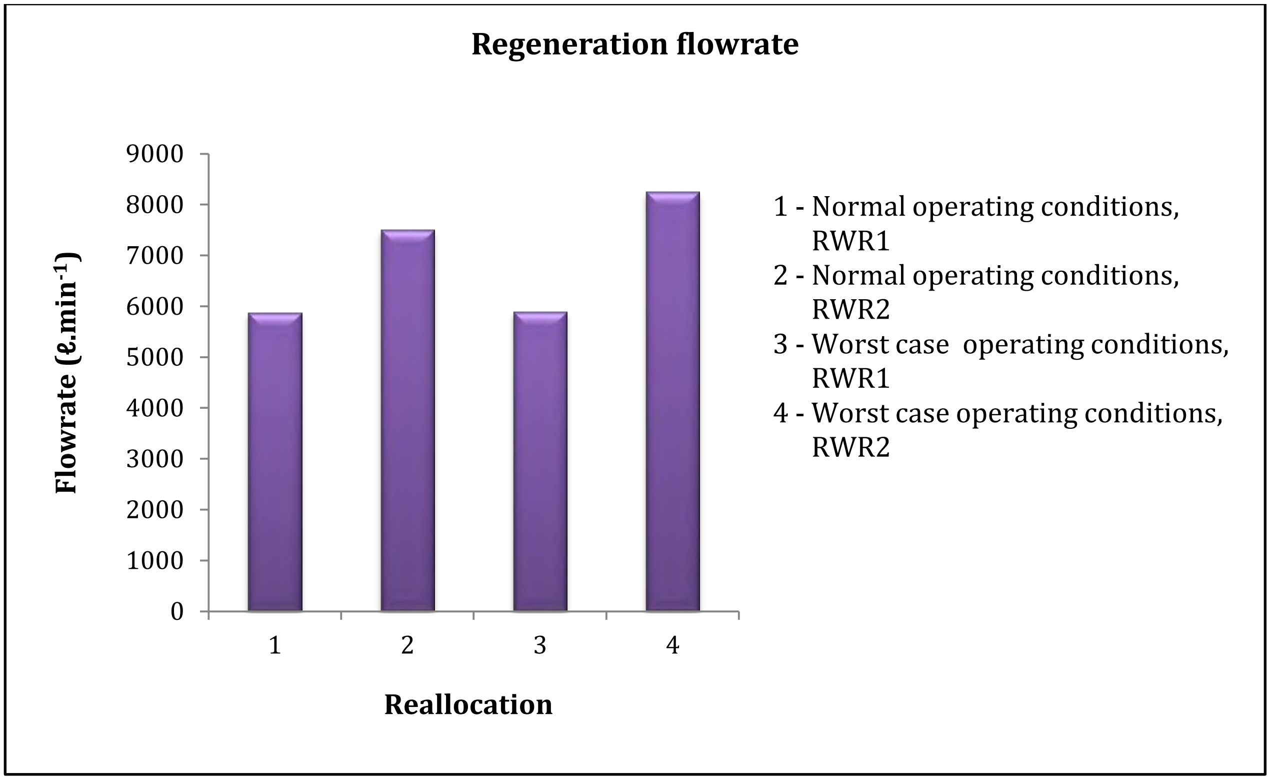

Figure 8-7: The regenerated water flowrate for the regenerated water regions for both operating and worst case operation

In comparison to regenerated water region 1 (normal and worst case operation) there was an increase in the minimum regeneration flowrate for regenerated water region 2 (normal and worst case operation). This occurred because in the second reallocation, sources which were previously available in the regenerated water region were shifted to the fresh water region, resulting in fewer sources available in regenerated water region 2 to meet the demand flowrates; thus a higher regenerated flowrate was required to meet the sink flowrates at the acceptable contaminant concentrations.

The regeneration flowrate required increased for the hypothetical worst case operating conditions as expected because more regenerated water was required to mitigate the effect of the poorer quality process water produced by the system.

The higher regeneration flowrate required in regenerated water region 2 (normal and worst case operation) will result in more regeneration units being required as compared to regenerated water region 1 (normal and worst case operation) because of the limited capacity of each regeneration unit.

The regeneration flowrates for the system where existing regeneration of the process water was considered with the Petax™ unit was higher than the corresponding flowrates for the system where the current regeneration was replaced with the Petax™ unit (**Figure 8-3**).

The disadvantage of this method is that when it determines the minimum regeneration flowrate it does not take into account which stream will be regenerated to meet the calculated minimum regeneration target. It therefore results in an inaccurate representation of the effluent flowrate. If this method is applied elsewhere, careful note must be taken to keep that in mind.

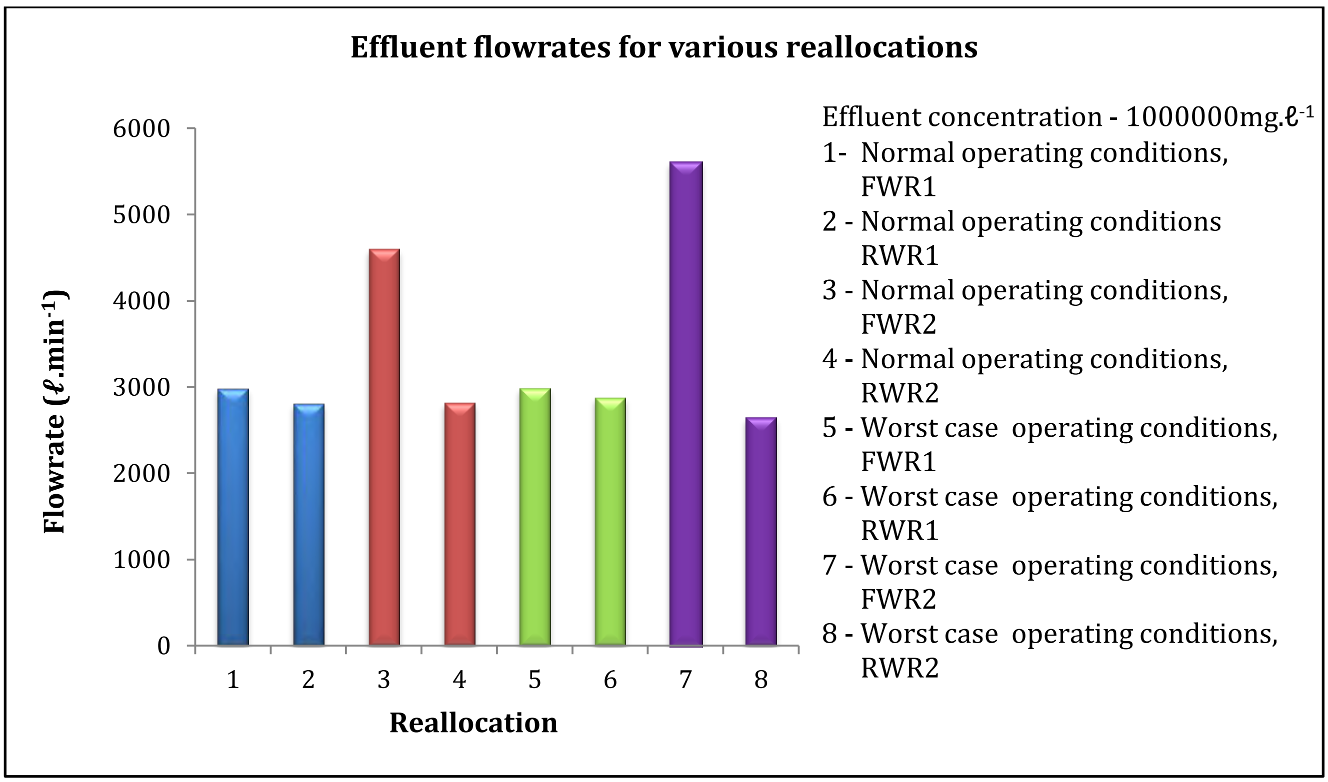

Figure 8-8: Effluent flowrate depending on the reallocation of the sources and sinks in the fresh water region and regenerated water region

A comparison was done between the effluent flowrates produced from the system for each of the different reallocations under normal operating conditions und worst case operating conditions. It is observed from **Figure 8-8** that for the reallocation procedure of Ng et al. (2009), the effluent flowrate from the fresh water region (fresh water region 1) was much higher than that in **Figure 8-4** in the system where the Petax™ unit replaced the existing regeneration for both normal and worst case operation. This occurred because the dissolved air flotation unit water source was included in the fresh water region 1 and there were no other demands in the region except the fresh water demands, the method therefore assumes that this water will be sent to effluent treatment; in reality this will be reused in the process. Therefore this increases the fresh water required and the effluent removed from the system which is an incorrect solution.

The effluent flowrate from regenerated water region 1 for normal and worst case operation were similar, with the regenerated water region 1 for the worst case operation being slightly lower than that of the normal operation; this was because water was lost in greater amounts elsewhere in the system due to the inefficient operation, such as rejects from the cleaners; this also applied to regenerated water region 2 for worst case operation, in reference to regenerated water region 2 for normal operation. However, even if these flows vary during operation it will not significantly affect he pinch point because these sink streams have high contaminant concentrations and will not be supplied by the sources which impact on the pinch.

The effluent flowrates for fresh water region 2 (both normal and worst case operating conditions) was greater than that of fresh water region 1. This was due to more sources and sinks being reallocated into the fresh water region 2. The effluent flowrate for fresh water region 2 under worst case operation was very high because the process water sources are available at higher contaminant concentrations and therefore considered unsuitable to meet the demands in the fresh water region and was considered by the method, to be delivered to effluent treatment. In practice, these sources will be reused in the process.

The effluent flowrate, under all operating conditions and reallocations, appears to be high but this was because the method assumes that a source will not be used to meet a demand which has an allowable concentration lower than that of the source and therefore will be sent to effluent treatment. In practice a combination of higher purity and lower purity sources will be used to satisfy a particular demand.

Therefore comparing the combined effluent flowrates of the fresh water region and regenerated water region, it was observed that the lower effluent flowrate was obtained for the reallocation procedure of Ng et al. (2009). Therefore it does indeed produce the minimum target for effluent flowrate.

In comparison to the corresponding reallocations for the system where the current regeneration was replaced by the Petax™ unit (**Figure 8-4**), the system with existing regeneration and the Petax™ unit (**Figure 8-8**) had a lower effluent flowrates. This was because in the system where existing regeneration and the Petax™ unit was investigated, more water was reused in the system due to the increased regenerated process water because of the inclusion of the regeneration units.

Therefore if one considers the various reallocations considered; it is clear that when the reallocation procedure is not performed correctly, it results in inaccurate fresh water and regenerated water required and effluent removed from the system. This implication of this is that an intervention scheme designed around these incorrect targets will therefore be ineffective. Therefore it is essential that the reallocation procedure as described by Ng et al. (2009) be performed correctly.

Comparing the combined effluent flow from fresh water region 1 and regenerated water region 1 with that of fresh water region 2 and regenerated water region 2, for both normal and worst case operation, the effluent flowrate was lower for the first reallocation system. This shows that the reallocation procedure of Ng et al. (2009) was accurate in determining the minimum fresh water, effluent and regeneration flowrates.

Considering the lower fresh water and regenerated water required for fresh water region 1 and regenerated water region 1, this reallocation scenario was considered for the water network synthesis. Therefore the targets obtained for fresh water region 1 and regenerated water region 1 were used for the water network synthesis. This also indicates that the reallocation procedure of Ng et al. (2009) was accurate in determining the minimum fresh water, effluent and regeneration flowrates.

8.1.3 Conclusions – targeting procedure for tissue machine number one

- From the targeting performed in **section 8.1.1** and **section 8.1.2**, it has been determined that the system where current regeneration was replaced by the Petax™ unit resulted in lower fresh water and regenerated water targets than the current regeneration scheme together with a Petax™ unit. Therefore consideration should be given to replacing the existing regeneration scheme with the system proposed by the pinch analysis where the existing regeneration scheme was replaced by the Petax™ unit.

- It has been concluded that the reallocation procedure for the fresh water region and regenerated water region described by Ng et al. (2009) does indeed produce the absolute minimum water targets.
- There will be an increased fresh water and regenerated water requirement under worst case operating conditions to compensate for (mitigate the effect of) the poorer quality process water such that demands can be supplied at the allowable process water quality; this was considered in the water network synthesis.

8.2 Tissue machine number two

In **Chapter 7** various applicable regeneration units were discussed and it was determined in **section 7.3**, that a microfiltration unit would be required for tissue machine number two in order to achieve the required regeneration of the pinch stream identified in **Chapter 6**. According to Ng et al. (2009), regeneration must occur across or above the pinch point in order for there to be a reduction in the fresh water consumption. Therefore the pinch stream, that is, the water from the main vacuum separator or the vacuum pumps, was selected for regeneration. It was assumed that all total suspended solids were removed from the pinch stream by the microfiltration unit, that is, a regenerated water source of 0 mg.ℓ^{-1} was available after regeneration.

The procedure described in **section 8.1** for tissue machine number one was applied to tissue machine number two. The full results tables and figures are available in **Appendix J**. This section will highlight the important findings from the pinch analyses performed. Details can be viewed in **Appendix J**.

Two different regeneration schemes were considered (as in **section 8.1**), one where current regeneration was replaced by a microfiltration unit placed across the pinch point and the other where the current regeneration scheme remains and the microfiltration unit placed across the pinch point was added to the system.

8.2.1 Current regeneration replaced by a microfiltration unit at the pinch point

In this section, the pinch analysis results for the system where the existing regeneration was replaced by the microfiltration regeneration unit are discussed. The initial pinch results presented in **Chapter 6** were used to determine the stream to be regenerated. This chapter highlights the results obtained by applying the ultimate flowrate targeting technique with the microfiltration regeneration unit.

8.2.1.1 Confirming the ability of the ultimate flowrate targeting technique to determine the global pinch point of a multiple pinch point problem

In **Chapter 6** the pinch point for tissue machine number two was determined to be the main vacuum separator or the vacuum pumps for normal operating conditions and worst case operating conditions respectively. The next step in the pinch analysis was to confirm if the pinch point determined by the pinch analysis method was indeed the global pinch point or a local pinch point. According to Ng et al. (2009), this method is accurate in determining a global pinch point for a multiple pinch problem without iterative calculations.

Various regeneration units were investigated (**Chapter 7**) and considering that the pinch concentration was 6 mg.ℓ^{-1} (which was a very low contaminant concentration), in order to achieve the required regeneration to 0 mg.ℓ^{-1} a microfiltration membrane unit was needed (**section7.3**).

The entire pinch stream, the water from the main vacuum separator and single breast roll chamber, was assumed to be regenerated to determine if the global pinch point has indeed been identified. Therefore assuming that a microfiltration unit was in the system, it produced a process water source with contaminant concentration of 0 mg.ℓ^{-1} and removing the water from the main vacuum separator and SBR chamber as a source, the water cascade analysis was re-performed. The results are available in **Table J-1** and **Table J-2** and **Figure J-1 to Figure J-4**; data from these tables have been extracted from the associated tables in **Appendix G**. Using this, the ability of the method to determine the global pinch point was investigated.

Table 8-5: Tissue machine number two, existing regeneration replaced by microfiltration unit, normal operating conditions, confirming global pinch point determination

Results from the water cascade analysis assuming regeneration of pinch causing stream	
Flow regenerated	The lines leaving the main vacuum separator and the SBR chamber. In reference to **Table** 5-7, this is S2.
Pinch causing streams after regeneration	Effluent to drain
Pinch flow rate	16.55 ℓ.min^{-1} (0.2900 kℓ.ton^{-1} tissue manufactured)
Pinch concentration	1000,000 mg.ℓ$^{-1}$
Minimum fresh water required	763.00 ℓ.min^{-1} (13.19 kℓ.ton^{-1} tissue manufactured)
Current fresh water usage – Minimum fresh water usage	7.810 kℓ.ton^{-1} tissue manufactured

The water cascade table from which the results in **Table 8-5** have been obtained is available in **Appendix G**. According to Ng et al. (2009), the stream selected for regeneration should be, but does not necessarily have to be, the pinch causing stream but that the regeneration must occur across or above the pinch point and that the flowrate to be regenerated to be taken from a net surplus at a given concentration level. This occurs for this pinch point and therefore the selection of the pinch point for regeneration was appropriate. It was assumed that the entire stream was regenerated; the result was that the pinch point shifted to the effluent stream. This was expected as the effluent stream should now limit the reuse of water in the system because it was required to be discharged to drain. Both the fresh water and effluent flowrates have been reduced. Therefore this method was accurate in determining the global pinch point in a multiple pinch system.

If the water cascade analysis was not accurate in determining the global pinch point of a multiple pinch problem then when the regeneration of the initial pinch stream was assumed, the pinch point would have shifted to another source and not the effluent stream. This is a quick step in verifying if the initial water cascade has been performed correctly. If it has not, then the pinch point will shift to another source rather than the effluent stream. Therefore one can rectify any faults before continuing with the pinch analysis.

The same concept was applied to the hypothetical worst case operation; results are available in **Table 8-6**.

Table 8-6: Confirming the global pinch point on tissue machine number two under normal operating conditions for the system where the existing regeneration scheme was replaced with a microfiltration unit

Results from the water cascade analysis assuming regeneration of pinch causing stream	
Flow regenerated	The lines leaving the main vacuum separator and the single breast roll chamber.
Pinch causing streams after regeneration	Effluent to drain
Pinch flow rate	16.55 $\ell.min^{-1}$ (0.2900 $k\ell.ton^{-1}$ tissue manufactured)
Pinch concentration	1000,000 $mg.\ell^{-1}$
Minimum fresh water required	870.0 $\ell.min^{-1}$ (15.03 $k\ell.ton^{-1}$ tissue manufactured)
Current fresh water usage – Minimum fresh water usage	5.97 $k\ell.ton^{-1}$ tissue manufactured

Following the calculation procedure applied for normal operating conditions, for worst case operation, the pinch shifted to the effluent stream (as it did for the normal operating conditions); therefore the water cascade analysis was accurate, once again, in determining the global pinch point of a multiple pinch point problem. There was an increase in the fresh water flowrate for the worst case operation, as compared to normal operating conditions. This was expected because more fresh water will be required to compensate for the poorer quality process water available to the system (as described in **Chapter 6).** Both the fresh water and effluent flowrates were reduced as compared to **Figure 6-2**.

Therefore the method was accurate in determining a global pinch point in a multiple pinch problem. This is a quick step in also verifying of the initial water cascade analysis has been performed correctly. If it has not, then the pinch point will shift to another source stream after the initial pinch causing stream has been treated, rather than shifting to the effluent stream.

8.2.1.2 Reallocations of sinks and sources into the fresh water region and the regenerated water region to obtain minimum fresh water, regenerated water, and effluent flowrates

For tissue machine number two the reallocations into the fresh and regenerated water regions were performed as described for tissue machine number one (**section 8.1.1**). All sources and sinks below a contaminant concentration below 20 mg.ℓ^{-1} are located in fresh water region 1 for the first reallocation, and remaining sources and sinks are located in regenerated water region 1. For the second reallocation, sources and sinks are shifted unit flowrates are exactly balanced in the fresh water region (fresh water region 2) and the regenerated water region (regenerated water region 2).

The sources and sinks were kept together (as described in **section 6.1**) to avoid unrealistic matching of streams. This means that the method of Ng et al. (2009) was applied in the reallocation however if in terms of the material balance only a portion of a particular source had to be shifted into various regions, here, the source was shifted entirely. This was done because in the mill, practically it is ideal to keep the various sources as a single flow rather than splitting the flow. This was due to the cost implications associated with splitting the various sources.

Within these reallocations, further separation occurs. In the fresh water region, the pinch stream can remain as is and not be regenerated or it can be regenerated to 0 mg.ℓ^{-1} total suspended solids. Since fresh water was assumed to be at 0 mg. ℓ^{-1} total suspended solids, the reallocation has been considered with the regenerated source falling into the fresh water region.

The water cascade analyses performed provide some insight to what the fresh water consumption can be depending on the reallocation-regeneration combination. In **Figure J-1** the pinch points occurring are illustrated.

The comparison between these reallocations was used to give an indication as to which targets should be used to develop a water network to achieve the minimum targets.

From **Figure J-1** it was observed that the pinch point remains as the combined flowrate from the main vacuum separator and the single breast roll chamber for both the normal and worst case operating conditions. Therefore it was identified that this was where the regeneration must be focused. A comparison was made between each of the fresh water regions from each reallocation. These fresh water flowrates are available in **Figure J-2**. The fresh water flowrate required under worst case operation was higher than for normal operation (reasons described in **section 8.1.1**)

Figure J-3 indicates the associated regeneration flowrate required for each of the reallocations, it was identified that regeneration will be required irrespective of the reallocation. However the reallocation for fresh water region 1 and regenerated water region 1 results in lower regenerated water required. Therefore existing regeneration units can be used to achieve the required regeneration and no additional cost will be incurred apart from the microfiltration unit required.

Figure J-4 presents the effluent flowrates for each of the fresh water regions and regenerated water regions for both normal and worst case operation. It was determined that the effluent flowrate for the fresh water-regenerated water combinations where no regeneration was considered had a higher effluent flowrate. This was because the method assumes that a source will not be used to meet a demand of higher purity than the source, this cascade's through the analysis resulting in more effluent removed from the system.

Therefore it was determined from the various reallocations and water cascades analysis that the method of Ng et al. (2009) produced the lowest effluent flowrate (as was determined for tissue machine one in **section 8.1.1**).

The effluent flowrate, under all operating conditions and reallocations, appears to be high but this was because the method assumes that a source will not be used to meet a demand which has an allowable concentration lower than that of the source and therefore will be sent to effluent treatment. This must be considered when applying the method such that an inaccurate representation of the targeted flowrates does not occur.

Table 8-7 highlights the results from the water cascade analysis performed applying the method of Ng et al. (2009).

Table 8-7: Results from the reallocation of the sources and sinks into the fresh water region and regenerated water region (by method of Ng et al., 2009) for the system where current regeneration was replaced with a microfiltration unit

Flowrate		Description
Pinch point	:	The lines leaving the main vacuum separator and the single breast roll chamber. In reference to **Table 5-7**, this is S2, with flowrates between 783 ℓ.min^{-1} to 1500 ℓ.min^{-1} at 6 mg.ℓ$^{-1}$ to 42 mg.ℓ$^{-1}$ depending on normal or worst case operation (**Table 6-14)**
Fresh water flowrate	:	763.00 ℓ.min^{-1} (13.19 kℓ.ton^{-1} tissue manufactured) to 870.0 ℓ.min^{-1} (15.03 kℓ.ton^{-1} tissue manufactured) (**Figure J-2**)
Regenerated water flowrate	:	920 ℓ.min^{-1} to 1000 ℓ.min^{-1} (**Figure J-3**)
Effluent flowrate	:	100 ℓ.min^{-1} at 1000,000 mg.ℓ$^{-1}$ (**Figure J-4**)
Reallocation selected for water network synthesis	:	That resulting from the method of Ng et al. (2009)

Therefore comparing the combined effluent flowrates of the fresh water region and regenerated water region, it was observed that the lower effluent flowrate was obtained for the reallocation procedure of Ng et al. (2009), that is fresh water region where the pinch stream was appropriately regenerated and the its' associated regenerated water region 1. Therefore it does indeed produce the minimum target for effluent flowrate. The fresh water, regenerated water and effluent water targets obtained from fresh water region where there was regeneration of the pinch stream and its' regenerated water region were used to develop the appropriate water networks in **Chapter 9**.

8.2.2 Current (existing) regeneration of process water in the tissue making process was considered with the microfiltration unit placed at the pinch point

In this section highlights the results obtained from the water cascade analysis performed for the system where the existing regeneration was considered with the inclusion of the microfiltration unit. By analysing two separate systems, that is, the system where existing regeneration was replaced by the microfiltration unit and where the existing regeneration was considered with the inclusion of the microfiltration unit, a comparison can be done to which would be the best approach in reducing the water consumption on tissue machine number two.

8.2.2.1 Confirming global pinch point determination ability of the method

The pinch point for this system was determined in **Chapter 6**. It must be confirmed that this was the global pinch point else the regeneration scheme proposed will be ineffective. The procedure described in **section 8.2.1** was applied to the system under consideration.

The method of Ng et al. (2009) has been stated to produce the global pinch point for a multiple pinch problem. This was verified by assuming regeneration of the pinch causing stream and observing if the pinch point shifts to another source stream. The entire vacuum pump flowrate was not regenerated, only a 1000 $\ell.min^{-1}$ was assumed to be regenerated so that a comparison could be made with the similar regeneration flowrate for the system in **section 8.2.1**. **Table 8-8** and **Table 8-9** contain the necessary data extracted from water cascade tables in **Appendix G-2**.

Table 8-8: Confirming the global pinch point on tissue machine number two under normal operating conditions for the system where the existing regeneration scheme was considered with the microfiltration unit placed across the pinch point.

Results from the water cascade analysis assuming regeneration of pinch causing stream	
Flow regenerated	1000 ℓ.min^{-1} (17.20 kℓ.ton^{-1} tissue manufactured)
Pinch causing streams	Effluent to drain
Pinch flow rate	28.37 ℓ.min^{-1} (0.4900 kℓ.ton^{-1} tissue manufactured)
Pinch concentration	1000,000 mg.ℓ$^{-1}$
Minimum fresh water required	367.69 ℓ.min^{-1} (6.350 kℓ.ton^{-1} tissue manufactured)
Current fresh water usage – Minimum fresh water usage	14.65 kℓ.ton^{-1} tissue manufactured

Table 8-9: Confirming the global pinch point on tissue machine number two under worst case operating conditions for the system where the existing regeneration scheme was considered with the microfiltration unit placed across the pinch point.

Results from the water cascade analysis assuming regeneration of pinch causing stream	
Flow regenerated	1000 ℓ.min^{-1} (17.20 kℓ.ton^{-1} tissue manufactured)
Pinch causing streams	Effluent to drain
Pinch flow rate	33.69 ℓ.min^{-1} (0.5800 kℓ.ton^{-1} tissue manufactured)
Pinch concentration	1000,000 mg.ℓ$^{-1}$
Minimum fresh water required	541.6 ℓ.min^{-1} (9.360 kℓ.ton^{-1} tissue manufactured)
Current fresh water usage – Minimum fresh water usage	11.64 kℓ.ton^{-1} tissue manufactured

From this water cascade analysis, it was observed that the pinch point shifts to the effluent stream for both normal and worst case operating conditions after the pinch causing stream was regenerated. This was expected because the effluent stream will now limit the total water reuse on tissue machine number two. Therefore the method was accurate in determining the global pinch point even under varying operating conditions.

Reallocations were then performed to separate the sources and sinks into the fresh water region and the regenerated water region so that the ultimate flowrate targeting technique could be applied. This is discussed in the sections which follow.

8.2.2.2 Reallocations of sinks and sources into the fresh water region and the regenerated water region to obtain minimum fresh water, regenerated water, and effluent flowrates

The reallocation procedure was performed as described in **section 8.2.1. Figure J-5** to **Figure J-7** represents the significant results obtained from the water cascade analysis tables in **Appendix G.2**.

All results obtained from the water cascade analyses are available in **Appendix J**, **Figure J-5** to **Figure J-8**.

Depending on how the reallocation of the sources and sinks are performed, a pinch point can either occur in the fresh water region or not. These reallocations are described in detail in **Appendix J**, **section J.2.2**.

In order to alleviate the pinch point, only a portion of the pinch point was assumed to be regenerated so that a comparison could be made with **section 8.2.1**. Due to only a portion of the pinch point being regenerated, it will still exist and reflect in the water cascade analysis and the pinch point will not shift to the effluent stream.

Irrespective of the type of reallocation of the sources and sinks performed, a pinch point does not exist in the regenerated water region.

The comparison was made between the fresh water flowrate for each of the reallocations in **Figure J-6.**

The fresh water consumption was greater for the fresh water regions where the pinch causing stream was not regenerated for both normal and worst case operating conditions as compared to when the pinch stream was regenerated (refer to **Appendix J**, **Figure J-6**). This was because the pinch stream (water from vacuum pumps) was not being appropriately treated.

The fresh water requirement was the same for normal and worst case operating conditions, for each respective fresh water region. This occurs because fresh water was only required for the Yankee, press and wire showers and water for the dissolved air flotation unit chemical dosing. All other demands can be supplied by process water because of the relaxed constraints for the demands on tissue machine number two. The fresh water requirement did not change for normal or worst case operation (because the purity requirement of the sinks mentioned above did not change) and therefore the requirement for fresh water remained unchanged. From **Figure J-6** is evident that in order for there to be a reduction in the specific fresh water consumption on tissue machine number two, regeneration of the pinch stream (water from vacuum pumps) was essential.

The associated regenerated water regions and regeneration flowrates are represented in **Figure J-7.**

Depending on the reallocation of sources and sinks, there will be additional regeneration required (apart from that of the pinch stream) in the regenerated water region.

This occurs because sources which were previously located in the regenerated water region were reallocated to the fresh water region, therefore less water was available in the regenerated water region to supply the demands at the allowable contaminant concentration; this required additional regeneration to compensate. More regeneration was required for the worst case operating conditions to compensate for the poorer quality process water so that demands can be supplied with water at the allowable contaminant concentrations.

A larger effluent flowrate occurred when the pinch stream was not regenerated; this was observed for normal and worst case operation in **Figure J-8**. This corresponds to the larger fresh water flowrates in **Figure J-6**. Therefore from this it was concluded that fresh water was continuously added to the system to supply the demands and this water was removed from the system as effluent.

Comparing the effluent flowrates for the normal and worst case operating conditions (**Figure J-8**), it was observed that the effluent flowrates were lower for the worst case operating conditions compared to the corresponding results for normal operating conditions. This was because during worst case operation, more water was lost through the rejects from the system, through rejects from the screens for example, as compared to normal operation.

It has been mentioned previously that the disadvantage of the method is that it targets for the minimum flowrates but it does not incorporate the consideration of which stream is selected for regeneration, and therefore there was an inaccurate representation of the effluent flowrate; this must be considered when applying this method.

By comparing the reallocation procedures applied during the water cascade analysis (**Appendix J, Figure J-5 to Figure J-8**), it was determined that the reallocation procedure of Ng et al. (2009) provides the minimum water targets. These targets are described in **Table** 8-10**.**

Table 8-10: Results from the reallocation of the sources and sinks into the fresh water region and regenerated water region (by method of Ng et al., 2009) for the system where current regeneration was used with the addition of the microfiltration unit

Flowrate		Description
Pinch point	:	Water from vacuum pumps at 42 mg.ℓ^{-1} to 47 mg.ℓ^{-1}
Fresh water flowrate	:	500 ℓ.min^{-1} (**Figure J-6**)
Regenerated water flowrate	:	1000 ℓ.min^{-1} (**Figure J-5**)
Effluent flowrate	:	300 ℓ.min^{-1} at 1000,000 mg.ℓ^{-1} (**Figure J-8**)
Reallocation selected for water network synthesis	:	That of Ng et al. (2009)

Therefore comparing by comparing the various targeted flowrates in **Figure J-5** to **Figure J - 8** is was observed that the method of Ng et al. (2009) did produce the minimum water targets; these minimum targets were used to develop the water networks in **Chapter 9**.

8.3 Conclusion

The purpose of performing various water cascades analyses with different fresh water region – regenerated water region combinations was to determine which would produce the lowest fresh water, regenerated water and effluent flowrates. In doing this it can also be verified if the method of Ng et al. (2009) does provide the minimum water targets via the water cascade analysis. Using these minimum water targets, effective water networks can then be developed to achieve the minimum water targets.

It has been determined from the water cascade analyses performed and discussed in **section 8.1** and **section 8.2** that the method of Ng et al. (2009) did produce the lowest fresh water, regenerated water and effluent flowrates and the system where current regeneration was replaced by an appropriate regeneration unit across the pinch point had the lower targets than the current regeneration scheme. These minimum targets are described in **Table 8-11**.

Table 8-11: Minimum water targets used to develop the appropriate water networks in Chapter 9.

Water targets applied for the development of the water networks	
Tissue Machine number one	
Fresh water target (**Figure 8-2**)	250 ℓ.min^{-1} to 300 ℓ.min^{-1}
Regenerated water target (**Figure 8-3**)	5000 ℓ.min^{-1} to 6000 ℓ.min^{-1}
Effluent water target (**Figure 8-4**)	5000 ℓ.min^{-1}
Tissue Machine number two	
Fresh water target (**Figure J-2**)	500 ℓ.min^{-1} to 550 ℓ.min^{-1}
Regenerated water target (**Figure J-3**)	915 ℓ.min^{-1}
Effluent water target (**Figure J-4**)	100 ℓ.min^{-1} to 900 ℓ.min^{-1}

The water targets determined from the reallocation process and associated water cascade analyses of Ng et al. (2009) were used in **Chapter 9** to develop the water networks to achieve the ultimate flowrate targets.

By considering all reallocation schemes it ensured that the networks developed will achieve the targeted water flowrates and that the targeted flowrates are the absolute minimum for the system.

Chapter 9 Water network synthesis

In **Chapter 8** various reallocations of the sources and sinks into the fresh water region and regenerated water region were considered. This was done in order to determine which water targets must be used to design the water networks to achieve the absolute minimum water target. This was done for both tissue machine number one and tissue machine number two.

When developing a water network to achieve the targets determined from the pinch analysis, one of the most important considerations was that there should be no interaction across the pinch point concentration, if the minimum fresh water target was to be achieved**.** If water was transferred across the pinch, it is called the fresh water penalty and will result in the wastewater increasing by the same amount as the amount of water transferred across the pinch.

One method developed to determine a network which will achieve the minimum water target is called the nearest neighbours algorithm and it based on the 'principle of nearest neighbours'. This method considered the constraint of not transferring water across the pinch point and determined the water networks via a material balance process. The method will be described briefly in **section 9.1**.

9.1 Principle of Nearest Neighbours

"To satisfy a particular water demand, the source streams to be chosen are the nearest available neighbours to the demand in terms of contaminant concentration" (Prakash and Shenoy, 2005). This means that a source which is slightly cleaner and a source which is slightly dirtier than the demand can be combined to meet the demand. The relative flows to be added are determined from material balances.

In this method *n* is considered as the number of sources and *m* is considered as the number of demands. Sources are labelled from S_1 to S_n in ascending concentration order with S_0 being fresh water. Similarly, demands are labelled from D_1 to D_m.

The flowrates of the sources required to meet the demand are determined by simultaneously solving the following two balances (Prakash and Shenoy, 2005):

$$\mathbf{F_{Sk,Dp} + F_{S(k+1),Dp} = F_{Dp}} \qquad \textbf{Equation 7}$$

$$\mathbf{F_{Sk,Dp}C_{Sk} + F_{S(k+1),Dp}C_{S(k+1)} = F_{Dp}C_{Dp}} \qquad \textbf{Equation 8}$$

Where:

D_p = Demand of given concentration level

S_k = Source with contaminant concentration just lower than the concentration of demand Dp

$S_{(k+1)}$ = Source with contaminant concentration just higher than that of Dp

F = Flow

C = Concentration

* Any set of consistent units may be used

It must be noted that these are solved such that inlet concentrations to the demand is at its maximum allowable concentration.

9.1.2 The Nearest Neighbours Algorithm

The following procedure is described by Prakash and Shenoy (2005):

Step 1: Start by considering the demand that has the most stringent purity requirement (i.e. the lowest contaminant concentration level). Denote this *D1* (i.e. *p=1*).

Step 2: If there exists a source *Sk* which has a concentration exactly equal to that of *Dp*, go to step 3; else, go to step 4.

Step 3: If $F_{Sk} \geq F_{Dp}$, then the flowrate is sufficient to meet the entire demand. Update $F_{Sk} = F_{Sk} - F_{Dp}$ and $p = p + 1$, and go to step 2.

Step 4: Choose the source Sk with contaminant concentration just below that of the demand Dp. Replace *k* by *s* and *(k+1)* by *t* in equations 6 and 7. Calculate $F_{Ss,Dp}$ and $F_{St,Dp.}$

Step 5: If both $F_{Ss,Dp}$ and $F_{St,Dp}$ are less than F_{Ss} and F_{St}, respectively, then the entire demand is met. Update $F_{Ss} = F_{Ss} - F_{Ss,Dp}$, $F_{St} = F_{St} - F_{St,Dp}$ and $p = p+1$, go to step 2.

If $FSs < FSs,Dp$, then use entire Ss (update $FSs = 0$) and replace *s* by *(s-1).* If $FSt < FSt,Dp,$ then use entire *St* (update $FSt = 0$) and replace *t* by *(t+1)*. Solve equations 6 and 7 again with these values of *s* and *t.* Repeat this step until the entire demand is met. Update $p = p+1$, and go to step 2.

Stop when all the demand have been satisfied i.e. when $p = m$

9.1.3 Quality of Wastewater

To reduce the amount contaminant in the effluent stream, it is required that the inlet concentrations to the demands are at their maximum value and hence the contaminants (fibre) are taken up by the units. This will results in more fibre recovery for the mill.

In order to ensure that the minimum fresh water target is met, with regards to fixed flow rate problems: all demands below the pinch must have their inlet concentrations equal to the maximum allowable values, whereas demands above the pinch can have inlet concentrations less than their maximum allowable values.

9.1.4 Applying the Nearest Neighbours Algorithm

The method of Prakash and Shenoy (2005) uses material balances to achieve the minimum water targets by ensuring that all sinks receive their maximum allowable contaminant concentration. This is so that contaminants are taken up by the units and not sent to drain or effluent treatment. This ensures maximum recovery and reuse.

The disadvantage of this is that it does not incorporate plant layout. It may therefore result in stream matching which is unrealistic e.g. to make up a 600 $\ell.min^{-1}$ flow at 30 mg. ℓ^{-1} may result in a combination of 550 $\ell.min^{-1}$ at 32 mg. ℓ^{-1} with 50 $\ell.min^{-1}$ at 0 mg. ℓ^{-1}. This is not a feasible connection due to low flow of 50 $\ell.min^{-1}$; it is impractical to be running a very small diameter tap-off line through the plant.

Therefore to ensure that the units receive water quality which would not adversely affect the product and operation, as well as minimise excessive water lines, units were allocated the cleanest water possible and it was attempted to meet a demand with a single source flow. This may result in a more expensive capital cost but it will have the benefit of not disrupting efficient operation. The user of the method must use his/her discretion when applying the method; if an unrealistic matching of sources and sinks occurs, the user needs to make a decision in respect to a more realistic matching of streams.

All networks were developed considering the following:

- current plant layout
- equipment availability
- storage

- the most feasible combination e.g. water from wire and press entering the couch pit was considered as a single source rather than separating them as this would be less cost effective

Once the network was determined for normal operation, the same network was tested for the hypothetical worst case operation. This was done to ensure that the network would produce satisfactory results if the ideal operating conditions were disrupted. This was done because if done independently, different networks may arise for the different operating conditions and it will not occur that two different water networks will be in used depending on the process conditions. The water network determination procedure was as follows:

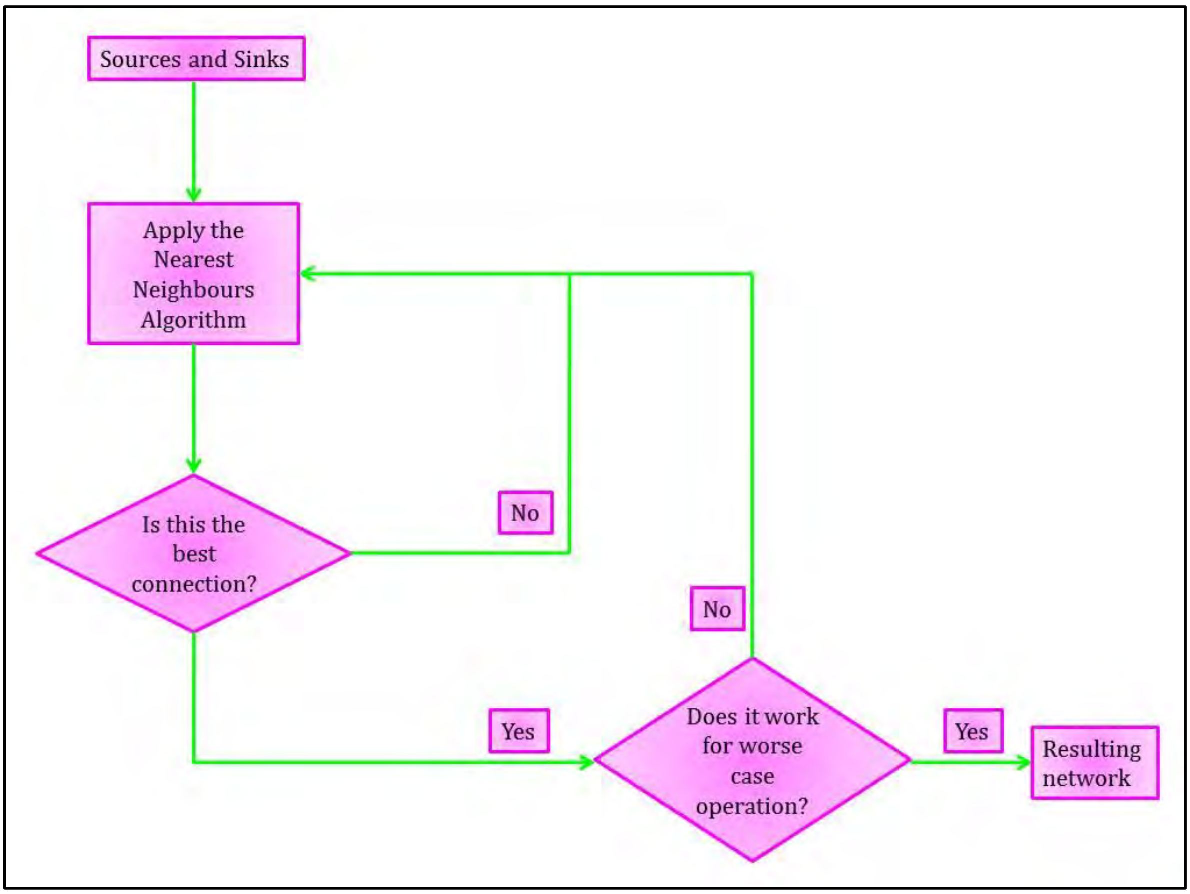

Figure 9-1: Procedure followed in determining the optimum network to obtain water network targets

Due to the large amount of data from each targeting procedure, only those of the final networks are included in **Appendix K**.

It would be a great task to shift from the current network configuration to the new recommended system in a single stage, therefore a step-by-step progression was considered. An option to reduce the specific water consumption by only reconfiguring the current network was also investigated; this network provides insight on to how the fresh water consumption can be reduced by reconfiguring the existing water network to optimise the connections between sources and sinks, rather than adding a new regeneration unit to the process. These networks developed for the tissue machines are described in **section 9.2**.

9.2 Water networks developed

The principle of nearest neighbours is basically this; use a source of slightly lower contaminant concentration than that allowable to the demand and a source at concentration slightly higher than that allowable to the demand, to satisfy the demand. These sources used are the 'nearest neighbours' to the demand. The method is based on material balances and aims at achieving the minimum targets by providing the maximum contaminant loading to the demand (sink). The networks are determined by using the algorithm (**section 9.1.2**) and the iterative procedure described in **Figure 9-1**.

Once the network configuration was determined, the network connections were examined to determine the feasibility of the connections. If a sink was being supplied by too many small flowrates, the network was refined such that each sink would be satisfied by at most, two different sources, such that a less complicated network results and hence there is less pumping and piping requirements.

When refining the networks, consideration was given to the plant layout, existing network configuration, existing equipment and storage. The final network calculation is detailed in **Appendix K,** all preliminary network calculations are available on the memory stick.

9.3 Tissue machine number one

This section contains the water networks developed to meet the minimum water targets calculated for tissue machine number one in **section 8.1.** It was determined from the various water cascade analyses performed that the reallocation method of Ng et al. (2009) does produce the minimum water targets and these targets were used to develop a water network as described in **section 9.1**.

9.3.1 Current regeneration replaced by the Petax™ unit placed across the pinch point

The network developed for the system where the existing regeneration was replaced by the Petax™ placed at the pinch point, represents the recommended system, that is, what the water network should be in-theory, to achieve the water targets determined for this system. Some sources have been combined as described in **section 9.2**. The tables contained the combined sources are available in **Appendix K**, **Table K-1** and **Table K-2** for normal and worst case operation respectively.

As discussed in **section 9.1.4**, the network developed for normal operating conditions must also operate efficiently under worst case operating conditions.

In **Appendix K**, the water networks developed for the normal and worst case operation are available. In this chapter only the final water networks developed are described using the process flow diagrams. For the development details, please refer to **Appendix K**.

For tissue machine number one the fresh water, regenerated water, vacuum pump water, flat box separator water and vibrating screen accepts were considered as separate sources. Water from the wire section, press section and single breast roll chamber were considered as a single source such that the current piping configuration under the machine can remain unchanged. This avoids the great cost associated with attempting to separate the lines under the machine.

In this water network configuration, fresh water was required for fresh water make-up and for the Yankee shower requirements. The regenerated source was assumed to be 5000 $\ell.min^{-1}$ at 20 mg. ℓ^{-1} as determined from the water cascade analysis. This corresponds to a single Petax™ unit with 25 disks or for better control, two Petax™ units with 15 disks each with the 5000 $\ell.min^{-1}$ split evenly between them. This water was used directly for all other higher quality water requirements. Therefore only a portion of the vibrating accepts was regenerated. Therefore additional piping will be required to split the vibrating screen accepts into two separate lines; one going to the regeneration unit and the other to the off-machine silo as is currently being done.

Vacuum seal water was recycled back to the vacuum pumps in the network developed. The existing pumping system can be used with line extensions to the suction of the fan pump where the remaining vacuum water will be pumped. All remaining sources were used for dilution at the fan pump.

Whilst the water source from the flatbox separator was considered as a separate source, it was added straight to the fan pump as dilution water. This connection was considered because if the flowrates of these sources change (under varying operating conditions), it will not have an effect on the operation because all the sources from under the machine are being used for dilution.

Fresh water make-up was added at the fan pump dilution in the event that excess water will be required before the headbox.

All demands receive higher purity water than required. This was to ensure that over-loading of contaminants in the system will not occur as well as to prevent accumulation of contaminants in the system. The network was designed such that it was very similar to the existing water network such that existing control schemes can be employed and so that an entirely new network will not have to be constructed as this would be very expensive.

It was confirmed that the water network developed for normal operating conditions will operate efficiently under worst case operation. In doing this, the water network developed will be efficient even under varying operating conditions.

A separate network could be developed to obtain the minimum targets determined for worst case operation from the water cascade analysis but, it will not be the same as the network developed to achieve the targets obtained for normal operating conditions. This must be considered because the network will not change depending on the contaminant concentration of the water sources (that is, the piping is fixed) therefore the network designed needs to be applicable to all situations.

Therefore the network developed for normal operation was applied to worst case operation to determine if the minimum water targets for worst case operation could be achieved.

It was observed that the respective flowrates for the sources had changed because of the undesired operation during worst case operation, but due to the network configuration and the way the sources were grouped, this will not have an effect on the process. In this way, the efficient operation of the system will not be disrupted even under varying water source purity and flowrates.

The networks developed from the method of Prakash and Shenoy (2005) are available in **Appendix K**, **Figure K-1** and **Figure K-2**.

In **section 9.3.2**, the water networks for the system where the current regeneration was considered in addition to the Petax™ unit placed across the pinch point. The networks for each of these systems are compared to determine a cost effective approach in moving from the current water network scheme to the recommended scheme.

9.3.2 Current (existing) regeneration of process water in the tissue making process was considered with the Petax™ regeneration unit placed at the pinch point

The networks devised for the system where existing regeneration of the process water was considered with the Petax™ fine filtration unit placed across the pinch point, provide insight as to where changes should be made to the current water network in order to reduce the water consumption.

9.3.2.1 Existing regeneration system with an alternate connection between units

Before an entirely new system was developed for considered for the system where existing regeneration of the process water was considered with the Petax™ fine filtration unit placed across the pinch point, the current system was examined to determine if a reduction in the fresh water consumption could be brought about by optimising the connection between the units only and not considering any additional regeneration.

Figure K-3, the water network developed using the method of Prakash and Shenoy (2005), is displayed in **Appendix K**.

All blocks in **Figure K-3** are labelled in reference to **Table 6-2** and **Table K-3**. All flowrates in **Figure K-3** are in $\ell.min^{-1}$ unless otherwise stated. In **Table K-3**, fresh water, dissolved air flotation filtered water, vacuum pump water, flat box separator water and vibrating screen accepts were considered as separate sources. Water from the wire, press and SBR chamber were considered as a single source such that the current piping configuration under the machine could remain unchanged. This will avoid the great cost associated with attempting to separate the source lines under the machine.

For the network in **Figure K-3**, fresh water was required for fresh water make-up and for the Yankee shower requirements. Vacuum seal water was recycled back to the vacuum pumps. The existing pumping system can be used with line extensions to the suction of the fan pump to which the remaining vacuum water will be pumped. All remaining sources will be used for dilution at the fan pump. The dissolved air flotation filtered water was used to satisfy the higher quality demands.

Whilst the water source from the flatbox separator was considered as a separate source, it was added straight to the fan pump as dilution water. This connection was considered because if the flowrates change, it will not have an effect on the operation because all these sources from under the machine are being used for dilution at the fan pump.

Fresh water make-up was added at the fan pump dilution in the event that excess water will be required before the headbox.

All demands receive higher purity water than required. This was to ensure that the system does not become over-loaded with contaminants as well as to ensure that there will not be accumulation of contaminants in the system.

It was observed from **Figure K-3** that the fresh water consumption can be reduced to10.26 kℓ.ton^{-1} tissue manufactured just by connecting the equipment units differently. This was achieved using the existing dissolved air flotation unit in the system with an alternate connection between units in the process. The water network calculation is detailed in **Appendix K, section K.1.5**.

9.3.2.2 Recommended water regeneration scheme and water network

Once the network for reducing the water consumption by alternate connection between the existing units was determined, consideration was also given to including the new regeneration unit along with the existing regeneration units, that is, adding the Petax™ unit to the system as well as keeping the dissolved air flotation unit and associated gravity strainer in the system. This water network is depicted in **Figure K-4** which is available in **Appendix K, section K.1.6,** this network considers the addition of a new regeneration unit to produce a 20 mg.ℓ^{-1} source.

The water network developed for normal operating conditions (**Figure K-4**) is labelled in reference to **Table 6-2** and **Table K-4**. The water network developed for worst case operation (**Figure K-5**) is labelled in reference to **Table 6-5** and **Table K-5**.

As described in **section 9.1.4**, the network developed for normal operating conditions must also operate efficiently under worst case operating conditions. Therefore the water network developed in **Figure K-4** was applied to the hypothetical worst case operation (**Figure K-5**).

In **Figure K-4** and **Figure K-5**, fresh water, dissolved air flotation filtered water, vacuum pump water, the Petax™ regenerated source, flatbox separator water and vibrating screen accepts were considered as separate sources. Water from the wire, press and SBR chamber were considered as a single source such that the current piping configuration under the machine could remain unchanged. This will avoid the great cost associated with attempting to separate the lines under the machine.

In these networks, fresh water was required for fresh water make-up and for the Yankee shower requirements. Vacuum seal water was recycled back to the vacuum pumps. The existing pumping system can be used with line extensions to the suction of the fan pump to which the remaining vacuum water will be pumped. All remaining sources will be used for dilution at the fan pump. The dissolved air flotation filtered water was used to satisfy the higher quality demands.

Whilst the water source from the flatbox separator was considered as a separate source, it was added straight to the fan pump as dilution water. This connection was considered because if the flowrates change, it will not have an effect on the operation because all these sources from under the machine are being used for dilution.

Fresh water make-up was added at the fan pump dilution in the event that excess water will be required before the headbox.

All demands received higher purity water than required. This was to ensure that the system does not become over-loaded with contaminants as well as to ensure that there will not be accumulation of contaminants in the system.

It was observed that **Figure K-4** (& **Figure K-5**) did not vary significantly from **Figure K-3**. This was because the regeneration efforts were being wasted by regenerating streams other than the pinch point (vibrating screen accepts). Due to the inclusion of all regeneration units, the fresh water was high to accommodate operation of all units, that is, fresh water was required for chemical dosing at the dissolved air flotation unit and there was also a loss from the system through the dissolved air flotation unit float. It was observed that there was additional fresh water being supplied to the fan pump, this was to bring the contaminant concentration down to 600 mg. ℓ^{-1} which was the maximum allowable contaminant concentration allowed to the fan pump.

It was determined that the network developed for normal operating conditions will operate efficiently under undesired operation at the compromise of added fresh water requirement. This was because a different network would achieve the minimum targets obtained previously in **Chapter 8, section 8.1.2** for the hypothetical worst case operating conditions but the network developed for normal operation was applied to worst case operation to determine the effect of this network on fresh water consumption. In order to achieve the absolute minimum targets for worst case operation as determined by the water cascade analysis a different water network compared to that required for normal operation would be required. However the water network was not going to change depending on the contaminant concentration of the water sources (the piping is fixed); therefore the network designed for normal operation must be applicable to all operating conditions.

It was noted that the flowrates have changed for the different sources for worst case operation because of the undesired operation, but due to the network configuration designed by the method of Prakash and Shenoy (2005) and the way the sources are grouped, this will not have an effect on the process operation.

In this way, the efficient operation of the system will not be disrupted even under varying water source purity and flowrates.

The water network was designed such that it was very similar to the existing network such that existing control schemes can be employed and so that an entirely new network will not have to be constructed as this would be very expensive.

Using the water networks developed in **section 9.3.1** and **section 9.3.2** (represented by **Figure K-1** to **Figure K-5)** a progression in moving from the current water regeneration scheme to the proposed regeneration scheme as determined from the water cascade analysis was developed. This is discussed in **section 9.3.3**.

9.3.3 Water network progression – from existing system to new recommended system

The water networks developed in **section 9.3.1, section 9.3.2** and **Figure K-**1 to **Figure K - 5** were used to develop a scheme in moving from the current regeneration scheme to the recommended regeneration scheme (**Figure K-1** and **Figure K-2**). This section details the step changes in the current water networks which have to be made such that the water network to achieve the absolute minimum targets can be developed in stages as this may be a more cost effective option.

The first system considered was the network developed by the method in Prakash and Shenoy (2005) (**Figure K-3)** where water reduction was achieved by alternate connections between the equipment units, in this way the existing regeneration scheme was applied and the connection between units was optimised. This is described in the process flow diagram in **Figure 9-2**.

9.3.3.1 Existing network, different connection between the units

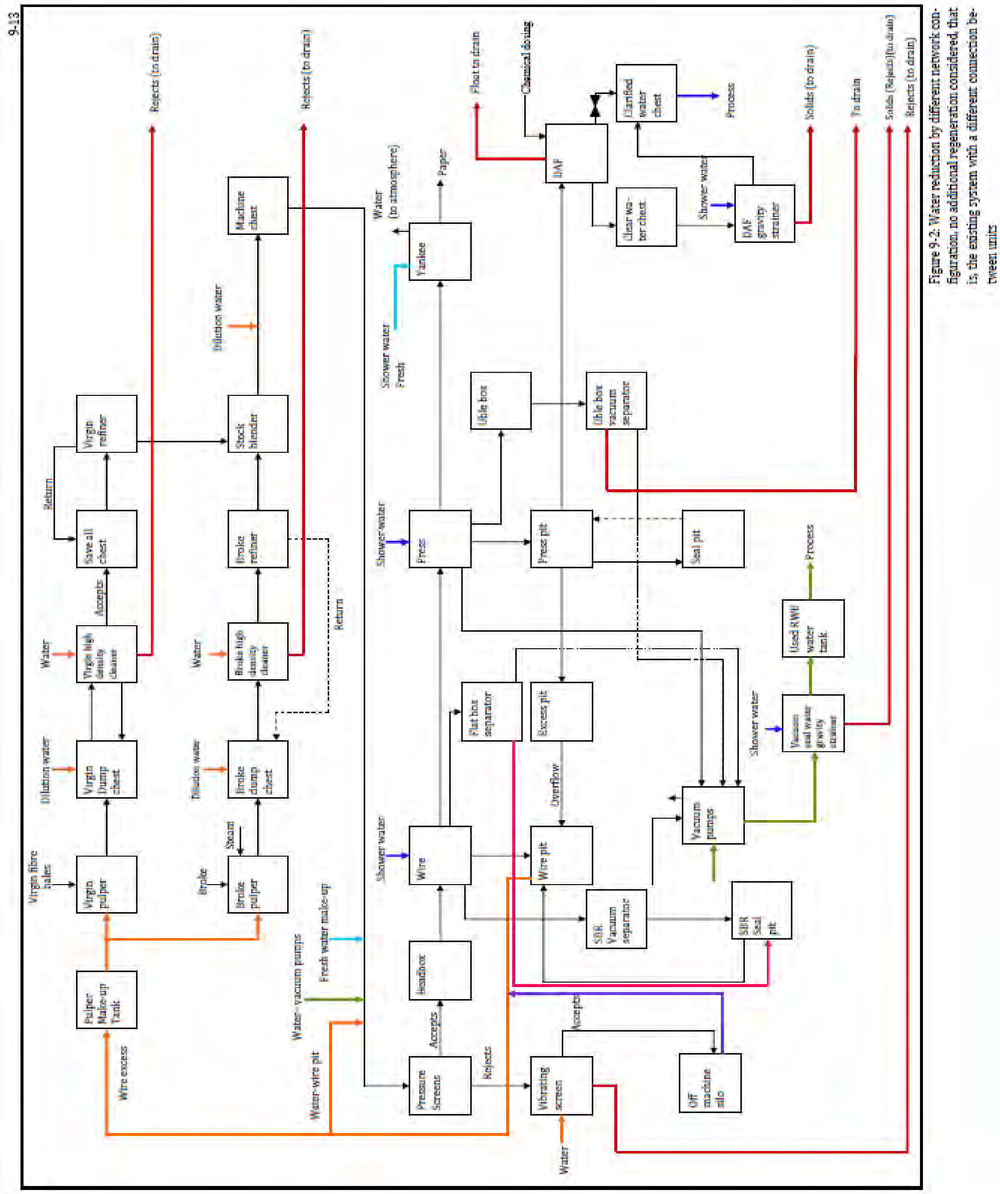

Figure 9-2: Tissue machine number one, fresh water reduction by existing regeneration scheme with a different connection between units

9.3.3.2 Converting to the new recommended system

The water network developed to achieve the water targets determined from the ultimate flowrate targeting technique (that is, **Figure K-1** and **Figure K-2**) represent the ideal water network as determined from the pinch analysis.

This section details the proposed steps to be taken in order to change from the existing water network to the recommended water network developed as a result of the study such that the transition between the water networks can be done in phases rather than as a single project as this will be expensive and time consuming and may be difficult to achieve in a single plant modification. The main considerations are highlighted below.

General points to consider:

1. The difference between the new suggested operation and current operation was that the current system has been designed to use either fresh or dissolved air flotation filtered water for the showers in the system and wire pit water to the fan pump; dilution was now also brought about using water from the dissolved air flotation unit.
2. The first network for the system where the existing regeneration was considered (**Figure** 9-3**)**, uses the dissolved air flotation unit filtered water for the shower water requirements compensated with fresh water for stringent requirements and then wire pit water for dilution
3. The water lines which use dissolved air flotation unit filtered water as shower water must first be installed, that is,
   - a main line from the dissolved air flotation unit filtered water chest and tap-off lines to the showers must be installed
   - a pump must be designed to provide a flowrate of double the current dissolved air flotation unit filtered water flow; it will not be used to its full capacity but it must be designed for the future work which will include the Petax™ unit for when the new system is installed
4. The dissolved air flotation unit feed water pump can be used to pump the water from the wire pit to the various points of addition (where ever the water is being used for dilution purposes), this can be done by either moving the dissolved air flotation unit feed water pump to the wire pit and extending the required tap off points or the discharge line to the various dilution points can remain the same and the pump suction can be extended. The

line going from wire pit as dilution water can be attached to the suction of the dissolved air flotation unit filtered water pump. Therefore dilution will occur using the wire pit water only.

5. From the water cascade analysis, a large regeneration flow rate was determined (≈6000 ℓ.min^{-1})
6. During water network design a flow of 5000 ℓ.min^{-1} was considered for the regeneration flowrate at the sacrifice of a fresh water penalty (fresh water addition) such that only a single regeneration unit was required. Therefore the entire pinch causing stream was not regenerated.
7. Upon calculations, only ≈3700 ℓ.min^{-1} was required at 20 mg.ℓ^{-1}, of course considering a fresh water penalty. Therefore a single unit can be used to regenerate 4000 ℓ.min^{-1} and the rest of the vibrating screen accepts can go to the wire pit for use with dilution at the fan pump. There was also a sacrifice of some purity (higher than 600 mg.ℓ^{-1}; ≈620 mg.ℓ^{-1}) if this is considered. If the purity of 600 mg.ℓ^{-1} is essential, then two regeneration units must be considered.

Considering the points above the change from the current regeneration scheme to the scheme recommended from the pinch analysis was broken down into two phases which are discussed in **section 9.3.3.2(a)** and **9.3.3.2(b)**.

9.3.3.2 (a) Phase one

1. Water from all vacuum separators, except the Uhle-box and vacuum pumps, must be delivered to the wire pit
2. Vibrating screen accepts must be delivered dissolved air flotation unit for regeneration
    a. The flow which is not sent to regeneration at the Dah must be sent to the suction of the fan pump
3. Vacuum pump water can be sent to the rand water board tank as in current operation; the flow which is not returned as seal water must be sent to the suction of the fan pump
4. A pump will be required; this pump will be used to deliver dilution water to the various chests from the wire pit
    a. The pump can be used later for delivering clarified water from the new regeneration unit to the showers and chests
5. A pump will be required to deliver the portion of the vibrating screen accepts to the regeneration unit

   a. It must be verified if the current dissolved air flotation feed pump can be re-sized to handle a flow of 5000 $\ell.min^{-1}$ and also handle the pressure drop associated with the filtration unit

6. Making these changes to the system will result in the process flow diagram in **Figure 9-3**.

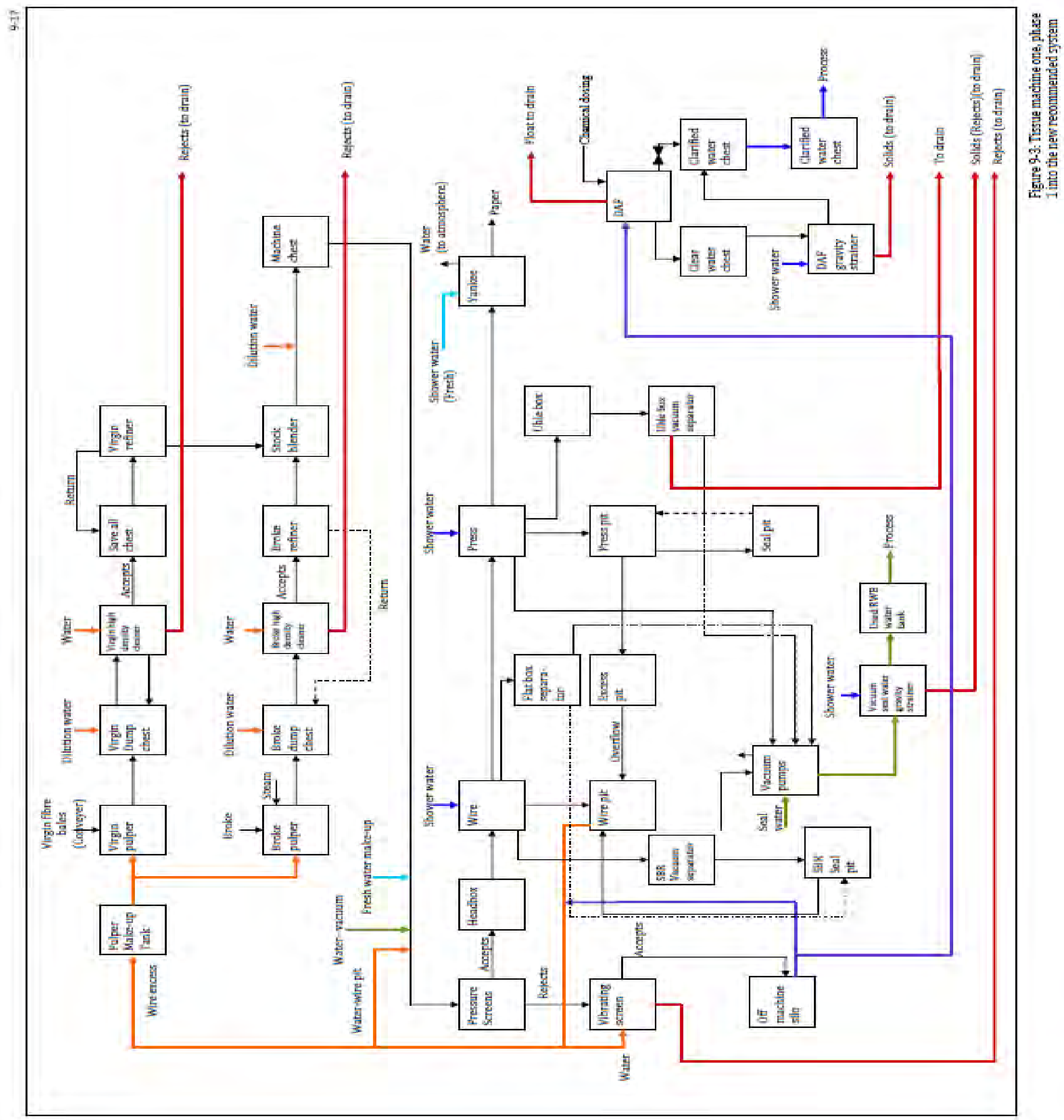

Figure 9-3: Tissue machine number one, phase one into the new recommended system

9.3.3.2 (b) Phase two

In moving from phase one and into phase two which will move the system from the current water network to the new water network the following must be done:

1. Replace the dissolved air flotation unit with a Petax™ unit
2. Pump mentioned in point 4, in **section 9.3.3.2(a)**, must be connected to the clarified water chest for the unit (this will be the current DAF clarified water chest)
3. The main line water line from this pump can be re-routed such than the tap-off points to the chests can remain the same. Shower water tap off points will need to be re-routed onto this main line so that the showers can be supplied by the regenerated water from the Petax™
4. All other connections will remain unchanged
5. **Figure 9-4** is the recommended network configuration and corresponds to the water network described **Figure K-1** and **Figure K-2**.

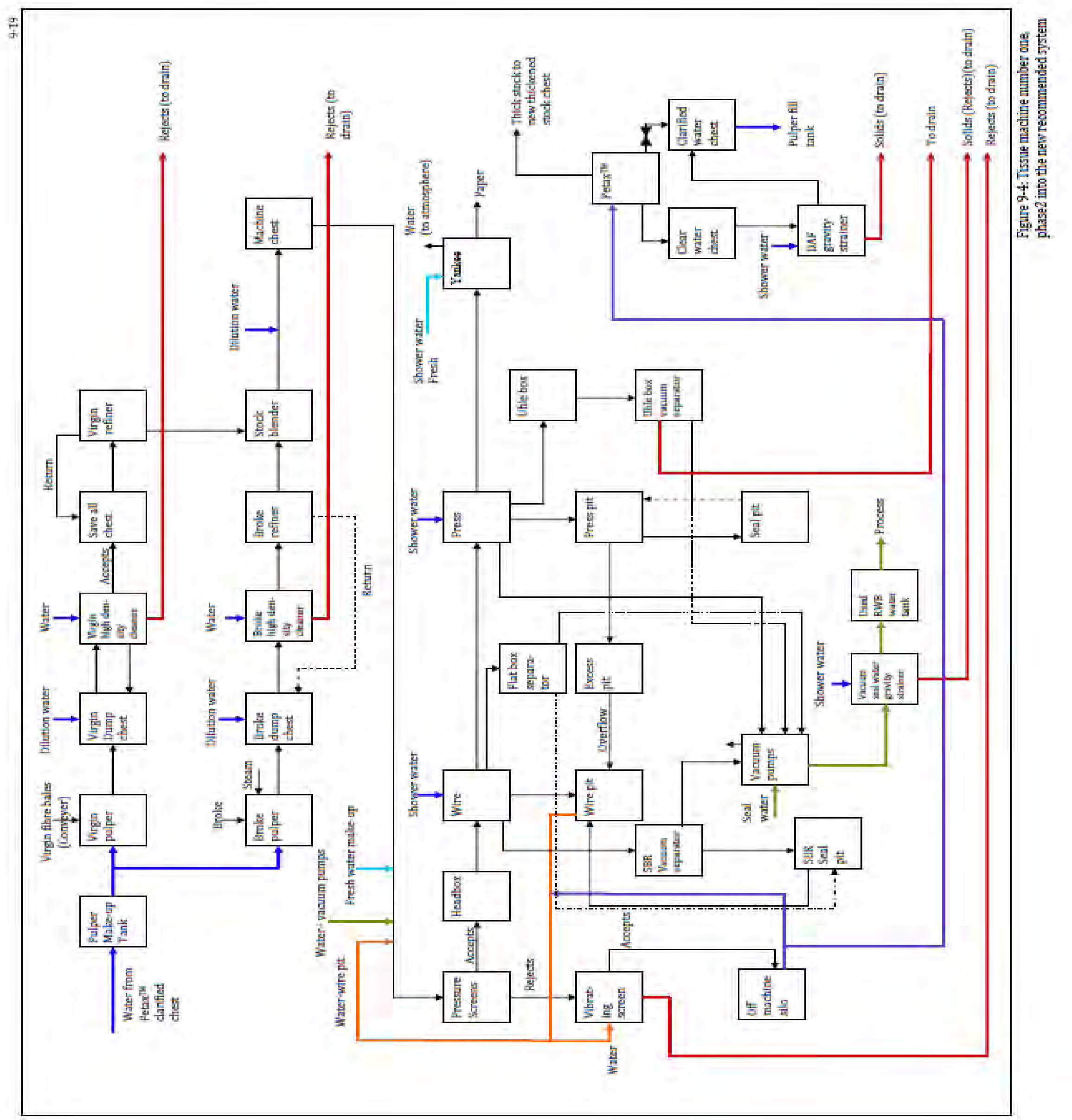

Figure 9-4: Tissue machine number one, phase two, recommended water network

9.4 Tissue machine number two

The procedure followed for tissue machine number one to determine the appropriate water network to achieve the ultimate water targets as determined from the water cascade analysis in **Chapter 8, section 8.2.1**, was applied to tissue machine number two. The details of the application are available in **Appendix K**. Only the final results will be discussed in this section.

9.4.1 Current regeneration replaced by a microfiltration unit at the pinch point

Applying the procedure followed for tissue machine number one (**section** 9.3.2) to tissue machine number two, the water networks for tissue machine number two were developed. The networks developed for this system represents the ideal water networks to achieve the ultimate flowrate targets as determined by the water cascade analyses.

The combinations of the sources considered are described and labelled in **Table K-6** and **Table K-7** for normal and worst case operation respectively. The demands are labelled in reference to **Table H-1** and **Table H-4** for normal and worst case operation respectively.

As done for tissue machine number one, the water network developed for tissue machine number two for normal operation was applied to worst case operation to determine if the water network configuration would be applicable to all operating conditions and to determine the associated effect on the fresh water consumption during worst case operation.

The final water network from the iterative procedure (as explained in **Figure 9-1**) is presented in **Figure K-6.**

All flowrates in **Figure K-6** are in $\ell.min^{-1}$ unless otherwise stated. In **Table K-6** the fresh water and regenerated main vacuum separator and single breast roll chamber water were considered as a single combined source as well was water from the wire and press entering the couch pit; water from the vacuum pumps, save-all pan, flatbox separator and vibrating screen accepts were considered as separate sources such that the current piping configuration under the machine can remain unchanged. This avoids the great cost associated with attempting to separate the lines under the machine.

In this system due to the large amount of fresh water required for the showers, the water was regenerated by a membrane to reduce the fresh water intake. The regenerated flowrate was

783 ℓ.min^{-1} at 0 mg. ℓ$^{-1}$. This regenerated water can be used directly at the showers or sent to the fresh water chest and then be pumped to the showers from the chest. The entire pinch causing stream was regenerated, that is, the water from the main vacuum separator and the SBR chamber was sent directly to regeneration. An additional regeneration flowrate of ≈ 900 ℓ.min^{-1} at 20 mg.ℓ$^{-1}$ was required to ensure that all demands were satisfied at their allowed contaminant concentrations.

Vacuum seal water was recycled back to the vacuum pumps. The existing pumping system could be used with extensions to the wire showers, the press uhle-box, vibrating screen showers, the turbo-separator and the machine chest.

Water from the save-all pan and the regeneration unit with regeneration concentration of 20 mg. ℓ$^{-1}$ was used for dilution at the broke pulper and recycled fibre pulper; all other sources as well as remaining save-all pan water were used for dilution at the low density cleaners and the pressure screens.

Fresh water make-up was added at the fan pump dilution in the event that excess water will be required before the headbox.

In order to achieve the absolute minimum targets for worst case operation as determined by the water cascade analysis a different water network compared to that required for normal operation would be required. However the water network was not going to change depending on the contaminant concentration of the water sources (the piping is fixed); therefore the network designed for normal operation must be applicable to all operating conditions.

It was noted that the respective source flowrates changed because of the undesired operation but due to the network configuration and the way the sources are grouped, this will not have an effect on the operation of the process. In this way, the efficient operation of the system will not be disrupted even under varying water source purity and flowrates.

All demands received higher purity water than required. This was to ensure that the contaminants did not accumulate in the system. The network was designed such that it was similar to the existing network such that the existing control schemes can be employed.

The information obtained by applying the method of Prakash and Shenoy (2005) to determine the water network configuration was used in **section 9.4.3** to determine the best way to move forward to the recommended water network.

Therefore it was concluded that the water network developed for normal operation (**Figure K-6**) will operate efficiently under undesired operating conditions at the compromise of added fresh water requirement (**Figure K-7**).

9.4.2 Current (existing) regeneration of process water in the tissue making process was considered with the microfiltration regeneration unit placed at the pinch point

Because the systems discussed in **section 8.2.1** and **section 8.2.2** were such different systems, separate water networks were designed for each. The system were the existing regeneration was replaced by the microfiltration unit represents a new water network configuration and regeneration placement to achieve the minimum water targets, whilst the system where the existing regeneration was considered with the microfiltration unit looks at minimal changing of the current water system to achieve the water targets. Comparing these two different systems it can be determined which system will provide a more cost effective solution in the long-term.

The targets determined by applying the ultimate flowrate targeting technique of Ng et al. (2009) was used for the development of the water network. This was selected because it provided the minimum fresh water and regenerated water flowrates as well as lower combined effluent water flowrates. The nearest neighbour's algorithm of Prakash and Shenoy (2005) was used to determine the networks (described in **section 9.1.4**).

9.4.2.1 Existing regeneration system with an alternate connection between units

Before a new water network was considered the current system was examined to determine if a reduction in the fresh water consumption could be brought about by optimising the connection between units and not considering any additional regeneration.

All blocks in **Figure K-8** are labelled in reference to **Table K-8** and **Table H-7**. All flowrates are in $\ell.min^{-1}$ unless otherwise stated. In **Table K-8** all sources are considered as separate sources such that the existing network configuration can be used with a changed in tap-off points. This will avoid the great cost associated with attempting to separate the lines under the machine.

In **Figure K-8**, fresh water was used for all high purity requirements, that is, shower water requirements at the Yankee, wire and press sections and for fresh water make-up. The vacuum seal water was recycled back to the vacuum pumps. The existing pumping system can be used with line extensions to the remaining wire showers and the save-all showers which have a less stringent purity requirement.

Water from the dissolved air flotation unit was used for shower water and as dilution water at the chests and the fan pump. Water from the save-all pan was used for dilution at the low-density cleaners and at the pressure screens.

Remaining sources were used for dilution at the low-density cleaners. This water had the lowest purity in the system (highest contaminant concentration), therefore by using this water only at the cleaners it prevents accumulation of contaminants in the system and allows for removal of these contaminants from the system at the low-density cleaners.

Whilst water from the flat-box separator was considered as a separate source, it can be sent straight to the low-density cleaners.

This connection scheme was considered because even if the flowrates of the sources from the wire and press section change, it will not have an effect on operation because the water from these sections, which are not regenerated at the dissolved air flotation unit or save-all, was used as dilution water only. The clarified water was not used at the showers or for higher purity water requirements.

Fresh water make-up was added at the pressure screens dilution in the event that excess water will be required before the headbox.

All demands were supplied with higher purity water than required. This was to ensure that the contaminants are not accumulated in the system.

The network in **Figure K-8** serves as a comparison to the new recommended system. From this network it was observed that the effluent flowrate corresponds to the water which was not reused in the system. From the water cascade analysis, the effluent was mainly water from the vibrating screen accepts which can be reused in the system; considering this, as well the large quantity of fresh water used in the system, it indicates that the current regeneration unit was not efficiently placed.

From **Figure H-4**, it was noted that for this system the minimum water requirement was ≈23 kℓ.ton^{-1} tissue manufactured. This can be reduced to ≈21 kℓ.ton^{-1} tissue manufactured by using an alternate water network. The information obtained by applying the method of Prakash and Shenoy (2005) will be used to develop a system for moving the regeneration scheme from the existing scheme to the recommended scheme from the water cascade analysis.

9.4.2.2 Recommended water regeneration scheme and water network

Once the network for reducing the water consumption by alternate connection between the existing units was determined, consideration was given to adding the microfiltration unit across the pinch point. The entire pinch stream was not regenerated; the flowrate regenerated was the same as that determined for **section 9.4.1**, this was to ensure that the regeneration unit will not have to be changed in the transition from the current system to the new system. This regenerated flow and fresh water intake are considered as the 0 mg.ℓ$^{-1}$ source in **Table K-9** and **Table K-10** for normal and worst case operation respectively.

The water network in **Figure K-9** is labelled in reference to **Table H-7** and **Table K-9**. The water network in **Figure K-10** is labelled in reference to **Table H-10** and **Table K-10**.

As discussed in **section 9.1.4**, the network developed for normal operating conditions must also operate efficiently under worst case operating conditions.

In **Figure K-9** all flowrates are in ℓ.min^{-1}. Aside from the fresh water sources, all other sources are considered as separate sources, as they currently occur in the process. This way the current water network can stay more or less the same with the exception of a few additions/removals of tap off points from the main water pipes. This will avoid the large costs associated with attempting to separate the lines under the machine.

In **Figure K-9**, the fresh water and regenerated water was used for all high purity requirements, this included most of the shower water requirements. Vacuum seal water was used for lower purity shower water requirements.

The water regenerated at the dissolved air flotation unit was used for vacuum seal water and for dilution at the various chests. All other sources were used for dilution at the pressure screens and at the low density cleaners. At these points the water purity requirements were not stringent and hence the regeneration effort of the save-all was wasted.

A fresh water make-up line was added at the pressure screens in the event that additional fresh water make-up was required.

All demands received higher purity water than required. This was to ensure that contaminants were not accumulated in the system.

This water network developed for this system was not very different from the existing network, the main difference between the recommended system and that of current operation was the inclusion of the new regeneration unit and removal of the unnecessary regeneration units. Previous pipe lines and pumps for the system can still be used with the connection points changed.

The flowrates required to be discharged to drain were considered as losses from the system. For tissue machine number two the water can be reduced to ≈8 kℓ.ton^{-1} tissue manufactured with the incorporation of a regeneration unit at the pinch point. All costs associated with the incorporation of this unit will be discussed in **Chapter 11**.

It was determined that the water network designed for normal operation (**Figure K-9)** will operate efficiently under undesired operating conditions at the compromise of added fresh water requirement (**Figure K-10**). In order to achieve the absolute minimum targets as determined by the water cascade analysis a different water network compared to that required for normal operation would be required. However the water network was not going to change depending on the contaminant concentration of the water sources (the piping is fixed); therefore the network designed for normal operation must be applicable to all operating conditions.

It is noted that the respective source flowrates have changed because of the undesired operation but due to the network configuration and the way the sources are grouped, this will not have an effect on the operation of the process. In this way, the efficient operation of the system will not be disrupted even under varying water source purity and flowrates.

All demands received higher purity water than required. This was to ensure that the contaminants did not accumulate in the system. The network was designed such that it was similar to the existing network such that the existing control schemes can be employed.

Using the water networks developed in **section 9.4.1** and **section 9.4.2** (represented by **Figure K-6** to **Figure K-10)** a progression in moving from the current water regeneration scheme to the proposed regeneration scheme as determined from the water cascade analysis was developed. This is discussed in **section 9.4.3**.

9.4.3 Water network progression - from existing system to new recommended system

This section details possible steps to be taken in converting the existing water network to the new proposed system (**Figure K-6 and Figure K-7**). These steps aim at making the transition from the old to the new system as easy as possible.

General points to consider:

1. The difference between the existing system and the new proposed system is that the current system regenerates water from the seal pit and off-machine silo at the save-all and the dissolved air flotation unit respectively. The new system proposes that the regeneration should be at the single breast roll chamber and main vacuum separator and vibrating screen accepts.
2. For the first network where existing regeneration was considered and the microfiltration unit was not considered to regenerate the pinch stream, that is, reducing the water consumption by an alternate network connection, only fresh water was used for shower water,; water from the DAF and save-all were used for stock dilution.
3. The vacuum seal water can be re-used as it is currently recycled in the system
4. Dissolved air flotation unit filtered water can be used for dilution water as it is currently being used in the system
5. For the first phase only a portion of the water from the vacuum pump was assumed to be regenerated, this was so the same microfiltration unit can be used in shifting to the new recommended system (this is described in **section 9.4.3.2(a)**)

9.4.3.2 (a) Phase one

- Water from the flatbox separator must be sent directly to the low density cleaners for dilution of the stock
- Water from the seal pit was sent to the save-all for regeneration, this is the current regeneration scheme but the water from the flatbox separator has been reallocated to the low density cleaners

- Water from the save-all pan is flow controlled such that the flowrate required at the pressure screens is satisfied entirely with the save-all pan water with the remaining water from the save-all pan used at the low-density cleaners
- Cloudy and clear water from the save-all is to be sent directly to the low-density cleaners, an extension of this line must be joined to the pressure screen inlet flow but this line must remain closed for this phase. It will be required in the phase 2 (**section 9.4.3.2(b))**
- Flow control will be required for a flowrate of 1000 $\ell.min^{-1}$ of water from the vacuum pumps will be sent to the microfiltration unit with the remaining water used in the process for the lower purity shower requirements at the save-all, turbo-separator vibrating screen and vibrating screen showers. The existing pipe and pump system is used with various tap-off points
- Seal water from the vacuum pumps can be supplied by water from the dissolved air flotation unit
- Introduce a microfiltration system to clean the vacuum seal water
    - This can be sent to the fresh water tank
    - Hence the same pump can be used for distribution
    - Will require piping and control valves
    - The old vacuum water lines must not be removed but just closed off because they will be required later
- A buffer tank for the dissolved air flotation unit filtered water (Clarified water tank can be used)
    - Therefore current pump system can be used
    - Extension line required for new demand lines
    - Control valves required for each new line
    - Water to be used for dilution of stock at broke and recycled fibre re-pulpers, turbo-separator, save-all chest and machine chest
- Separate chests for clear and cloudy water
    - This is currently in existence
    - Together with associated piping and valves
- The pressure screen vibrating screen accepts must be controlled as follows:
    - Flowrate required at the low density cleaners must be delivered first and completely satisfied

    - The remaining water from the vibrating screens will be sent to regeneration, this is a low flowrate (~800 ℓ.min^{-1} **, Figure K-10**)
    - May require additional pump with associated piping and instrumentation
- Flat-box separator water to be sent directly to the low density cleaners

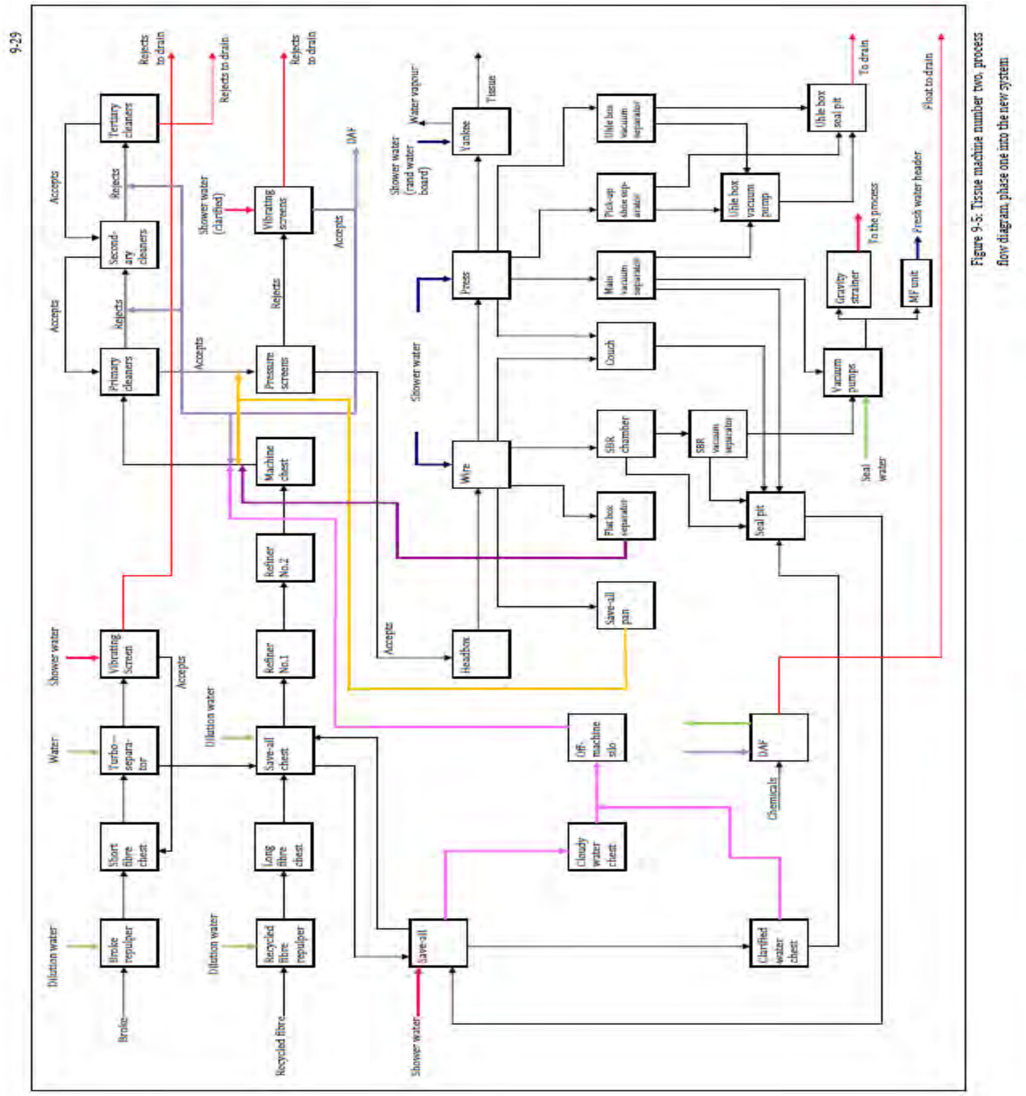

Figure 9-5: Tissue machine number two, phase one, recommended water network, this also corresponds to the system where the fresh water consumption was reduced through alternate connection between units.

9.4.3.2 (b) Phase two

- Additional tap-off points must be added to the broke repulper, recycled fibre repulper and save-all chest
- Replace the DAF with a rotary-disc filter, e.g. Petax™ system,
    - To reduce
        - Chemical costs
        - Fresh water costs (less 200 ℓ.min^{-1})
    - Water from here can go to tank previously used for DAF water storage
- Water from the SBR chamber and main vacuum separator must be sent to the microfiltration unit; this microfiltration unit will be cleaning the vacuum seal water
    - Vacuum seal water can be diverted back to old operation (hence the closing of the line rather than removal)
    - Tap-off points to turbo-separator, machine chest dilution water and vibrating screens and save-all showers must be added from the gravity strainers
- Water from the couch to be sent directly to the fan pump suction rather than being mixed with other water at the silo

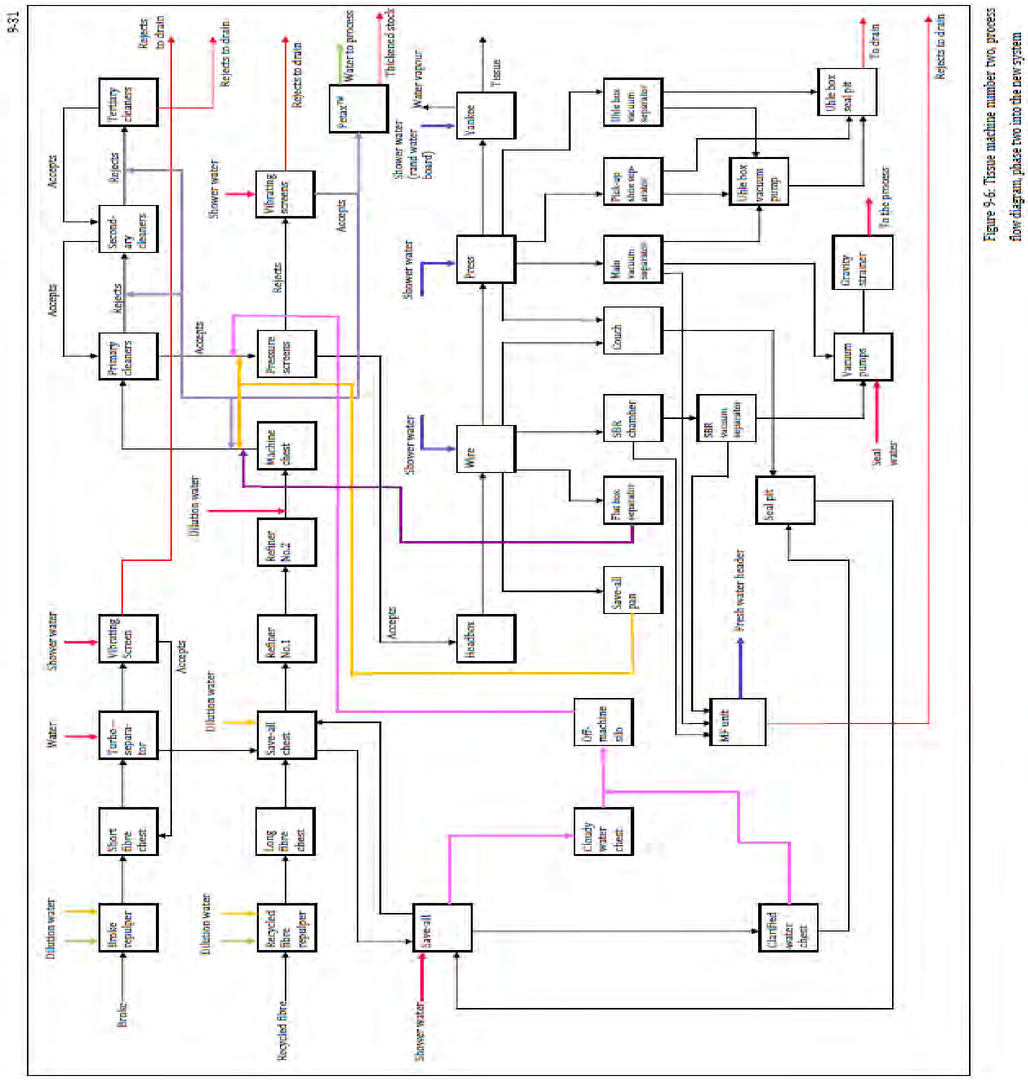

Figure 9-6: Tissue machine number two, phase two, recommended water network

9.5 Conclusion

The water networks developed in this chapter by the method of Prakash and Shenoy (2005) were designed to achieve the minimum water targets for tissue machine number one and tissue machine number two as determined by the ultimate flowrate targeting technique of Ng et al. (2009) in **Chapter 8**. These designed networks were used to determine the cost effectiveness in moving from the current system into the new recommended system. **Chapter 11** details the costs associated in implementing these systems.

Chapter 10 Cationic demand

This section describes in theory how the cationic demand will vary through the system, for both tissue machine number one and tissue machine number two, if uncontrolled. This is to provide some insight to the degree of variation of properties which are currently not posing a problem to the efficient operation of the system. As the water system becomes more tightly closed, problems may arise where properties, such as the cationic demand, which were previously not a control problem, may now become a factor which adversely affects operation.

10.1 Cationic demand theory and application

Bhardway et al. (2004) define cationic demand as the amount of cationic polymer needed to render the fibres isoelectric.

The paper/tissue making furnish (fibre and other material) has an electrical charge on its surface. This charge can have an effect on both the process and the product. The surface charge in a paper/tissue machine has a direct effect on the performance of retention and chemicals. Charge can also have an impact on sizing efficiency, deposit control and dewatering rates.

During their research study Hubbe et al. (2004) decided to include practical implications of charge measurement…*Charge effects in a papermaking furnish system are due to a form of static electricity… Hubbe et al. (2004).* The principle is based on like charges repel and opposite charges attract.

Charge on the fibre surface is due to:

- acidic and basic groups (e.g. carboxylic acid groups) on the surface. These groups can dissociate. The hydrogen ions (which have a positive charge) dissociates from the surface to become dissolved in the surrounding water, resulting in the fibre surface having a negative charge.
- charge can occur because of crystal structure

- charge can occur by adsorption i.e. charged particles such as colloidal material, salt ions and long-chain molecules (polyelectrolyte's) from the water attach to the surface of the fibres

One of the primary components of paper/tissue making furnish is cellulosic fibres. Due to ionisation of acidic groups of lignin and hemicellulose of the cellulose fibres causes them to possess a negative charge when suspended in water. Fatty acids and resin acids also contribute to the negative charge. (Bhardway et al., 2004)

Charge contributions to the paper/tissue making furnish come from various sources including:

- black liquor carry-over
- dissolved products of bleaching
- wood resins
- soaps used in deinking
- various paper/tissue making additives

The abovementioned sources usually contribute a negative charge to the papermaking furnish.

The various chemical and mechanical procedures which the fibres are subjected to effects the fibre morphology. According to Bhardway et al. (2004) the change distribution will vary with change in morphology.

The main method of charge determination is via titration. The aim of the titrations is to determine the surface and colloidal charge amount, per unit volume, of a sample of process water or fibre slurry (Hubbe et al., 2004).

If one considers a sample of white-water with an excess of negative charge; the cationic demand is the amount of positive polymer needed to exactly neutralise the negative charge. The most commonly used method of determining the endpoint of a charge titration is the streaming current or "SC" method.

> *…Zeta potential is defined as the electrical potential very close to the surface of a solid material immersed in a water solution. By knowing the magnitude of zeta potential, it is possible to estimate whether a suspension of particles will have enough mutual,*

electrostatic repulsion to prevent the particles from coming together…Hubbe et al (2004)

Two different methods can be employed to determine zeta potential depending on the sample. For small particles (fibres o fillers) microelectrophoresis (ME) is used. For charge near the surface of the fibres the 'fibre-pad' streaming potential (SP) method is employed.

The benefits of charge monitoring include troubleshooting, optimisation, control and development.

It must be noted that salts in the system effect charge determination. Manual testing should be done to obtain the best wet-end operation and to obtain the cost and amount of chemicals to be used, thereafter online control can be considered.

Hubbe at al. (2004) discuss that zero charge is not necessarily the best in practice; rather a *…good charge is a steady charge…Hubbe (2004)*

The usual range of charge concentration in paper/tissue making fibres is 20 $\mu eq.g^{-1}$ to 300 $\mu eq.g^{-1}$ (Bhardway et al., 2004).

When a system has a suspension which is relatively *dirty* it contains anionic trash as well as lignins. The *dirt* contribution to the pulp occurs when > 25 % of dirty pulp is used. These *dirty pulps* are pulps such as ground wood, thermomechanical pulp, recycled pulp and de-inked pulp. Due to the operation of systems with maximum recycling of white-water, suspensions may become dirty even if it is made with clean pulps. Clean pulps are considered as bleached or unbleached softwood and hardwood pulps.

Tanaka and Ichiura (1999) define the cationic demand as the amount of cationic polymer required to neutralise the charge of a suspension per given amount of stock solution.

In general, papermaking stock, industrial wastewater and suspended solids in municipal sewage have a negative charge (Tanaka and Ichiura, 1999). There is no standard method for determining cationic demand; the most commonly used is titration with appropriate cationic polyelectrolyte.

The closing of white-water circuits has become common practice in paper/tissue mills and this could lead to an accumulation of anionic trash in the system.

Anionic trash catchers reduce the cationic demand of anionic trash and hence decreases its' interaction with polymers.

The complete work of Zhang et al. (2009) has detailed trends on the effect of:

- pH on the cationic demand of filtrate samples
- dissolved colloidal substances on the filler retention in single retention system
- Anionic trash catchers dosage on the cationic demand of filtrate samples
- highly-substituted cationic-starch dosage on first pass retention in multi-component retention system
- dissolved colloidal substances with different DS on filler retention in multi-component retention system
- highly-substituted cationic-starch dosage on first pass ash retention in multi-component retention system
- filler retention of 20 % high-yield pulp containing furnish in different retention systems

It was found by Zhang et al. (2009) that the higher the dissolved colloidal substances (DCS) the higher the brightness. This high content of dissolved colloidal substances has an adverse effect on the first pass retention and first pass ash retention of high-yield pulp as well as on the filler retention of high-yield pulp. However with the addition of anionic trash catchers, higher filler retention can be achieved. Dissolved colloidal substances proved to be an efficient anionic trash catcher which improves the effectiveness of retention aids.

The cationic demand was selected as an additional parameter to monitor when the water are closed. The cationic demand is important because it affects the retention in the system, sizing efficiency, deposit control and dewatering rates. It is stated by Bhardway et al. (2004) that typical ranges are between 20 – 300 $\mu eg.g^{-1}$. The effect on the cationic demand on the closing of the water system was done by examining how the values would increase if the material balance was left uncontrolled with respect to cationic demand.

The cationic demand plays an important role in the retention of fires during formation; therefore the effect of the new recommended system on the cationic demand was investigated. The cationic demand was predicted using a mass based average in the material balance through the system.

10.2 Tissue machine number one cationic demand results

This section highlights the cationic demand trends predicted for tissue machine number one if the water network is closed and the cationic demand is left unmonitored and uncontrolled.

The cationic demand data was obtained by measurement of this parameter through the system. All testing was performed by S.A.Paperchem. In the analysis of the proposed water network which resulted of the pinch analysis, these measured values were used to compare with those iterated for using the mass balances. During the iterations it was assumed that there was no cationic demand control present in the system. The cationic demand data from the iteration on the material balance was compared to the experimental value; the lower (more negative) the cationic demand was used as the cationic demand value in the next iteration. This was to determine the effect on the system if the cationic demand was not controlled.

Figure 10-1 illustrates the cationic demand variation through the system for the existing operating system. It shows the change in moving through the system from the virgin fibre chest through the headbox. Due to chemical dosing there was some reduction of the cationic demand until it reached the headbox. It was observed that the white-water had a higher cationic demand than the furnish at the headbox. This was possibly due to the fines content in the white-water which causes a higher cationic demand because of the negative charge on the fines. **Figure 10-2** and **Figure 10-3** illustrate the trends observed for the cationic demand through the system for tissue machine number one. The remaining trends can be observed in **Appendix L.**

The regeneration unit considered should also aid in controlling the cationic demand as it will be removing fines from the system.

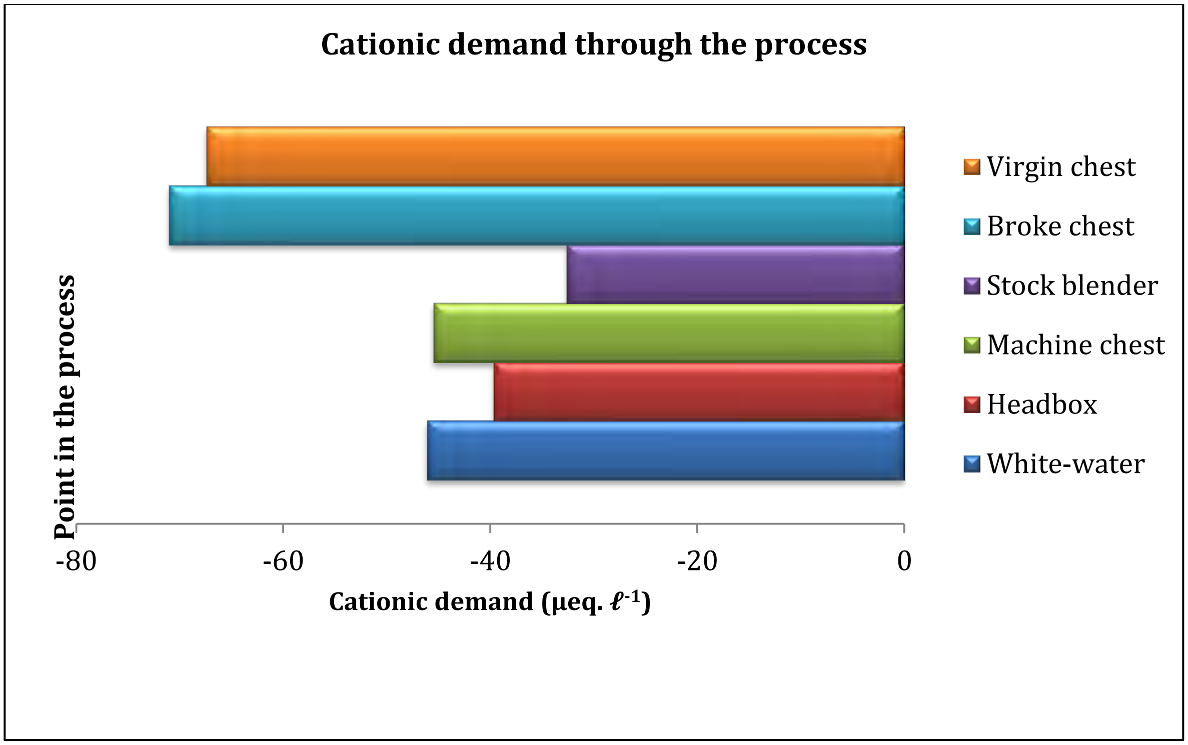

Figure 10-1: Variation of cationic demand through the process, tissue machine number one

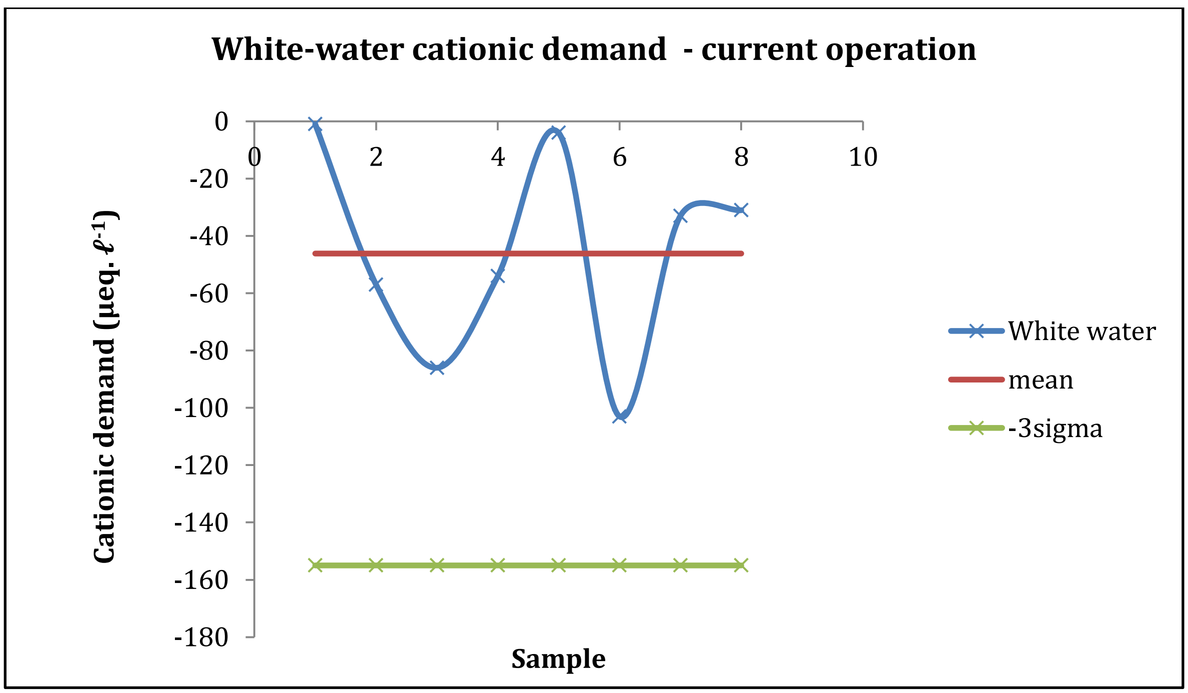

Figure 10-2: Tissue machine number one, cationic demand variation of the white-water. This corresponds to data measurements taken during the sample period. There was control of the cationic demand via dosing with an appropriate polymer

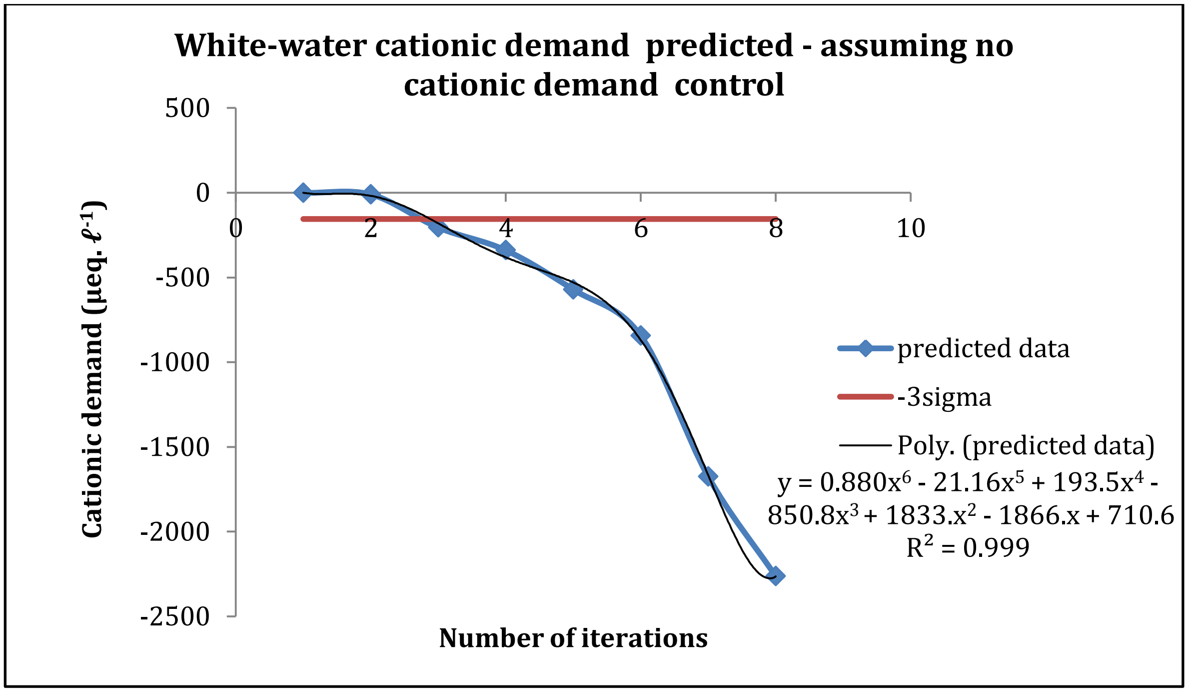

Figure 10-3: Tissue machine number one, predicted cationic demand values of the white-water in assuming no control of the cationic demand once the new network is implemented

10.3 Tissue machine number two cationic demand results

This section highlights the cationic demand trends predicted for tissue machine number one if the water network is closed and the cationic demand is left unmonitored and uncontrolled.

Figure 10-4 illustrates the cationic demand variation through the system for the existing operating system on tissue machine number two. It describes the change in moving through the system from the virgin fibre chest through the headbox. Due to chemical dosing there was some reduction of the cationic demand from the stock preparation through to the headbox. It was observed that the white-water has a lower cationic demand than the furnish at the headbox. In comparison to **Figure 10-1**, this indicates that there was possibly better retention on tissue machine two because fines in the white-water was the major contributor to cationic demand, therefore if the cationic demand was lower on tissue machine number two than on tissue machine number one, then the operating control was better on tissue machine two than on tissue machine number one.

The regeneration unit considered should also aid in controlling the cationic demand as it will be removing fines from the system.

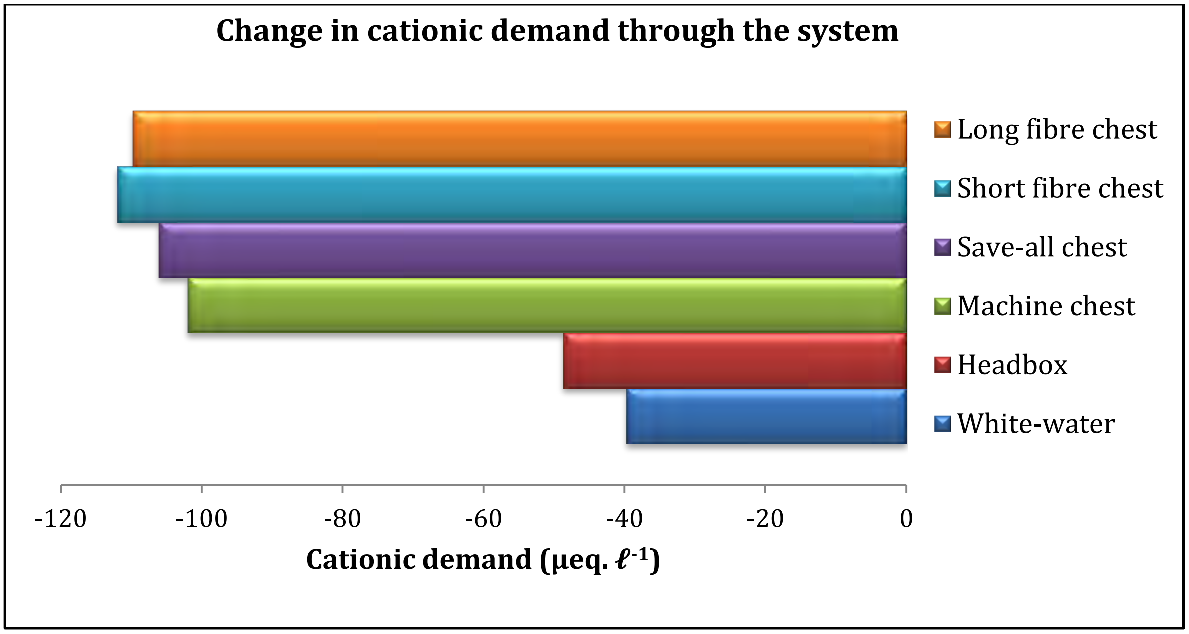

Figure 10-4: Variation of cationic demand through the process, tissue machine number two

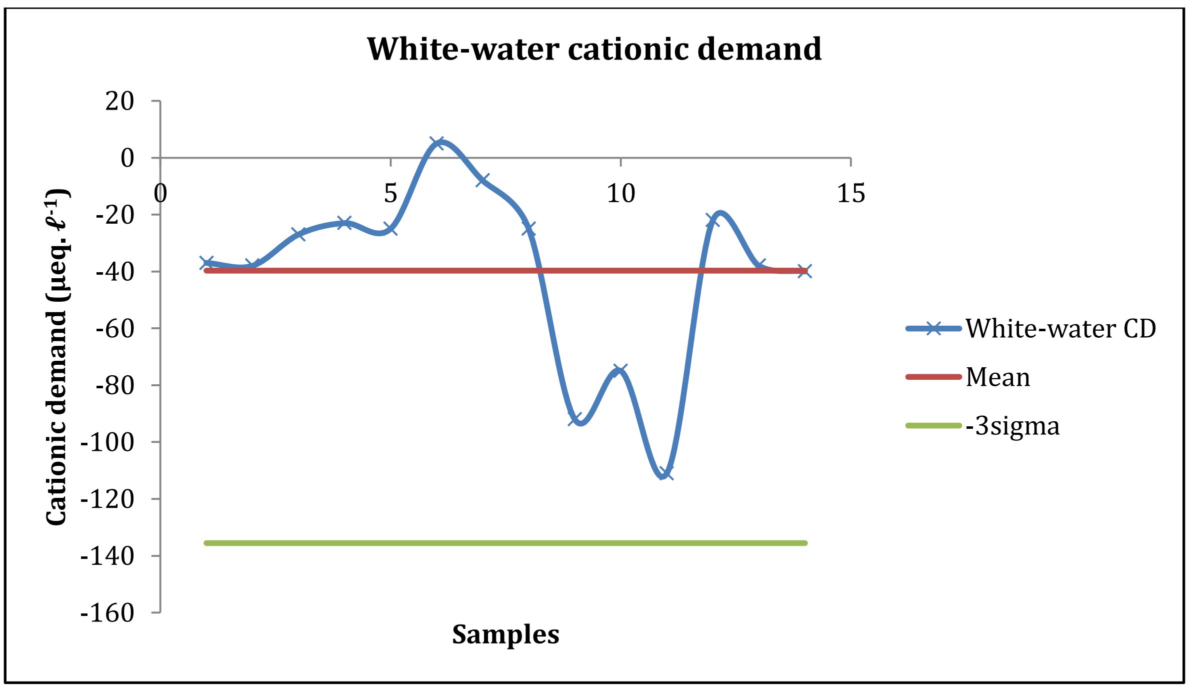

Figure 10-5: Tissue machine number two, cationic demand variation in the machine chest. This corresponds to data measurements taken during the sample period. There was control of the cationic demand via dosing with an appropriate polymer

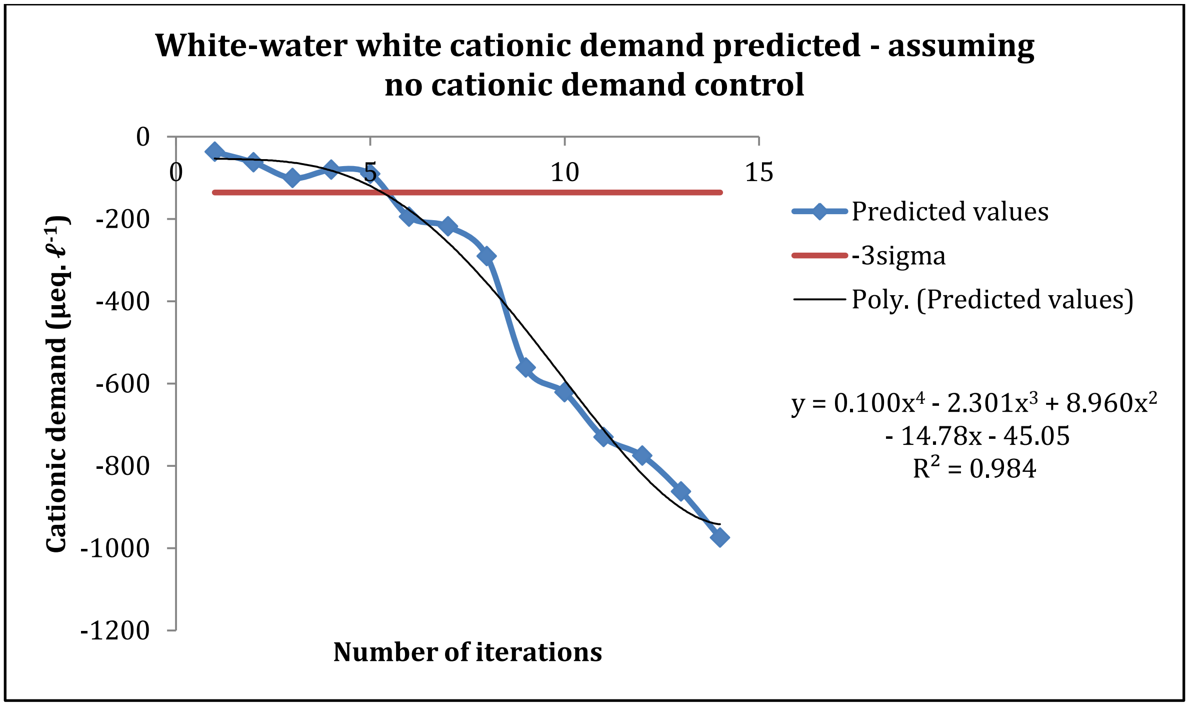

Figure 10-6: Tissue machine number two, predicted cationic demand values at of the white-water in assuming no control of the cationic demand once the new network is implemented

10.4 General discussion – cationic demand

Figure 10-2 and **Figure 10-3** and **Figure 10-5** and **Figure 10-6** and the figures in **Appendix L**. display a similar pattern. For present operation, the cationic demand increases (more negative) and decreases (more positive) periodically indicating the effectiveness of the system control in place. The cationic demand values are also always well above three standard deviations indicating that the control is effective.

According to Bhardway et al. (2004), the cationic demand value should fall between -20 µeq.g^{-1} and -300 µeq.g^{-1}. Observing the predicted plots for cationic demand for the sampled units for both tissue machines, it was noted that the cationic demand values extend below -300 µeq. g^{-1} after the third or fourth iteration. This is an exaggerated value because in the iterations the lower cationic demands were used, but the iteration procedure does not incorporate cationic demand control. From the graphs of the predicted cationic demand variation at the carious sampled units, it was observed that in order to maintain efficient operation of the system, the cationic demand must be efficiently monitored and controlled.

It must be noted that it has been assumed that the regeneration unit will have no effect on the cationic demand. From the literature it was noted that the unit will reduce the cationic demand (more positive) which has a favourable effect on retention. Therefore the predictions were an exaggeration. In practice the trends would appear as they appear for current operation.

The regeneration units selected will aid in controlling the cationic demand due to the removal of the cationic contaminants in the system. Together with this and the associated control of cationic demand, the system will not become over-cationised.

Chapter 11 Costing

This section contains the results obtained from the costing calculations performed. All quotes, indexes, and discounted operating cost statements and the discounted cash flow statements can be viewed in **Appendix M** (all calculation sheets are available on the memory stick.). It was assumed that the mill operates 365 days a year.

The fixed costs were assumed to be zero because it was assumed that engineers at the mill will be monitoring the operation of the unit and that mill's insurance will cover the newly installed units.

11.1 Tissue machine number one

It was determined that a suitable unit to achieve the required regeneration purity was a Petax™ fine filtration unit (**Chapter 7, section 7.3**). The costing and return on investment was determined as described in **Appendix M**. The cost of the Petax™ unit was obtained by direct quote from the suppliers for a unit sized to achieve the required regeneration. It was determined that two 20 disc units would be required. All associated costs were determined as described in **Appendix M.**

The following tables detail the costs calculated. The discounted cash flow statement is available in **Appendix M, section M.1.** The costing assumes that existing regeneration has been replaced by the Petax™ fine filtration unit.

The indirect costs have been quoted as a part of the direct costs. It was assumed that all fibre removed from the water by the regeneration unit was reused in the process.

Table 11-1: Breakdown of costs and savings associated with the installation of the Petax™ fine filtration unit on tissue machine number one

Breakdown of costs	R (1000000)	
Fixed capital investment (once-off)		11.48
Direct costs	11.48	
Indirect costs	N/A	
Operating cost (annual)		27.32
Fixed costs	N/A	
Variable costs	27.32	
Savings (annual)		29.73
Reduced water consumption	1.97	
Chemical reduction	1.92	
Power reduction	0.069	
Fibre recovery	25.75	

It was assumed that the units purchased will be paid back in ten years. Because there is no product being produced, and the costing is aimed to quantify the potential of the savings if the unit is purchased, the discounted cash flow statement was used; however it was assumed that there was not any tax because there was no sale of a product to make a profit. The discounted cash flow statement is available in **Appendix M**.

Return on investment – 17%

11.2 Tissue machine number two

It was determined that a microfiltration unit would be required to achieve the required regeneration (**Chapter 7, section 7.3**). The costing and return on investment was determined as described in **Appendix M**. The cost of the microfiltration unit was obtained by direct quote from the suppliers for a unit sized to achieve the required regeneration. All associated costs were determined as described in **Appendix M**.

The following tables detail the costs calculated. The discounted cash flow statement is available in **Appendix M, section M.2**. The costing assumes the addition of the microfiltration unit.

It was assumed that fibre removed from the water at regeneration was lost from the system and therefore an added operating cost.

11.2.1 Microfiltration unit and existing dissolved air flotation unit

The table below indicates the costs and saving associated with the membrane skid required and using the dissolved air flotation unit currently in the system to achieve the extra regeneration required. The save-all has been removed.

Table 11-2: Breakdown of costs and savings associated with the installation of the microfiltration unit on tissue machine number two with the dissolved air flotation unit for added regeneration

Breakdown of costs	R (1000000)	
Fixed capital investment		3.07
Direct costs	2.64	
Indirect costs	0.43	
Operating cost		2.18
Fixed costs	N/A	
Variable costs	2.18	
Savings		3.27
Reduced water consumption	3.11	
Power reduction	0.16	
Effluent reduction	-	

It was assumed that the units purchased will be paid back in ten years. Because there was no product being produced, and it was aimed to quantify the potential of the savings if the unit was purchased, the discounted cash flow statement was used; however it was assumed that there was not any tax because there no sale of a product to make a profit. The discounted cash flow statement is available in **Appendix M**.

Return on investment – 30.79%

11.2.2 Microfiltration unit and new Petax™

The economic benefit of replacing the replacement of the dissolved air flotation unit with the Petax™ fine-filtration unit was also investigated. Removing the dissolved air flotation unit would have a further reduction on operating costs because the associated chemical costs will be removed.

The table below indicates the costs and savings associated with the membrane required and the replacing the dissolved air flotation unit with a Petax™ fine-filtration unit.

Table 11-3: Breakdown of costs and savings associated with the installation of the microfiltration unit on tissue machine number two with the dissolved air flotation unit for added regeneration

Breakdown of costs	R (1000000)	
Fixed capital investment		11.52
Direct costs	8.37	
Indirect costs	3.15	
Operating cost		2.76
Fixed costs	N/A	
Variable costs	2.76	
Savings		5.29
Reduced water consumption	3.11	
Chemical reduction	1.93	
Power reduction	0.25	
Effluent reduction	-	

It was assumed that the units purchased will be paid back in ten years. It was assumed that the units purchased will be paid back in ten years. Because there was no product being produced, and it was aimed to quantify the potential of the savings if the unit s purchased, the discounted cash flow statement was used; however it was assumed that there was no tax because there no sale of a product to make a profit. The discounted cash flow statement is available in **Appendix M**.

- Return on investment – 16.74%

The return on investment for replacing the DAF with the Petax™ fine filtration units was lower than with using the microfiltration unit with the DAF currently in the system. This was because in **section 11.2.1**, only a single regeneration unit was assumed to be purached, that is, the microfiltration unit. In **section 11.2.1**, the DAF was replaced by the Petax™, which also must be purchased. Since both have the same pay-off period, it results in the latter option having a lower return on investment, however, this does not mean that this is a less efficient than the former; it should be better in the long-term as DAF chemicals will no longer be required.

11.3 Conclusion

From the costing procedure it has been determined that an investment in new technologies will have a cost benefit as well as associated process benefits. The regeneration units selected have the potential to remove the total suspended solids as well as chemical oxygen demand and biological oxygen demand.

This will allow for the process water to be re-used for the more stringent water purity requirements. These units prevent accumulation of chemical oxygen demand in the water system which will prevent scaling in the drying section and the removal of biological oxygen demand through these units will prevent slimes breakouts.

Chapter 12 Summary of results

The water cascade analysis of Ng et al. (2005) was performed on both tissue machine number one and tissue machine number two. Due to the difference in system constraints for each of the machines, the water cascade analysis has led to two vastly different solutions to alleviate the problem of excessive fresh water usage on each of the machines. This section summarises the key results obtained from the research study on both of the tissue machines.

12.1 General points to consider

- The aim of the study was to determine if a calibrated and verified material balance could be used to reduce the specific water consumption on a tissue machine
- A process integration approach was selected over equipment modifications because it offers a long term, cost effective solution (**Chapter 3**)
- The method selected after an extensive review (**Chapter 3**) was the ultimate flowrate targeting technique of Ng et al. (2009) (**Chapter 4**) because it was most suitable for application to this system
- Material balance process model was constructed on an Excel and Matlab platform (**Chapter 5** and **Appendix B** to **Appendix F**)
- Sampling and statistical data analysis were performed to obtain necessary process data (**Appendix A**, **Appendix C** and **Appendix D**)
- Sampling period data and process data were used to calibrate the material balance
- A process model was used to determine water requirements at varied operating conditions
- Pinch point and fresh water region - regenerated water region process configurations were performed to determine the bottleneck in the system and the minimum fresh water, regeneration and effluent flowrates (**Chapter 6** and **Chapter 8**)
- For a detailed comparison the following various water cascades were considered:

Table 12-1: The various water cascade analysis performed on tissue machine number one and tissue machine number two

Tissue machine one				Tissue machine two			
Current regeneration replaced by the proposed regeneration unit		**Existing regeneration considered with addition of the proposed regeneration unit**		**Current regeneration replaced by the proposed regeneration unit**		**Existing regeneration considered with addition of the proposed regeneration unit**	
Operating conditions	Worst case operation	Operating conditions	Worst case operation	Operating conditions	Worst case operation	Operating conditions	Worst case operation
a b c d e f	a b c d e f	a b c d e f	a b c d e f	a b c d e f	a b c d e f	a b c d e f	a b c d e f

a. Water cascade analysis to determine the pinch point

b. Confirm the global pinch determination by assuming the regeneration of the pinch stream. Doing this the pinch should shift to the effluent stream as this should be the stream which now limits total reuse of water in the system

c. Fresh water region process configuration where all streams with contaminant concentration below the regeneration concentration are found in the fresh water region

d. Regenerated water region process configuration where all streams with contaminant concentration above the regeneration concentration are found in the regenerated water region

e. Fresh water region process configuration where the reallocation procedure followed is such that the material flows in the fresh water region and regenerated water region are exactly balanced as in Ultimate flow rate targeting technique of Ng et al with regeneration placement (2009). This will result in sinks of $C_{sink} > C_{reg}$ present in the regenerated water region

f. Regenerated water region process configuration where the remaining sources and sinks after fresh water region process configuration from (e) has been performed will be present in this regenerated water region

12.1 Tissue machine number one

- Initial pinch analysis identified the vibrating screen accepts as the pinch causing stream (**Chapter 6, section 6.2**)
- An extensive literature survey lead to the Petax™ fine filtration system being selected as the unit to achieve the desired regeneration (**Chapter 7**, **section 7.3**)
- The various cascades analyses were compared for the best process configuration for water usage reduction (**Chapter 8, section 8.1**)
- This was determined to be the fresh water region - regenerated water region process configuration which corresponds to the reallocation procedure described by Ng et al. (2009)
- Appropriate water networks to achieve the minimum targets was developed using the nearest neighbours algorithm of Prakash and Shenoy (2005). Only that of the absolute minimum targets was designed for (**Chapter 9**)
- Reducing the water consumption by only altering the water network was also investigated. It results in a reduction from 21 kℓ.ton^{-1} tissue manufactured to ≈11 kℓ.ton^{-1} tissue manufactured (**Figure 9-2**)
- A systematic progression in shifting from the current system to the new recommended system is described in **section 9.3.3**; it is a two stage process (**Figure 9-3** and **Figure** 9-4)
- The recommended system theoretically has the potential to reduce the specific water consumption from 21 kℓ.ton^{-1} to ≈7 kℓ.ton^{-1}. It considers a single regeneration unit, which is, the Petax™ fine filtration unit of 5000 ℓ.min-1 capacity and 25 disks. All other regeneration units have been removed.
- This system theoretically has the potential to reduce the fresh water consumption, the regeneration flowrate, effluent to treatment, power consumption and chemical costs (**Chapter 11, section 11.1**)

- The method has been proved to be accurate in determining the minimum fresh water, regenerated water and effluent flowrates provided that it is applied correctly and that an accurate material balance is available
- The variation in the cationic demand through the new system was investigated. If the system is left uncontrolled, the cationic demand will increase exponentially (**Chapter 10, section 10.2**). Therefore increased monitoring through the system is required
- There will be a fixed capital investment of R 11.48 million required if the recommended system is considered (**Chapter 11, section 11.1)**
- The recommended system will have an annual operating cost of R 27.32 million with an annual savings of R 29.73 million
- The return on investment for the recommended system is 17 % assuming a ten year payback period for the equipment purchased
- Total expected benefits
    - improved process water quality
    - reduced chemical oxygen demand
    - reduced biological oxygen demand
    - reduced fresh water consumption

12.2 Tissue machine number two

- Initial pinch analysis identified the water from the main vacuum separator and SBR chamber or vacuum pumps (**Chapter 6, session 6.3**)
- Extensive literature survey lead a microfiltration unit being selected as the unit to achieve the desired regeneration (**Chapter 7**, **section 7.3**)
- The various cascades analysed were compared for the best option for water usage reduction (**Chapter 8, section 8.2**)
- This was determined to be the fresh water region - regenerated water region process configuration which corresponds to the reallocation procedure described by Ng et al. (2009)
- Appropriate water networks to achieve the minimum targets was developed using the nearest neighbours algorithm of Prakash and Shenoy (2005). Only that of the absolute minimum targets was designed for (**Chapter 9**)

- Reducing the water consumption by only altering the water network was also investigated. It results in a reduction from 25 kℓ.ton^{-1} tissue manufactured to ≈21 kℓ.ton^{-1} tissue manufactured (**Figure 9-5**)
- A systematic progression in shifting from the current system to the new recommended system is described in **section 9.4.3**; it is a two stage process (**Figure 9-5** and **Figure** 9-6)
- The recommended system theoretically has the potential to reduce the specific water consumption from 21 kℓ.ton^{-1} tissue manufactured to ≈8 kℓ.ton^{-1} tissue manufactured. It considers a single regeneration unit, which is, the microfiltration unit of 1000 ℓ.min^{-1}. All other regeneration units have been removed
- This system theoretically has the potential to reduce the fresh water consumption, the regeneration flowrate, effluent to treatment, power consumption and chemical costs
- The method has been proved to be accurate in determining the minimum fresh water, regenerated water and effluent flowrates provided that it is applied correctly and that an accurate material balance is available
- The variation in the cationic demand through the new system was investigated. If the system is left uncontrolled, the cationic demand will increase exponentially (**Chapter 10**). Therefore increased monitoring through the system is required
- For the costing process, two separate calculations were performed; one purchasing the microfiltration unit only and using the existing dissolved air flotation unit in the system for the added regeneration, and the second considers removing the dissolved air flotation unit and replacing it with a Petax™ fine filtration system. In both cases the save-all has been considered as removed from the process (**Chapter 11, section 11.2**)
- Microfiltration unit and existing dissolved ait flotation unit (**Chapter 11, section 11.2.1**)
    - There will be a fixed capital investment of R 3.07 million required if the recommended system is considered
    - The recommended system will have an annual operating cost of R 2.18 million with an annual savings of R 3.27 million
    - The return on investment for the recommended system is 30.79 % assuming a ten year payback period for the equipment purchased
- Microfiltration unit and new Petax™ fine filtration system (**Chapter 11, section 11.2.1**)
    - There will be a fixed capital investment of R 11.52 million required if the recommended system is considered

  - The recommended system will have an annual operating cost of R 2.76 million with an annual savings of R 5.29 million
  - The return on investment for the recommended system is 16.74 % assuming a ten year payback period for the equipment purchased
- Total expected benefits
  - improved process water quality
  - reduced chemical oxygen demand
  - reduced biological oxygen demand
  - reduced fresh water consumption

Chapter 13 Overall discussion for the project

Excessive water consumption in the pulp and paper industry, as well as in other industries, is a problem which can no longer be ignored. Water, a previously abundant resource, is becoming increasingly expensive; due the large quantities required; this has impacted heavily on the pulp and paper industry. Combined with stringent environmental regulations, this has resulted in a drive towards more efficient water treatment and reuse. One of the main obstacles faced is that most treatment has little or no economic benefits,

More efficient water reuse has always been important in the industry (**section 2.2**) but priority is usually given to changing from one regeneration unit to another as the regeneration technology changes, that is, the same process streams are regenerated by different regeneration units; research is not usually conducted to investigate where the regeneration unit would be effectively placed to achieve the required regeneration or to investigate the best possible connection between units. It is this concept that this research project aims to bring to light; that time should be taken to investigate various regeneration possibilities and network configurations before selection and placement of regeneration units occurs. The ultimate aim being to reduce the specific water consumption, in this case the research was conducted on the tissue machines at KCSA but the concept of process integration methods can be applied to any industry to bring about a reduction in the water consumption.

When such a task is undertaken, due to the intense amount of work required, there needs to be an understanding between the plant and the individuals conducting the research because of the requirements and the demands of the project. It is in no way a small feat to take on a project of this magnitude and adequate support is required from the mill personal.

Such projects are usually done by consultant companies; this project aims also to illustrate the potential of applying a process integration method; the method being an appropriate water pinch technique.

The concept of process integration is well known but it has been more extensively developed for energy (thermal) pinch analysis. In recent years there has been significant work in developing and applying the concepts of energy pinch analysis to develop methods for utility pinch analysis.

Initial work was based on systems where water is used mainly as a mass separating agent, that is, the flowrate of water into and out of the process was from a material balance perspective, unchanged; the main concern in these methods was the contaminant removed from the system.

However this concept of water merely being a mass separating does not apply to all process; in many processing systems water forms an intricate part of the process, this is the system that occurs in the pulp and paper industry. Recent works have been developed for such systems. It is therefore important, when deciding on applying a water pinch analysis method, that the type of system is understood so that an appropriate method can be selected, because an inappropriate method would obviously produce inaccurate results and associated analysis.

At the time of commencement of the project (March 2010), the most appropriate method available was that of Ng et al. (2009), the ultimate flowrate targeting technique with regeneration placement. The procedure is a non-iterative numerical pinch analysis procedure capable of determining the global pinch point of a multiple pinch problem in a single calculation step. The method has also been automated but it is not applicable to all processing systems as yet and therefore was not considered. It was also suggested by Bedard et al. (2001) that if such a detailed analysis is required that it requires an automated approach then it is best approached using verified software package available for the system under investigation.

One of the biggest challenges faced in the project was acquiring process data. The plant must be invested in the project, in order to obtain accurate results from the study and it should be made clear as to which are the significant parameters of operation. If parameters are included as important, the plant must make it a priority to ensure that all data needs required regarding these parameters, are readily available.

For the purpose of the project, the total suspended solids in the process water were considered as the most vital parameter in respect to total water reuse. The effect on the cationic demand was included to get an idea of how, in theory, the other parameters may vary if the recommendations from the project are implemented.

In order to determine the values of the total suspended solids and cationic demand variation through the system, data sampling was required because insufficient information was available in the system or on the piping and instrumentation diagrams. The data was then used to determine the material flowrates through the system. All details are discussed in **Chapter 5**.

When performing the water pinch analysis, the candidate feels it best that one uses actual process data for the sources. The sink contaminant concentrations can be set at some maximum allowable value to ensure that water requirements will be met. The maximum allowable values of he sinks can be determined from the equipment specifications. The sources however should be tested to determine the contaminant concentrations and these data values should be used in the water pinch analysis; this is used to investigate the system capability, that is, what quality sources can actually be produced by the system? The concept behind using the actual system data for the sources is that one cannot ensure that sources are going to be available at certain desired contaminant concentrations or between ranges of contaminant concentrations that we require because this depends on the system operation. If one theoretically fixes these data points into a range which is wanted, it will result in an inaccurate representation of the system and therefore an inaccurate water pinch analysis. A realistic approach to the problem is 'how can I use what I have more efficiently?' rather than 'what are the ideal contaminant ranges for the water sources and sinks in order to achieve favourable results?'; the latter is impractical because many process changes will have to made in order to get the system operating in the 'ideal' range which you have set for the system; it will also require very stringent process control which even at the best of operation is difficult to manage.

From the results obtained, it was determined that applying a water pinch approach does have an advantage because it identifies the point in the system which is limiting reuse of water in the system, that is, the pinch point. This pinch point is important because it is around this point where regeneration efforts should be focused. If regeneration occurs away from this point, then it will not have as a big effect in the reduction of fresh water as it would have if regeneration occurred around the pinch point, that is, regeneration efforts are less effective as you regenerate further away from the pinch point. This is the purpose of performing a pinch analysis; it gives a clear indication of the most efficient point at which to regenerate. The method applied to this study (the ultimate flowrate targeting technique of Ng et al. (2005))

has the added advantage of also targeting for the minimum regeneration flowrate and the minimum effluent flowrate aside from just identifying the pinch point and determining the minimum fresh water consumption. The disadvantage of the method is that it does not take into account the stream which will be regenerated when targeting for the minimum regeneration flowrate; this results in an inaccurate representation of the effluent discharged in the regenerated water region. This must be kept in mind when applying this particular method.

When considering regeneration, the regeneration requirements must be understood and only after an extensive literature survey should the most effective and appropriate unit be selected. This is detailed in **Chapter 7, section 7.2** and **section 7.3**. This resulted in the selection of a Petax™ fine filtration unit for tissue machine number one and a small microfiltration unit for tissue machine number two.

Comparing the pinch analysis for each of the tissue machines, it was observed that the pinch analysis methods are very sensitive to the contaminant concentrations allowed to the sinks and the contaminant concentrations of the available sources. The more stringent the requirement, the more fresh and regenerated water required. The comparison between the two tissue machines showed this. On tissue machine one the requirements were more stringent therefore a larger amount of fresh water and regenerated water was required as compared to tissue machine number two. Tissue machine one and tissue machine two have almost the same minimum freshwater requirement even though tissue machine number two has a higher production rate. This was because the constraints were more relaxed on tissue machine number two - this resulted in the cleanest water source being the limiting water source and hence the selection of the membrane filtration unit as the most appropriate regeneration unit. The minimum regeneration flowrate for tissue machine number one was also much higher than that of tissue machine number two (5000 $\ell.min^{-1}$ for tissue machine one versus 1000 $\ell.min^{-1}$ for tissue machine number two) because of the difference in allowable contaminant concentrations to the demands.

From this study it was determined that careful attention should be given to operation of the vacuum, the wire and press sections. The operation of these sections impacts heavily on the source contaminant concentration. It should be determined which vacuum levels are the optimum and these should be monitored and maintained; they are currently being monitored but must be confirmed regularly to ensure optimum operation.

The water networks developed for tissue machine number one and tissue machine number two to achieve the minimum targets have been developed such that the new network is as close as possible to the existing network but with regeneration focussed at the optimum point (pinch point) determined from the water cascade analysis. In this way, it was attempted at avoiding accumulation of contaminants in the system which were not previously a problem but due to increased recirculation of process water in the new network, it may now pose a problem in the future. Possible problems include accumulation of BOD, COD and scaling at the Yankee.

With the increased recycling, there will be a temperature rise in the system. This will have a positive effect on retention as well as a lower thermal demand at the Yankee. It will also have an effect on the moisture content of wet web, that is, the moisture content will be reduced. A 1 % reduction in moisture content corresponds to a 4 % reduction in energy requirement during drying.

The recommended system resulting from the water pinch analysis also has the advantage of reduced effluent to effluent treatment, lower chemical costs and lower energy consumption because of removal of obsolete equipment (**Chapter 8** and **Chapter 11**).

This study has shown that this type of analysis has the potential to bring about substantial reduction in utilities. The method is proven to be successful if applied as described by Ng et al. (2009). Theoretically the savings are ≈ 67 % of the current water consumption. It does rely heavily on the accuracy of the material balance therefore effort must be made by the plant to ensure data requirements are provided timeously in order to achieve accurate results.

Costing performed as described in section **Chapter 11**, indicated that a good return on investment can be expected on the purchase of the new regeneration units because of the savings associated with the new recommended regeneration units and water network configuration.

This study marks the beginning of a conversation regarding water network and regeneration optimisation. This is the first step in the pinch analysis procedure, it has identified the potential of the method to contribute to water consumption reduction and it is from this point where the analysis needs to be developed further, if required. The next step, if more detail is required, would be to apply a verified simulation programme such as WINGEMS which has been specifically designed for the pulp and paper industry in combination with a water pinch programme such as WaterPinch, so that analysis can be taken a step further and so that a greater range of contaminants can be considered.

Considering the topic of investigation, whether a calibrated and verified material balance can be used to reduce the specific water consumption, it has been proven that it can. In theory the system has the potential to achieve good return on investments due to the resulting savings. Water pinch analysis provides a detailed, transparent analysis of the water usage at a plant and identifies the bottlenecks in the system which limits total reuse of water within the operating system; it also identifies the absolute minimum fresh water requirement, minimum regeneration flowrate and the minimum effluent flowrate for a given system and it aids in the determination of correct regeneration placemen. The water network to achieve the determined minimum water targets can be developed from one of the various water network development techniques. Water pinch analysis is a tool which should be considered in all areas of the production industry for a cost effective, long term, water reduction strategy.

Chapter 14 Conclusions

The aims of the study were highlighted in **Chapter 1, section 1.3**. A calibrated and verified mass balance of the mill's tissue making processes was developed as described in **Chapter 5, Appendix E** and **Appendix F**.

These material balance models were used to assess the corresponding change in specific water consumption for each machine through rerouting of process streams and installation of new equipment and the environmental impacts thereof by applying the method of Ng et al. (2009). This is presented in **Chapter 6, Chapter 7, Chapter 8** and **Chapter 9**.

An improvement strategy is presented in **Chapter 9** in moving from the current water system to the proposed system which was a result of the pinch analysis.

The pinch analysis technique proved to be effective in providing a systematic approach to reduce the specific water consumption.

It was determined from the study that various methods are available and their applicability is dependent on the type of process under investigation. It is therefore important that the process under investigation be understood before the pinch analysis method is selected.

The method most applicable to the tissue making process was the ultimate flowrate targeting technique of Ng et al. (2009) (**Chapter 3** and **Chapter 4**). This method was able to identify the pinch point of a multiple pinch problem and determine the minimum fresh water, minimum regenerated water and minimum effluent flowrate that can be achieved on each of the tissue machines. The pinch analysis method can also be used to investigate the degree of regeneration which is required. This is described in **Chapter 7, section 7.2**. It was determined that a fine filtration unit would be required for tissue machine one and a microfiltration unit would be required for tissue machine two. These selected units were applied to the ultimate flowrate targeting technique.

These regeneration units were applied across the pinch point. This was because if regeneration occurs above the pinch point there is a reduction in the effluent flowrate only. If regeneration occurs below the pinch point there is a reduction in fresh water only. Therefore to reduce the fresh water, the regenerated water and the effluent water, regeneration must occur across the pinch point. This is described in **Chapter 4**.

It was identified from the pinch analysis that the regeneration required was sensitive to the total suspended solids of the sources in the system. This was observed from the two different pinch points which occur for the different tissue machines. The tissue machine one pinch point was the vibrating screen accepts and that of tissue machine two was the main vacuum separator and single breast roll chamber or the vacuum pumps.

It was also identified that the pinch analysis and associated regeneration requirement was highly dependent on the operation of the vacuum, press and wire sections because of the effect of these section on the source contaminant concentration.

By applying the method of Ng et al. (2009) it was determined that there can be a potential reduction in the fresh water requirement by ~60% on both the tissue machines. This will have a corresponding effect on the effluent flowrate.

It was identified from the water cascade analysis operation that the disadvantage of the method of Ng et al. (2009) was that it did not remove the regeneration flowrate from the source flowrate which was selected for regeneration; it therefore did not provide an accurate representation of the effluent flowrate from the regenerated water region. This was overcome by removing the regenerated flowrate from the targeted minimum effluent flowrate and verifying the removal of the flowrate via an overall material balance.

By applying the nearest neighbour's algorithm of Prakash and Shenoy (2005), water networks to achieve the targeted water flowrates from the pinch analysis was developed. Using these water networks an improvement strategy in moving from the current water system to the recommended system was developed. This is described in **Chapter 9**.

The contaminants of interest were the total suspended solids and the cationic demand. As the water network is closed there could be possible accumulation of contaminants which were not considered in the research study. It was observed in Chapter 10 that there will be an increase in the cationic demand of the system if it is left untreated. This can also occur with chemical oxygen demand and biological oxygen demand. There could be an added adverse effect of precipitation at the Yankee due to the increased recycle of the process water. Therefore if the water system becomes more closed, these parameters must be closely monitored and effectively treated if required.

However it must be noted that the effective placement of an appropriate regeneration unit across the pinch point will have a reduction in total suspended solids, chemical oxygen demand and biological oxygen demand which in its reduction is a benefit on its own.

Another added benefit is due to the increased recycling of process water there could be an increase in the temperature profile across both the tissue machines. The increase in temperature will have associated reduction in the energy requirement for drying. It will also aid in retention of fibre across the wire which will also improve the process water quality.

The advantage of the process integration approach is that it provides a solution to reduce the fresh water consumption which is based on a sound theoretical basis. The analysis clearly identifies the bottleneck which limits the utility reuse in the system. By appropriately treating the bottleneck in the system the water reuse can be increased.

The research study was conducted in a very detailed procedure which considered various operating conditions, regeneration possibilities and numerous network configurations; all this was used to compare the different solutions obtained from the application of the pinch analysis technique. From these solutions obtained the most cost effective (but appropriate) solution was selected and then costing was determined for the selected system. However, whilst a detailed approach was taken in this research study, the procedure can be applied first to a general system and then the detailed analysis can be undertaken only if necessary. For example, in this study, the pinch point could be determined from a less detailed material balance by using general process flows and assumed contaminant concentrations. Once the pinch point was determined from the preliminary analysis, then testing and data analysis could be performed on the area around the initial pinch point and then the pinch analysis re-performed. This would reduce the amount of sampling and data analysis required. This approach will still be successful because it is only the sources and sinks near the pinch which have a significant effect on the minimum water targets and therefore the same result as that of he detailed procedure would be obtained.

Water pinch analysis can be applied to a processing system. The type of processing system must be identified so that an appropriate pinch analysis method can be selected for application to the system such that the results produced from the pinch analysis will be accurate and that it will result in the reduction in the fresh water consumption of, and effluent produced from, a process.

Chapter 15 Recommendations

This study has shown that a pinch analysis method can be an effective tool to reduce the specific water consumption. It is therefore recommended that:

1. A consulting company should be approached to perform a pinch analysis which incorporates more contaminants and consider more process properties into the analysis. The consulting company will also be able to simulate various process scenarios.
2. A simulation package which is specifically designed for the pulp and paper industry be used in conjunction with a water pinch analysis package to perform the analysis on the tissue machines

In the simulation of the process and associated water pinch analysis, the effect of a more closed water network on the biological oxygen demand and the chemical oxygen demand and also investigate the possibility of precipitation on the Yankee dryer.

In addition to this the following has been identified that the vacuum, wire and press sections must be carefully monitored to ensure that the system is maintained at the appropriate operating conditions.

Process parameters which need to be monitored include:

- Vacuum levels
- First pass retentions
- Refining energies
- Chemical dosing rates in the system
- Chemical dosing at the dissolved air flotation units
- Dissolved air flotation unit efficiencies

Chapter 16 References

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