APPLICATION OF WATER NETWORK OPTIMIZATON AT MPACT LTD, SPRINGS MILL

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Declaration

I, Leshen Vurdiah, declare that

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Abstract

The pulp and papermaking industry is highly water intensive. Many factors such as environmental concerns, rising costs of fresh water and effluent disposal have prompted mills to reduce their fresh water demand. This can be accomplished by water network closure, which is the replacement of fresh water with regenerated process water. A completely closed system has been implemented in some mills with substantial investment in water treatment units. But, for most mills capital investment is limited and contaminant accumulation due to network closure is a concern. This problem has been addressed by the application of water pinch investigations at paper mills. However, these methods are severely limited to a single contaminant analysis. This project sets out to address this limitation by developing a numerically based method that can optimize a multi-contaminant system. The water network for Board Machine 3 and clarification at the Mpact, Springs mill was investigated. For this first stage investigation, total suspended solids (TSS) and chemical oxygen demand (COD) were selected as the contaminants to be investigated. The material balance of the system was developed and solved in Excel. These results were verified by stream property measurements and used to verify and initialize the optimization program written in the General Algebraic Modelling System (GAMS) software. The water network structure was successfully optimized and the reduced fresh water requirement was calculated by substitution of the fresh water used for high pressure showers with regenerated water. Furthermore, a range of regenerated water TSS concentrations were evaluated. The resulting fresh water reduction curve identified the point at which COD concentrations limit further fresh water reduction. Reaching this critical point requires the installation of suspended solids removal units to consistently produce water with a TSS concentration of 28 ppm or less. Further improvement requires treatment units for COD reduction such as aerobic or anaerobic systems which represent a large capital investment. For this reason, it was decided that the critical point for this study would be the network closure at which COD became limiting, corresponding to a fresh water reduction of 31% from 819 tons/day to 569 tons/day. A control scheme to effect the fresh water replacement was also proposed.

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Nomenclature

Parameters	Description
$A_{h,i}$	Binary parameter representing network connection existence between source i and sink h 0 = no connection 1 = connection exists
$PC_{j,k}$	Process stream j composition for contaminants k
$TotSource_{i}$	Total flow from source i
$TotSourceComp_{i,k}$	Total flow from source i composition for contaminants k
$Flow_{h,i}$	Flow from source i to sink h
$FlowComp_{h,i,k}$	Compositions of flows from source i to sink h for contaminants k
$TotSink_{h}$	Total flow to sink h
$TotSinkComp_{h,k}$	Composition of total flow to sink h for contaminants k
Q	Heat duty
x	Stream total suspended solids weight fraction
y	Stream chemical oxygen demand weight fraction
Subscripts	
h	Sinks
i	Sources
j	Process stream
k	Contaminants

Abbreviations

CMW	Common mixed waste
COD	Chemical oxygen demand
DICOPT	Discrete and continuous optimizer
DOF	Degree of freedom
ERWAT	East Rand Water Care Company
FWRR	Fresh water replacement ratio
GAMS	General algebraic modelling system
ISO	International Organization for Standardization
M	Mixer
MINLP	Mixed integer non-linear problem
NLP	Non-linear problem
PAMSA	Paper Manufactures Association of South Africa
PRASA	Paper Recycling Association of South Africa
FWD	Fresh water demand
S	Splitter
SA	Save-all
SAWC	Save-all water chest
TAPPI	Technical Association of the Pulp and Paper Industry
TDS	Total dissolved solids
TSS	Total suspended solids
TU	Treatment unit
U	Process unit
WP	Waste plant
WPA	Water pinch analysis
WWC	White water chest
UKZN	University of KwaZulu-Natal

Glossary

Active constraint	The subset of constraints that limit further improvement of the objective variable during optimization.
Backwater	Machine water recovered from the forming and press sections of a paper machine to be sent back to the approach flow and stock preparation.
Consistency	The fibre mass fraction of a pulp or paper mill process stream expressed as a percentage.
Constraint	The set of equality and inequality relationships that impose boundaries on the solution space of an optimization problem.
Contaminant	Any undesirable species present in a process or water network stream that may negatively impact mill operability.
Fibrillation	The physical removal of the fibre primary wall and release of fibrils to increase the surface area, promote inter-fibre bonding and fibre hydration.
Furnish	The stock mixture consisting of fibre, water, chemicals and any other materials entering the paper machine.
Langelier Saturation Index	An approximate indication of calcium carbonate saturation of a water stream. The index will indicate streams with a high potential for either corrosion or scaling.
Marginal value	The change in the optimized objective variable by relaxing a constraint and making a unit change in the constraint value.
Mixer	The hypothetical unit in which multiple source streams of varying quality may enter and a single outlet stream leaves. Composition of the outlet stream is determined by material balance across the mixer unit.
Sink	The water demand of a process or treatment unit to be met by its associated mixer unit. Process units may have multiple sinks if different water quality water streams are required.
Sizing	The process whereby the paper or paper board product's resistance to liquid penetration is increased.
Source	Any water stream that can be re-used elsewhere in the water

	network structure in order to reduce the fresh water source demand.
Splitter	The hypothetical unit in which a single stream from a process or treatment unit is split into multiple source streams. The source streams have the same composition.
Stickies	Tacky contaminants found in recycled paper mills originating from adhesives and waxes in the raw material.
Super structure	The hypothetical structure in which all network connections are possible.

1. Introduction

The paper making process is highly water intensive and paper mills no longer have the luxury of unlimited water resources (Thompson et. al., 2001; Parthasarathy and Krishnagopalan, 2001; Abou-Elela et. al., 2008). Effluent discharge also needs to be reduced due to increasing pressure of environmental legislation that imposes discharge limits on industries (Iancu et. al., 2009; Bagajewicz et. al., 2000; Castro et. al., 1999; Tokos et. al. 2013). In addition, International Organization for Standardization certification, ISO 14001, is renewed every four years with annual surveillance audits conducted to ensure compliance. The reduction of fresh water usage not only benefits the environment but also has financial benefits such as reduced energy costs from heating fresh water; effluent volume reduction and hence lower disposal costs to municipalities and the recovery of usable fibre.

There are however risks to reducing the fresh water usage such as the build-up of *contaminants* in the water recycle loop that may be detrimental to product quality, and the increased process unit sensitivity to fluctuations because of the greater interdependence (Parthasarathy and Krishnagopalan, 2001). Even though water network closure has its risks, the systematic application of established techniques can greatly improve mill economics without jeopardising mill operation. Although fresh water usage is moderate at the Mpact, Springs mill, it can be halved based on international best practice (McDonald, 2004).

1.1 Mill description

The Mpact, Springs mill in the Gauteng region, Figure 1-1, was opened in 1954. It is situated in the Upper Vaal water region and uses 4 ML/d of fresh water which is supplied by the East Rand Water Care Company (McDonald, 2004). Effluent water is sent to the East Rand Water Care Company (ERWAT) wastewater treatment facility before discharge to river. Mpact is located in close proximity to two pulp and paper mills: Sappi Paper and Paper Manufacturing, Enstra mill and the Kimberly Clark tissue and converting, Enstra mill. The Sappi mill draws its water from the Rand Water Board and has a water usage of 25.5 ML/d, of which 50% is treated sewage (McDonald, 2004). The Kimberly Clark mill, like the Mpact mill, receives its water from the East Rand Water Care Company and has a water usage of 2.7 ML/d (McDonald, 2004).

Figure 1-1 Aerial photograph of the Mpact, Springs mill (mill records)

The Mpact mill consists of two multi-ply board machines that produce carton board and folding box board. Board machine details are presented in Table 1-1 (McDonald, 2004). The BM3 system consists of 7 semi-former vats, each building a ply, before finally entering the pressing section which consolidates the multi-ply sheet. The BM6 system on the other hand, has 7 headboxes which layer the fibre suspension onto the fourdrinier fabric before the sheet is consolidated in the press section.

Table 1-1 Mpact, Springs mill board machine information (McDonald, 2004)

Machines	**Board Machine 3**	**Board Machine 6**
Type	SemiFormer Vat; Bertrams Dorries	Pressure Former/ Short Fourdrinier
Product	Carton Board/ Chip Board	Carton Board
Width	2.45 m	3.85 m
Capacity	35 000 tpa	105 000 tpa
Installed	1954	1971

The Mpact, Springs mill uses secondary fibre as a raw material source for its pulping process. The use of recycled paper is rapidly increasing due to pressure from government legislation to reduce landfill loading as well as the scarcity of forestry resources (Arminen et. al., 2013). World pulp and paper production was 403 million metric tonnes in 2011, with recycled fibres constituting 53% of this amount (Gulsoy et. al., 2013). The drive towards sustainable production has resulted in increased recycled fibre recovery rates, as seen in Figure 1-2, thereby increasing the raw material resource availability and making it an economically attractive alternative to virgin fibre (Bajpai, 2013).

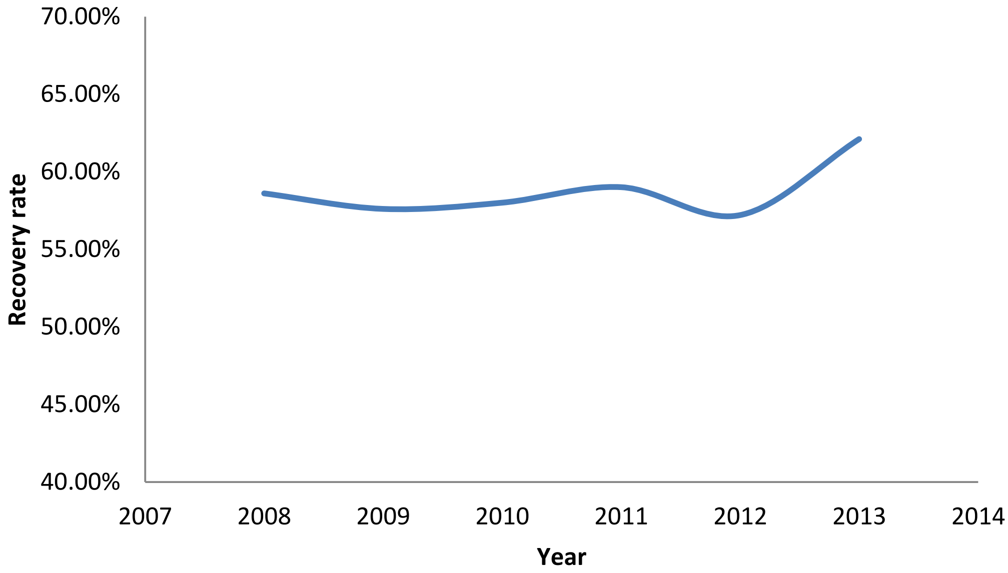

Figure 1-2 *South African Recycled fibre recovery rates (Paper recycling association of South Africa, 2014)*

The recovered paper is sorted and graded according to type. Raw material grades at the Spring's mill include common mixed waste (CMW); recycled kraft paper and paper board (K3 and K4); broke; flat news; heavy letter, mechanical and bleached hardwood. K3 and K4 is pre- and post-consumer packaging respectively. Bleached hardwood is a virgin fibre material obtained from Eucalyptus trees. The problem with the recovered paper repulping system is the presence of contaminants in the raw material. Inks, staples, adhesives and polystyrene must be removed from the pulp stock before the paper machine. Furthermore, food contaminated paper, oil-soaked paper and sanitary paper cannot be used as a source of secondary fibre.

Flat news and Heavy letter raw material are relatively clean but high in ink particles. Ink particles create dark spots in the final board product which is unacceptable in printing applications. The BM6 underliner system has a dispersion plant to reduce the effect of ink on product quality. The steam required to operate the dispersion plant directly affects the boiler house fresh water demand. Conversely K4, the post consumer packaging material and CMW, are high in inks, staples, polystyrene, and sand. Extensive cleaning and screening is required to remove the high and low density contaminant material. Cleaning operations are usually performed in the low consistency range of 1-3% which requires large amounts of stock dilution water. The use of secondary fibre and the associated cleaning technologies required have been addressed by authors such as Smook (1992) and Bajpai (2013).

Another problem with secondary fibre is recovered paper can only be recycled approximately 10 to 12 times before it can no longer be used for paper making (Gulsoy et. al., 2013). This is due to the loss of swelling capability and decreased fibre contact surface area which negatively affects paper product strength properties (Gulsoy et. al., 2013; Smook, 1992). Therefore, the paper industry still requires virgin fibre sources to maintain product strength properties, but as a substitute rather than a primary raw material source.

The Mpact mill water network is already partially closed with only a few fresh water users. These are the boilers for steam generation, showers for felt and wire cleaning, and chemical dilution. The mill water demand is met by fresh water and regenerated process water. Regeneration is accomplished within the board machines by save-all units and externally by the clarification system. These processes serve to remove the suspended solids from the water streams and permit water reuse for stock dilution; chemical dilution; machine showers and vacuum pump seal water. The save-all units also serve to recover fibre for reuse on the paper machine. The combined stream water quality in terms of pH, total suspended solids (TSS), conductivity, chemical oxygen demand (COD) and temperature is measured at the clarifiers. Biocide is dosed according to COD concentrations, to reduce microbial growth.

1.2 Aims and detailed objectives

The aims and detailed objectives of the project were as follows:

Aims:

- Suggest a fresh water reduction strategy whilst maintaining product quality and meeting process requirements

Detailed objectives:

- Develop the Board Machine 3 material balance
- Acquire historical mill data and conduct stream property measurements to solve the material balance
- Develop a degree of freedom table to solve the material balance with the minimum amount of specified information
- Construct an optimization program to reduce the Board Machine 3 fresh water demand
- Verify the optimization code by reproducing the material balance results
- Investigate the effect of varying regenerated water quality on the fresh water reduction potential

1.3 Hypothesis

Water network optimization may be used to reduce the fresh water demand of a multiple contaminant recycled fibre mill water network, whilst still maintaining product quality.

1.4 Dissertation description

Chapter 1 provides a brief introduction to the Mpact Springs mill and its requirement for fresh water reduction. The project aims, objectives and overall hypothesis were outlined. In **Chapter 2** the relevant literature is reviewed. Water usage in a pulp and paper mill is discussed, as well as the various available fresh water reduction methodologies compared. **Chapter 3** deals with the development, solution and verification of the Board Machine 3 material balance. Measurement uncertainty is quantified and its implication on the results presented. The optimization algorithm is developed in **Chapter 4** using the General Algebraic Modelling System (GAMS) software and MINOS solver. Model equations and quality *constraints* are discussed. In **Chapter 5** the results of the optimization are discussed. The effect of varying regenerated water quality is investigated and a control strategy for implementation is proposed. The concentration constraint sensitivity is provided as tool for future improvement of the model. **Chapter 6 and 7** are the project conclusions and recommendations respectively. The **Appendices** include material balance source data, the degree of freedom table, data acquisition methods, logical representation of water network structure and commented GAMS model code. The GAMS model and supporting Excel files are provide on the attached CD-ROM.

2. Literature

In this chapter the pulp and paper making process is discussed with regard to unit operations, water usage and water network contaminants. Water pinch analysis is then introduced and both graphical and numerical methodologies are compared. The project's water network optimization method is then developed based on the merits of previous University of KwaZulu-Natal (UKZN) water pinch projects and those in literature.

2.1 Pulp and papermaking

Numerous process innovations led to the development of two distinct stages in papermaking.

2.1.1 Stock preparation

The first step is pulp formation, in which the raw fibrous plant material is converted into a suspension of fibres in water. This is achieved by either a mechanical, chemical, or semi-chemical pulping procedure depending on the required pulp characteristics. The two major chemical pulping methods are the kraft process and the sulphite process. The kraft process occurs under alkaline conditions and is the preferred chemical pulping method. The sulphite process occurs under acidic conditions and is generally no longer used (Smook, 1992).

The type of final product determines the major contaminants which are required to be removed from the raw materials by stock preparation operations. Ink is not a concern in fluting medium because it is an inner layer in corrugated cardboard and will not need high optical properties. Filler clays and coatings affect tissue manufacture because a clean, free draining stock is needed (McKinney, 1995).

2.1.2 Forming

The second stage in papermaking is the utilization of this clean pulp in the paper machine to produce the finished paper product. The fourdrinier-type machine is shown in Figure 2-1 and a brief description of the major steps is provided (Smook, 1992).

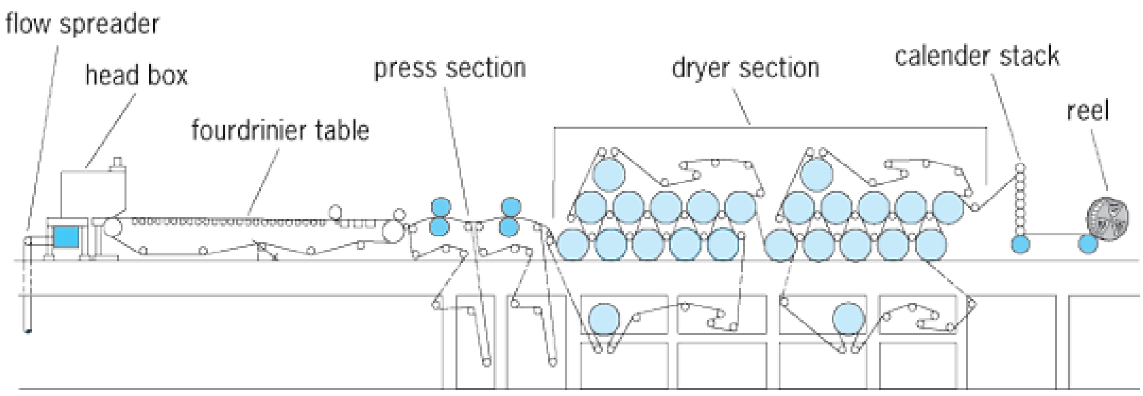

Figure 2-1 Schematic of fourdrinier paper machine (Smook, 1992)

Flow spreader	takes the incoming pipeline stock flow and distributes it evenly across the machine width.
Head box	the headbox discharges a uniform jet of papermaking stock onto the moving forming fabric.
Fourdrinier table	the endless, moving fourdrinier fabric forms the fibres into a continuous matted web while the fourdrinier table drains the water by suction forces.
Press section	the sheet is conveyed through a series of roll presses where additional water is removed and the web structure is consolidated.
Dryer section	most of the remaining water is evaporated and fibre-to-fibre bonds are developed as the paper contacts a series of steam heated cylinders.
Calender stack	the sheet is passed through a series of roll nips to reduce thickness and smooth the surface.
Reel	the dried, calendered sheet is accumulated by winding onto a reel.

The BM3 paper machine has a semi-vat former which is illustrated in Figure 2-2 (Smook, 1992). This replaces the flow spreader and fourdrinier table seen in Figure 2-1. The stock filled vat has a revolving horizontal cylinder former and drainage through the wire surface results in the deposition of a fibre layer. The fibre layer is then transferred to the press section via a felt by the couch roll. This roll has a perforated shell with a vacuum box inside to assist with fibre layer transfer and removal of water before pressing.

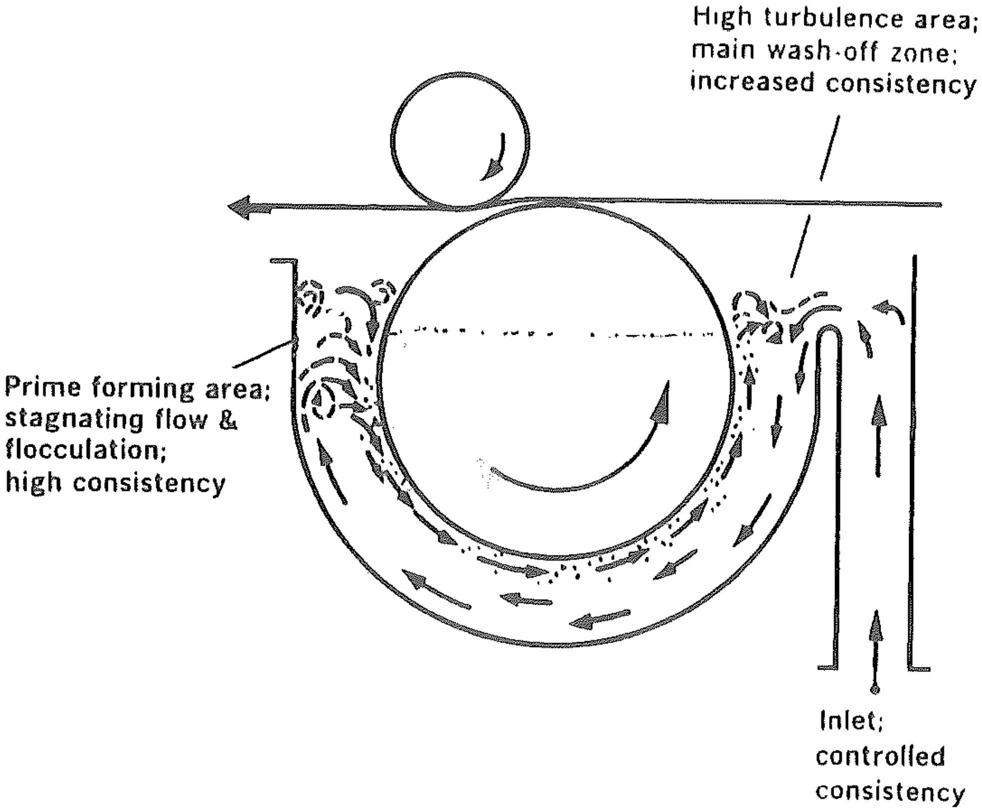

Figure 2-2 Counter flow vat former (Smook, 1992)

2.2 Paper mill water usage

Extensive research into cleaner production techniques, improved process unit operation and effluent management has resulted in the dramatic decrease in water usage at mills. The specific water usage of a recycled fibre mill decreased from 100 kl/t in the 1950s to 2 kl/t in 2003 (McDonald, 2004).

Water-rich countries such as Sweden, Finland, Canada and the northern United States are far less driven to reduce water consumption, and to a large extent the volume of water consumed by the industry in these countries increased (McDonald, 2004). The situation cannot be taken lightly and the countries concerned need to join in the global movement to conserve vital resources. Other than regional differences, the specific water consumption varies within the industry. Shukla (2013) states '...the optimum closure target is specific to each mill because of the considerable differences in process configurations...'. Table 2-1 shows the water requirements for different mill types (Kerr, 2010a). The Mpact, Springs mill belongs to the integrated unbleached category. Current specific water usage based on a 90% fibre yield is 9.2 kl/ton pulp.

Table 2-1 Comparison of specific water consumption for different mill types (Kerr, 2010a)

Mill Type	**No. mills**	**Minimum (m^3/ton pulp)**	**Mean (m^3/ton pulp)**	**Maximum (m^3/ton pulp)**
Integrated bleached	104	35.6	93.6	192.8
Integrated unbleached	**44**	**13.6**	**45.5**	**98.4**
Paper Mill (>100 t/d)	218	0.4	32	580.8
Paper Mill (<100 t/d)	135	1.2	72	350
Bleached Market Kraft Pulp	32	45.2	89.6	136
Newsprint (mechanical)	40	35.6	78.8	284.4

During pulping newer machines operate at a higher *consistency* of between 12 and 16%, compared to low consistency operation of between 4 and 8% (Kerr, 2010b). This is done to reduce energy costs because at a higher consistency there is less water so the work of pulping is performed on the fibres and not the water. Also, the pulping time is reduced. However, the high shear causes excessive hydration and *fibrillation*, and the stock requires dilution to approximately 5% consistency before pumping (Kerr, 2010b).

The white water circuit is a common feature in paper mills. Machine *backwater* is fed to units to reduce the fresh water requirement. The counter-current system ensures the final product receives water of the highest quality (fresh water), and the units upstream receive progressively dirtier water. In this way high product quality is maintained. Water is also used in the paper machine showers. Here water quality is an important consideration, because the shower nozzles are designed for a maximum contaminant concentration. If this maximum is exceeded, plugging of the showers will result. The highest quality water is fed to the boiler for steam production. The steam is used in the pulper to assist the pulping action, and in the drying section to heat the cylinders. Water quality has to be carefully maintained to prevent deposits on the boiler tubes that would reduce the heat transfer. Also low pH or high dissolved oxygen in the feed water will result in tube corrosion. Boiler water treatment chemicals are added to avoid this.

Papermaking chemistry is another important consideration. It is defined as the surface and colloid chemistry of papermaking *furnish* components (Kerr, 2010c). This furnish consists of various components which are responsible for product properties such as basis weight, two-sidedness, strength, colour, opacity, brightness, liquid resistance and permanence. These components include (Kerr, 2010c):

- Dissolved electrolytes
- Suspended fibres – Contributes to total suspended solids
- Suspended fibre fines – Contributes to total suspended solids
- Suspended filler particles – Contributes to total suspended solids
- Water
- Surface-active molecules (either alone or as aggregates) (Examples: detergents, dispersants, wood extractiver, defoamers)
- Dissolved polyelectrolytes (Examples: polyacrlyamides, cationic starch, wet strength agents, dry strength resins, etc.) – Contributes to chemical oxygen demand
- Aggregated *sizing* molecules

Another important measurement is COD which relates to the amount of organic material that is '...susceptible to oxidation by a strong chemical oxidant...' (Clesceri et al., 1989). Organic material needs to be carefully controlled as it may lead to microbial formation and poor product quality. Micro-organisms present a health risk and levels can be controlled using chemical additives such as biocide. The dichromate reflux method is the preferred method for COD measurement. Organic matter is 'oxidized by a boiling mixture of chromic and sulphuric acids. A sample is refluxed in strongly acid solution with a known excess of potassium dichromate ($K_2Cr_2O_7$)' (Clesceri et al., 1989).

2.3 Development of water pinch analysis techniques

As early as the 1960s, extensive research in process integration was being conducted, with fields such as heat integration leading the way (Foo, 2009). Process integration is the systematic application of engineering principles to improve resource management and effectively reduce utility usage.

2.3.1 Graphical based methods

Thermal pinch analysis was used to investigate the energy management in a process network and ultimately reduce the network energy requirement. Process streams requiring cooling and therefore able to release energy were termed ‘hot’ streams. Similarly, process streams requiring heating were termed ‘cold’ streams. The streams were then grouped to form hot and cold composite curves. The pinch analysis then plotted these composite curves on the same axes to graphically represent the amount of network integration possible as the overlap region between the two composite curves. A typical thermal pinch graph is shown in Figure 2-3. The reduced hot, $Q_{h,min}$, and cold, $Q_{c,min}$, duties can be easily read off the graph. The pinch point is the intersection of the two composite curves that limit further overlap and energy requirement reduction. It also indicates the position in the process network where further investigation in unit operation may alleviate the thermal pinch.

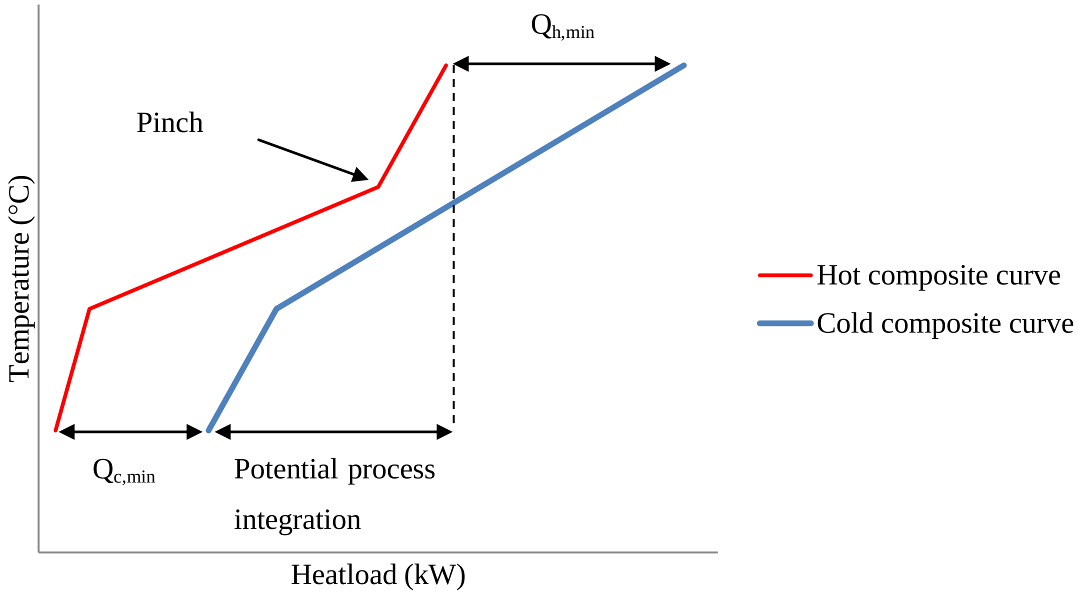

Figure 2-3 Typical thermal pinch graph

The success of heat exchanger network synthesis motivated researchers such as El-Halwagi and Manousiouthakis to investigate the analogous nature between mass and heat integration (Foo, 2009). From this endeavour, water pinch analysis (WPA) developed which can be viewed as a special case of mass integration. Wang and Smith (1994) were the first to tackle the problem of WPA by adapting the thermal composite curves approach to suit a mass transfer based environment. Water flow rates replaced heat flows on the x-axis and water purity replaced temperature on the y-axis. Their limiting composite curve method did provide an early methodology to reduce fresh water requirement, however it had severe limitations. The first problem is that the pinch point relocation after the inclusion of regeneration processes may lead to inaccurate calculated utilities in some cases (Kuo and Smith, 1998). Secondly, it was limited to a single contaminant analysis. Castro et al. (1999) sought to improve on these methods by accounting for multiple pinch points but like all works at that stage, it was limited by the assumption of all the processes being mass transfer based (Castro et al., 1999).

This assumption is valid for processes that use water as a medium to remove a contaminant load. It is applicable for units like washers and cleaners, but cannot account for non-mass transfer based operations such as cooling and steam generation. At the Mpact mill, a significant amount of water is used as coolant for glands, seals and vacuum pumps, as well as feed for the boilers. Hallale (2002) addressed this problem by developing the water surplus diagram which accounts for non-mass transfer based water using operations. However it was a tedious graphical approach that was later replaced by the quicker water cascade technique (Manan et al., 2004). The water cascade technique also permitted the investigation of regeneration and process modifications (Manan et al., 2007).

The WPA methods described provide a means to calculate the minimum utility requirement and as such were termed flow rate targeting methods. From these flow rate targets, network design methods were developed in order to achieve the targets in the process environment. Many insight-based water network synthesis techniques were critically reviewed by Foo (2009) in which flow rate targeting and network design methods are compared. Various flow rate targeting methods such as limiting composite curve, mass problem table and water surplus diagram are discussed (Foo, 2009). However, he acknowledges network design methods that do not require the prior solution of the flow rate targets. These techniques are more versatile than the group depending on the flow rate targets and include methods like source-sink mapping, source-demand approach, and the load table. The two stage approach of pinch analysis is merely a standard practice amongst researchers rather than a necessary solution procedure (Foo, 2009).

Source-sink mapping was used by Parthasarathy and Krishnagopalan (2001) in the mass integration of a Kraft pulp mill. Although a Kraft mill has different process constraints compared to a recycled fibre mill, the methods presented in the paper are general enough to be universally applicable. A *source* is any aqueous process stream that can either be used or potentially recycled by the process. A *sink* is a process unit or operation that receives sources. A sink may also be known as a generator since it may produce a source of a different quality. This graphical method uses the plot of the flow rate or species load on the y-axis and the species composition on the x-axis, as shown in Figure 2-4 (Parthasarathy and Krishnagopalan, 2001).

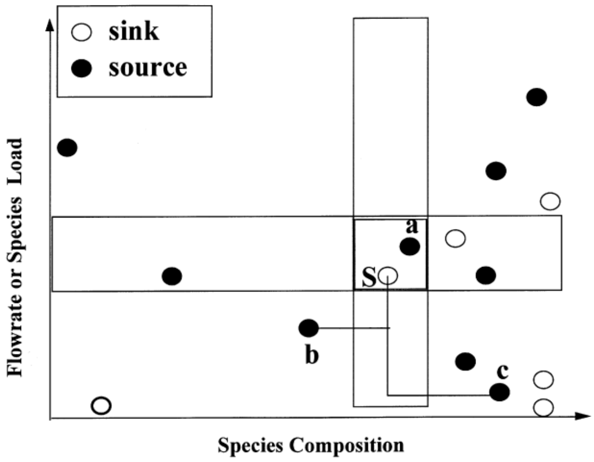

Figure 2-4 Source-sink mapping (Parthasarathy and Krishnagopalan, 2001)

The sources are represented with filled circles and the sinks with open circles. The bands around a sink represent the sink constraints with respect to flow rate and species composition. The intersection of the bands is the operating region and any source in this region can potentially be sent to the sink. In Figure 2-4 the operating region around sink 'S' is shown with source 'a' a valid match to meet the sink's demand. However, mixing of sources 'b' and 'c' will also yield a potential match for the sink. The problem of which source to send to the sink to minimize the fresh water usage can be solved using the lever arm rule, based on the material balance equations (Parthasarathy and Krishnagopalan, 2001):

$$F_{FW} + F_{Source} = F_{Sink} \qquad \text{Equation 2.1}$$

$$F_{FW} \times x_{FW} + F_{Source} \times x_{Source} = F_{Sink} \times x_{Sink} \qquad \text{Equation 2.2}$$

Solving Equation 2.1 and 2.2:

$$\frac{F_{FW}}{F_{Source}} = \frac{x_{Sink} - x_{Source}}{x_{FW} - x_{Sink}} \qquad \text{Equation 2.3}$$

Where, F_{FW} is the fresh water total stream flow rate

F_{Source} is the source total stream flow rate

F_{Sink} is the sink total stream flow rate

x_{FW} is the fresh water composition

x_{Source} is the source composition

x_{Sink} is the sink composition

The source with composition nearest to the sink composition, or smallest horizontal distance on Figure 2-4, will reduce the fresh water demand.

Graphical techniques such as source-sink mapping are simple, easy to interpret and provide initial solutions to water network synthesis problems. In addition, they provide insight into the extent of low cost options of recycling and mixing before more capital intensive techniques like water treatment are considered. However, graphical techniques are limited as to the complexity of the system concerned. As the number of sources and sinks increase, a numerical approach becomes more appropriate.

2.3.2 Numerically based methods

The numerical approach requires the solution of a non-linear problem (NLP) which can be achieved using computational software with built-in solvers. Depending on the size and complexity of the system, this may require excessive processing power. The first mathematical method was developed by Takama et al. (1980) in which a superstructure of all the possible network configurations were tested. Alva-Argaez et al. (1988) then developed a method that incorporated ideas from graphical approaches to minimize the total annual network cost whilst considering geographical, control and safety constraints (Manan et al., 2007). The non-linearity of the water network mathematical formulation was addressed by Castro et al. (2008) in which the non-linear program is replaced with a series of linear programs that are solved successively. The advantages of this method is that all the possible sequences are tested, therefore the local optima can be avoided and the global optimum can be more easily reached; and that this method is able to handle multiple contaminants simultaneously. The drawback of this approximation is that some of the feasible region is lost, although this does not affect the optimal solution significantly (Castro et al., 2008). However, the more serious disadvantages include the inability to account for treatment units and the more demanding computational power required compared to standard initialization problems. Chakraborty (2009) also addressed the limitations of mixed integer non-linear problem (MINLP) methods when handling ‘topologically constrained water-recycle networks’. His method proposes a linearization for the bi-linear term formed by the product of the logical network connection variable and the continuous flow variable. This effectively reduces the problem complexity to a mixed integer linear problem (MILP) which ‘guarantees global optimality’ and reduces computational effort. Other authors who have addressed global water network optimization include Karuppiah and Grossmann (2006) and Teles et. al. (2012).

A multiple objective, multiple contaminant water network optimization procedure has also recently been developed using GAMS software for the optimization (Boix et al., 2011). In this study the three objectives simultaneously minimized were: The water network fresh water demand, the regenerated water flow rate entering the treatment units and the number of network connections. Decreasing the fresh water input will require an increase in regenerated water flow rate. This will result in increased operating costs, the impact of which is minimized by the second objective function. The third objective function relates to the network complexity and capital investment required for piping connections.

The University of KwaZulu-Natal, Pollution Research Group have applied WPA techniques to a variety of industrial networks. A common method was the use of Water Tracker software by Linnhoff-March with the Water Pinch module. The GAMS solver was used to perform the calculations. The Water Tracker software is a valuable tool in constructing and solving the water network material balances. It can handle multiple contaminants, varying flows and treatment units. The user can also include penalty costs for factors such as corrosion, fouling and scaling. The software was used by Slabbert (2006) in his analysis of a Kraft pulp and paper mill, by Schneider (2002) in his analysis of AECI Bioproducts and by Mansfield (2005) to find the optimum effluent treatment at a pulp and paper mill. Mansfield also used WinGems simulation software to validate the results of the Water Pinch module. Gardner (1999) used a graphical approach to analyse a Chlor-Alkali complex. The two-composite curve method was applicable because the system was reduced to a single contaminant due to chemical reaction. His work was later extended by Gianadda (2002) in which a combined water and material pinch analysis was performed at the Chlor-Alkali complex using GAMS.

Many of the previous WPA methods discussed are grassroots design techniques. This means the analysis is performed prior to water network construction and the results can be directly implemented. However, in the case of an existing water network such as at the Mpact mill, these methods become less applicable as the capital investment required to implement the changes will be substantial. This may result in an infeasible solution. To address this problem retrofit techniques have been developed to provide a cost effective solution to WPA of existing networks. '...A good retrofit approach should exploit opportunities to maximise usage of existing facilities while trying to minimize utility cost. This often makes a retrofitted network look quite different from the optimum grassroots design...' (Manan et al., 2007).

Savelski et al. (2009) applied heuristics retrofit techniques to the sour water network at an oil refinery to reduce the fresh water consumption and sour water generated. A heuristics approach uses engineering decisions specific to the water network being analysed in order to guide the network optimization. It does not follow a rigorous mathematical procedure and because it conforms to the demands of management, its solutions are more likely to be accepted for implementation. The drawback is optimal solutions are not guaranteed (Savelski et al., 2009). Manan et al. (2007) applied retrofit water pinch analysis to a pulp and paper mill water network. This provided valuable insight into the application of these techniques at the Mpact mill. They found the retrofitted network can reduce fresh water consumption by 80% and waste water generation by 95%. These figures are impressive, but the network concerned did not have a regeneration unit and the analysis suggested the installation of one which accounts for the dramatic improvement. The Mpact mill already has regeneration units therefore such improvements cannot be expected. In addition, Manan et al. (2007) decided the stream fibre content was the most important factor limiting the water pinch so a single contaminant method was utilized.

Numerical methods have also been developed to tackle retrofit water analysis. Crisp and fuzzy optimization for single contaminant water network retrofit (Hul et al., 2007), an evolutionary genetic algorithm for multiple contaminants (Shafiei et. al., 2004), and a multiple contaminant tree-searching algorithmic procedure that guarantees global optimality were considered (Bagajewicz et al., 2000). The latter procedure is valid for the Mpact mill water pinch analysis however; it uses the concept of a key contaminant to handle the multiple contaminant situation. At a process unit in the network the minimum fresh water flow required to remove each contaminant is determined, and the contaminant corresponding to the largest of these flows is designated the key component. This approximation, although valid, was deemed unnecessary as more rigorous multiple contaminant methods exist. The concept of a bottleneck island was introduced by Iancu et. al. (2009) in which contaminants, with an 'overall mean pseudo-driving force' for mass transfer similar to that of the key contaminant, are grouped. They found optimization with respect to fresh water minimization, considering the contaminants in the bottleneck island, provided a simpler network topology than when the key contaminant was considered alone.

Water network optimization is not limited to fresh water usage minimization. Authors such as Feng and Chu (2004) and Bagajewicz and Faria (2009) have considered the economic implication of such an optimization. Bagajewicz and Faria (2009) proposed a retrofit methodology with economic factors of net savings and return of investment as objective functions. The cost of fresh water and waste water generation was incorporated into the cost objective function. They concluded that '...targeting maximum savings does not necessarily generate the most profitable solution...' (Bagajewicz and Faria,, 2009). This method handles multiple contaminants and produces solutions that are economically feasible which assist in the project implementation. Tudor and Lavric (2011) proposed a dual-objective water network optimization in which fresh water usage as well operating costs are minimized. The operating cost objective function was modelled as the sum of the pumping and piping costs with pipe length between nodes and the economic pipe diameter as the variables. An environmental impact objective may also be included in the optimization as demonstrated by Tokos et. al. (2013). However, project implementation is not the focus of this project. This first stage investigation aims to provide information regarding the previously unknown Board Machine water network, as well as provide an estimate of the possible fresh water reduction.

Literature could not provide a single methodology that handles such a multi-contaminant retrofit fresh water minimization scenario in which costs are disregarded. Two options remained (Foo, 2011):

1. Use a single contaminant analysis and perform a water pinch analysis for each contaminant separately. For each water pinch exercise determine if other contaminants exceed their concentration limits. Impose a fresh water penalty to adjust these concentrations to an acceptable level. Select the lowest penalised fresh water demand as the optimized value.
2. Utilize any numerical method that can optimize the multi-contaminant system simultaneously.

Although the first option is simpler, its applicability is limited. Any improvement on the few fresh water users at the Mpact mill may be offset or negated completely by large fresh water penalties. This would defeat the purpose of water pinch analysis and therefore was not considered for further investigation. It was decided that the second option of a fully numerical solution specifically designed for the Mpact mill system would be developed.

The thesis by Gianadda (2002) proved to be especially useful and was used as the basis for this project's method. In the combined water and material pinch analysis, stream components were either contaminants or resources depending on the network position (Gianadda, 2002). The system was simplified by separating process streams from water network streams and disregarding stream component reclamation. Gianadda used the GAMS software, and the available code together with the GAMS user guide provided the necessary tools to develop this project's GAMS model.

Contaminants may be defined as the waterborne species which restrict the reuse of water in the system during water network closure. The choice of contaminants affects both the scope and the complexity of the problem. Too few contaminants would lead to a simpler but more unreliable solution. One may be totally unaware of serious mill problems caused by omitted contaminants resulting in a solution that cannot be implemented. On the other hand, too many contaminants will lead to an overly complex problem that may not have a solution at all. In addition, the computational power and calculation time required will increase exponentially with increasing problem complexity. For this first stage investigation, two contaminants will be selected to manage the model size and complexity whilst justifying the need for a multi-component methodology. The program will be written such that additional contaminants can be added to develop the analysis.

For the required network modelling, contaminants must obey the law of conservation of mass. This eliminates pH and temperature as potential contaminants. TSS is an indication of the amount of fibre in a stream and is the classic contaminant used in water pinch analysis at a paper mill. The COD has also been justified in Section 2.2. The TDS is important because dissolved ions relate to mill operability. Chloride ions are responsible for corrosion, calcium ions for scaling and deposition, and a host of other ions affect the wet end chemistry in paper making. However, only a grouped TDS concentration measurement was possible. Chlorides and calcium ions have individual concentration limits based on stream conditions such as temperature and pH. So a grouped concentration limit for TDS could not be imposed. Furthermore, the calculation of ion concentrations would require aquatic speciation to be added to the model. This is an additional complication and is beyond the scope of this primary investigation. For these reasons TDS was eliminated as a potential contaminant in the model. The model was developed and optimized for TSS and COD as contaminants.

2.4 Water network superstructure

The water network consists of streams of varying quality. The problem faced is the reallocation of these aqueous resources in order to replace fresh water usage and hence reduce Board Machine fresh water demand. This was addressed by utilizing a network superstructure in which all possible network configurations were possible, Figure 2-5. Process units were modelled with a *mixer* (M) receiving water from all other process units (U1, U2, etc.), and a *splitter* (S) discharging water to all other process units. Fresh water could enter any process unit mixer. Also, process units could discharge water directly to the treatment unit (TU). The water treatment unit would then improve the quality of the water and through a splitter either return it to any process unit or discharge it as effluent.

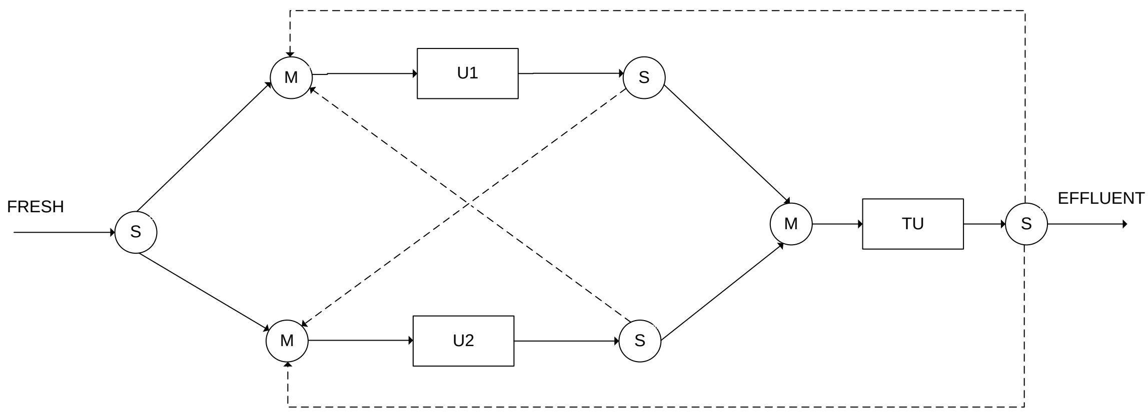

Figure 2-5 Superstructure of water network for a simple two process unit system (Based on Gianadda, 2002)

Some process units may only supply water to the water network, such as the thickening unit, and are termed sources. Likewise, some process units may only receive water from the water network, such as the refining unit, and are termed sinks. However, all other units are both sources and sinks. Figure 2-6 shows the definition of the total sink stream to be the sum of the mixer inlet flows. Similarly the total source stream is the sum of the splitter outlet flows. The splitter condition of constant composition applies. Although process streams are not part of the water network, they are included to ensure material balance over each process unit.

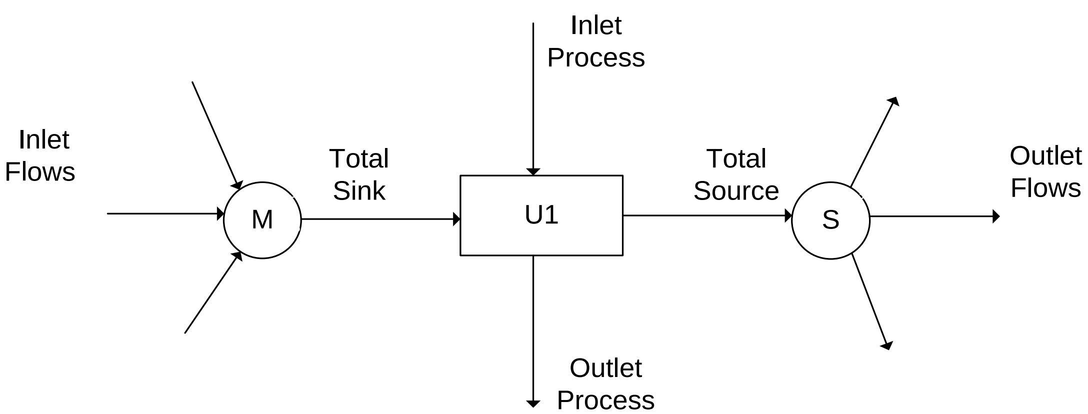

Figure 2-6 Single process unit with associated mixer and splitter (Based on Gianadda, 2002)

The superstructure optimization approach has been extended by Liu et. al. (2012) in which processes may have a single or two outlet streams of differing quality. This affects water resource reallocation and the subsequent network configurations obtained.

2.5 Solver selection

The General Algebraic Modelling System (GAMS) software was used to model and optimize the water network system. It is designed for large, complex problems and allows the user to focus on model formulation. The optimization problem is then handled by the extensive library of solvers which cater for linear, non-linear and mixed-integer situations. The water network optimization required the solution of a constrained mixed integer non-linear problem. The GAMS solver DICOPT (discrete and continuous optimizer) is able to solve such a problem.

Matlab software was another tool available to perform the optimization. However, it lacked the solver function required to handle the constrained mixed integer non-linear problem. Matlab can optimize constrained non-linear problems using the fmincon function. The Matlab environment was also difficult to work in since it required the extraction of variable coefficients to generate the constraint matrix. This is especially time consuming for very large system such as the water network, and limits the potential of model add-ons or alterations. GAMS on the other hand was user friendly since constraints could be defined as equations containing variables on either side of the equality operators. Furthermore, due to the compact set notation built into GAMS, a set of equations could be defined with a single statement. GAMS also allows the user to select the equations to be sent to the solver and hence the ability to test various scenarios and objective variables. GAMS software had been used previously by Giannada to perform a similar superstructure optimization on a water network. The basis of the model formulation was derived from this work (Gianadda, 2002).

2.6 Environmental concerns

South Africa’s water scarcity is directly related to its climatic conditions. The distribution of mean annual rainfall measured in millimetres and position of large dams (with a capacity greater than 2 million cubic metres and/or a dam wall that is higher than 15m) is shown in Figure 2-7 (Hattingh et al., accessed 25/10/2013). The western and southern areas of South Africa receive little rain and rely heavily on the management of water resources though dams. Figure 2-8 shows that most mills in the pulp and papermaking industry are located in the higher annual rainfall region of eastern South Africa (PAMSA, accessed 21/01/2014). The only mill in the Western Province is in Cape Town and is supported by the large concentration of large dams in the area.

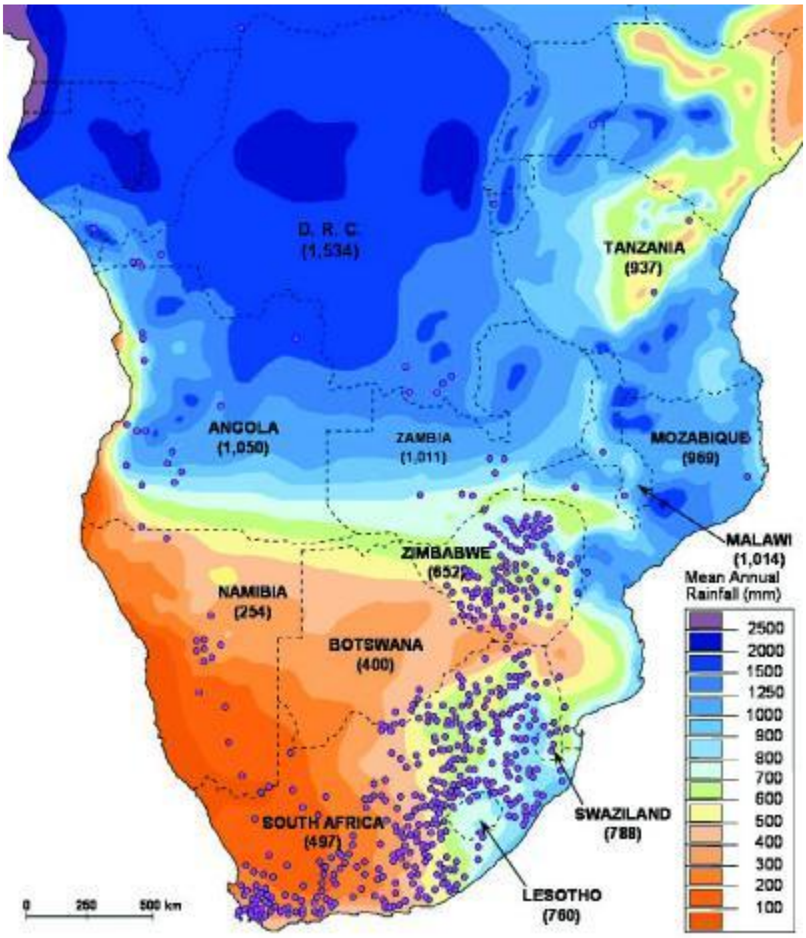

Figure 2-7 Distribution of South Africa's mean annual rainfall and position of large dams (Hattingh et al., accessed 25/10/2013)

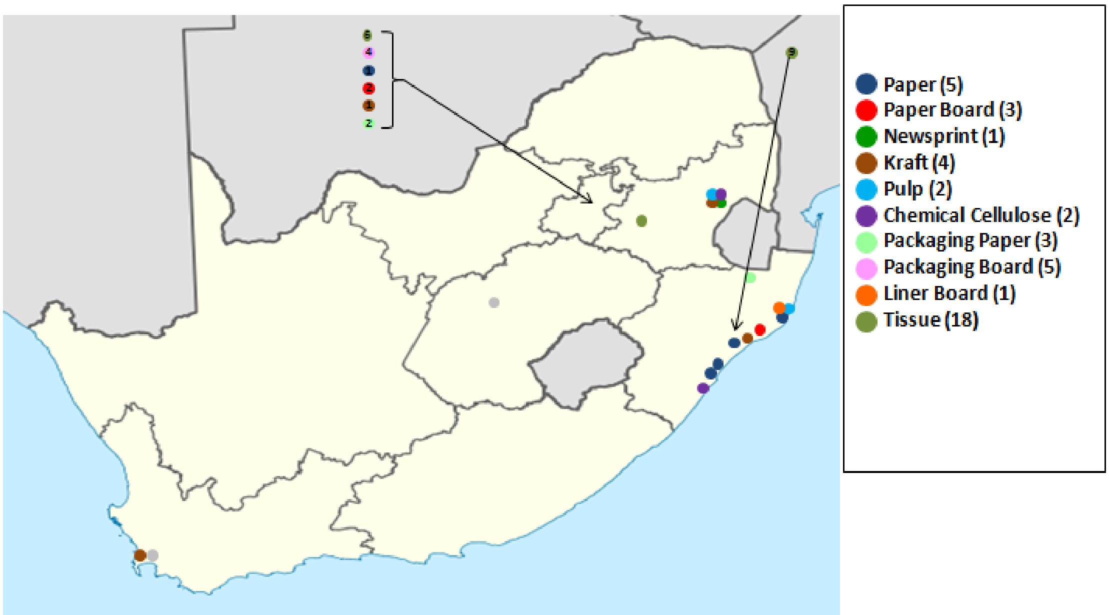

Figure 2-8 Location of paper, pulp, chemical and tissues mills in South Africa (PAMSA, accessed 21/01/2014)

Many rural areas still do not have the proper infrastructure for basic sanitation, hence the pollution of river water with faecal matter that damages downstream environments and promotes the spread of diseases such as cholera. Human habitation also introduces pesticides and other industrial wastes into water sources. This serves to deteriorate the quality of available water which is a primary requirement for life. Although industrial development is vital for the growth of a country's economy, this cannot come at the cost of the degradation of its natural resources and the quality of life of the people. According to the Spokesperson for the Department of Environmental Affairs and Tourism, JP Louw, '...Responsible environmental living is critical if South Africa is to realise its development objective of a better life for all...' (PAMSA, 2006/7). To this end, government has established legislation that controls industrial use and discharge of resources such as water. Before 1998, water was viewed as a source and only the contamination of these sources was managed. The polluter had to pay for water contamination. However, since 1998 the focus has broadened to the entire water ecosystem. The polluter must still account for his discharge but additionally the relationship between the landscape and the water users drives a sustainable solution (Hattingh et al., accessed 25/10/2013).

The National Water Act 36 of 1998 has led to the implementation of initiatives such as the National Water Resources Strategy, Waste Discharge Charge System and Catchment Management Agencies (Slabbert, 2006):

- The National Water Resource Strategy will determine the quality and quantity of water available in the different catchments.
- The Catchment Management Agencies will allocate the available water.
- The Waste Discharge Charge System charge industries for discharging water and contaminants to the environment (Slabbert, 2006).

The National Water Act 36 of 1998 has not been amended since its inception. However, several regulations have been included to be read together with the act (Centre for Environmental Rights, accessed 12/01/2014). The National Water Resource Strategy of 2004 has since been revised in 2013 to facilitate the implementation of the National Development Plan of 2011 (National Water Resource Strategy, accessed 30/06/2014).

The Mpact, Springs mill recognises the importance of water management and is ISO 14001 certified. This means that the mill is committed to an international standard of environmental management (Slabbert, 2006). The standard helps the organization reduce its negative environmental impact and comply with the relative laws and environmental regulations. Regular audits also ensure compliance and continued improvement.

2.7 Concluding remarks

An introduction to pulp and papermaking was provided and the water usage of paper mills discussed. Next the development and limitations of water pinch analysis was discussed. Due to the nature of the problem to be solved, a numerical approach was required. Various numerical techniques were discussed, and it was found that an adaptation of the method by Gianadda (2002) was most appropriate. The GAMS modelling environment was briefly discussed. Finally environmental concerns with regard to paper mill operation in South Africa were addressed. In the next chapter the Board Machine 3 material balance is developed and solved. The material balance is verified by comparing calculated and measured stream properties.

3. Phase 1 – Material balance of Board Machine 3

In the previous chapter papermaking theory; the water usage and water network of a paper mill was discussed. The development of water pinch and numerical optimization methods were then addressed. In this chapter the development and solution of the Board Machine 3 material balance is presented. Source data and supporting calculations are provided in Appendix A.

3.1 Hypothesis

A unique solution of the Board Machine 3 material balance can be found using the minimum number of stream information specifications.

3.2 Structure development

The Mpact, Springs mill consists of two board machines, namely BM3 and BM6. Since the focus of this project is the development of a numerical optimization method that would identify a fresh water reduction strategy, it was decided that the entire Board Machine 3 would be investigated. The developed method could then be applied to Board Machine 6 in future work to obtain the combined Springs mill fresh water reduction potential.

The system was not to be too simple, because the material balance would later be used as tool by mill operators. However, it could not be too complex either as this would greatly increase the time required to solve it as well as complicate the optimization.

A set of rules was developed to assist in the material balance construction:

1. **Include major paper-making process steps**
   This rule ensured the mass balance model would represent the Board Machine 3 operation. It would allow mill operators to change process stream input parameters according to varying Board Machine conditions for different products and/or grades, thus providing a tool for improved mill operation.

2. **Represent all fresh water users**

   It was important to quantify all the fresh water users since the objective of the subsequent optimization program is to reduce these stream flow rates. Also, a greater number of fresh water users represent more water reuse opportunities.

3. **Include unit operations that affect water network stream quality**

   The clarifier discharge water is available for reuse in the machine, however the inclusion of this rule accounted for water streams within the Board Machine 3 that could potentially replace fresh water. For instance, a unit operation like the save-all removes fibre from the Machine pit water stream thereby reducing the total suspended solids load in the water sent to the save-all water chest. If the quality of this stream is better than clarifier discharge water, it would result in a greater fresh water reduction through re-use.

4. **Do not include low flow rate (less than 50 t/d) or intermittent streams unless they are process streams**

   The inclusion of every stream in Board Machine 3 would over-complicate the mass balance model and optimization program. A lower flow limit of 50 t/d was considered suitable. It is recommended that this limit be investigated in future work by including lower flow rate streams. Inclusion of additional streams would require reformulation and solution of the material balance and GAMS model. Intermittent streams were disregarded since the aim was to develop a steady-state model.

The application of these rules resulted in the mill network structure presented in Figure 3-1. The fresh water users are the chemical stream (F11) for the dilution of starch, and the high pressure showers (F18 and F43).

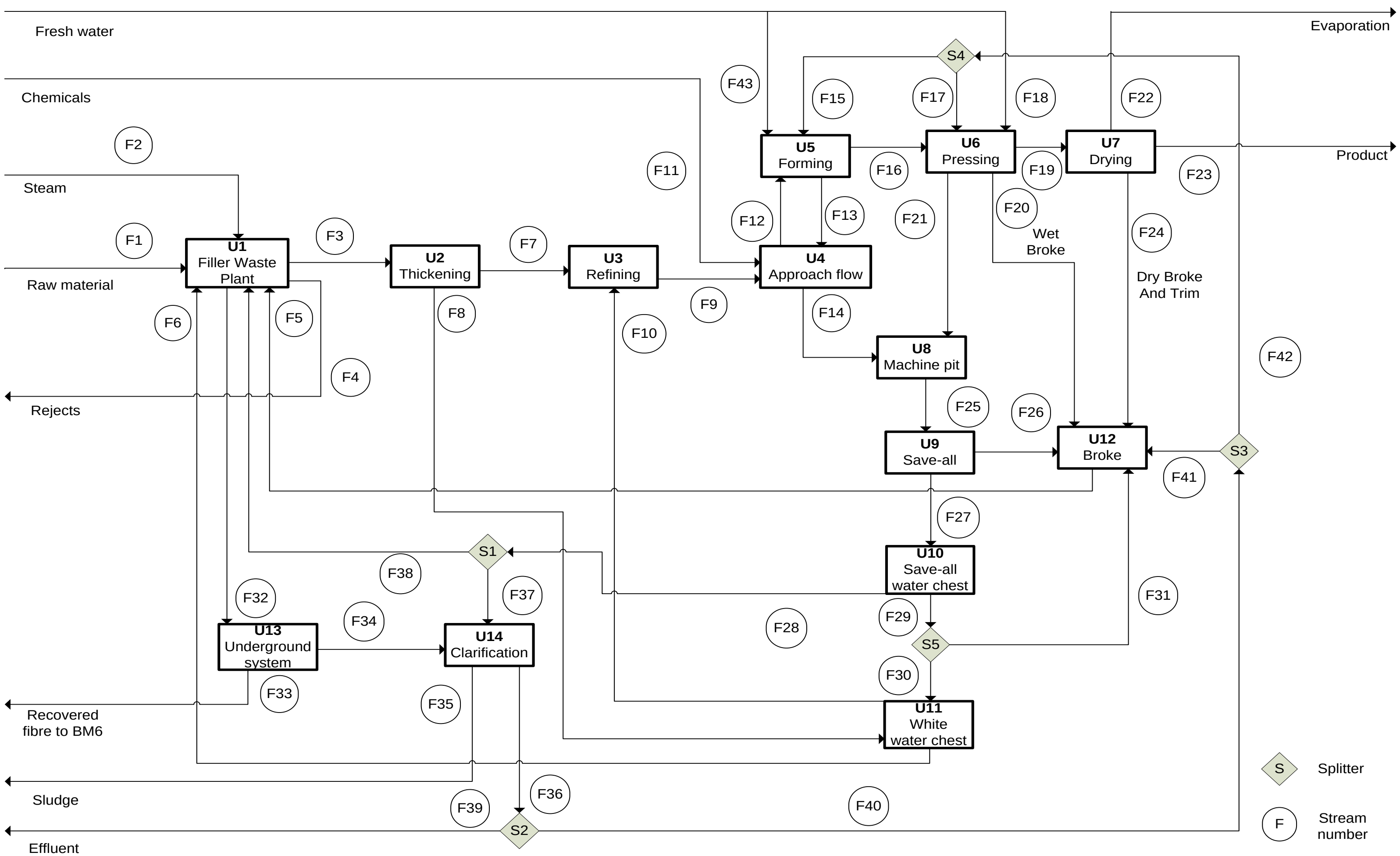

Figure 3-1 Existing Board Machine 3 process flow diagram

The Board Machine 3 process flow diagram shown in Figure 3-1 represents the existing Mill network configuration. The following narrative describes the process blocks and the streams connecting them:

Process block: Filler waste plant (U1)

In this block the recovered fibre known as raw material (F1) is pulped and cleaned. Broke (F5) is also used to substitute raw material usage and is fed to the pulper. The broke stream is a combination of machine product that does not meet customer quality specifications, wasted product due to poor machine operability and the reclaimed fibre from the machine water circuit. Water from the Save-all water chest (U10) and from the White water chest (U11) is used for pulping and cleaning the stock, which are streams (F38) and (F6) respectively. Steam (F2) is used in the pulper to assist in the pulping action thereby reducing the pulping time required. The cleaned stock (F3) is then sent to thickening (U2), whereas the rejects from the cleaning operation (F4) are removed via waste skips. Plant drain water (F32) is sent to the Underground system (U13).

Process block: Thickening (U2)

In this block the cleaned stock at a consistency of approximately 0.9% is thickened to a consistency of 4.2%. Cleaning operations are efficient at low consistencies; however subsequent operations such as refining must be performed at higher consistencies. Therefore, stock thickening is required. The thickening unit is basically a perforated drum rotating in a stock bath. A fibre mat forms on the outside shell of the drum as it rotates out of the bath, and the water drains through this mat into the drum via gravity. The thickened stock is then scraped off the drum before it re-enters the stock bath. The thickened stock (F7) is then sent to refining (U3). The water removed from the stock stream (F8) is sent to the White water chest (U11).

Process block: Refining (U3)

In this block the thickened stock undergoes mechanical action in the refiners. The stock passes a narrow gap between a stationary and a rotating refining plate. Each plate is grooved and the bar edges serve to crush and fibrillate the individual fibres. This increases the inter-fibre bonding and improves sheet formation. The refined stock (F9) is sent to the machine approach flow. Dilution water is used to control the consistency in the refiner feed since consistency is a critical parameter to refiner operation. The dilution water (F10) is taken from the White water chest (U11).

Process block: Approach flow (U4)

In this block the refined stock is chemically treated (F11) with retention aid before entering the Board Machine (F12). The retention aid assists in the Forming section (U5). Backwater (F13) that drains from Forming is used to dilute the stock in the approach flow. Stock entering the Forming section must be at a low consistency of approximately 0.9%. Surplus water (F14) is sent to the Machine pit (U8).

Process block: Forming (U5)

In this block the diluted stock enters the seven semi-vat formers which are used to create the multi-ply fibre mat. The former is illustrated in Figure 2-2. Low pressure showers (F15) are used to clean the forming roll before it rotates back into the vat, thereby preventing it from becoming blocked. High pressure showers (F43) are used to trim the edges on the forming wire and ensure the board product has a uniform width. The fibre mat (F16) leaves the forming section at a consistency of approximately 15% and enters the Pressing section (U6).

Process block: Pressing (U6)

In this block the fibre mat is further consolidated by passing through a series of press rolls supported by a pressing fabric. The applied load is carefully controlled to ensure water removal without crushing the sheet. Showers are used to clean the pressing fabric to prevent blockages and improper water drainage. Low pressure showers (F17) operate continuously, whereas the high pressure showers (F18) operate on timers. This is done to ensure proper cleaning of the pressing fabric, but also because continuous operation of the high pressure showers would damage the pressing fabric. The water pressed out of the sheet (F21) is sent to the Machine pit (U8), and the pressed sheet (F19) at a consistency of approximately 53% is sent to the Drying section (U7). When the board machine starts up, time is required to feed the sheet between the numerous nips of the machine. If there are any board machine problems in the drying section, the mill operators are able to break the sheet at the press section. The pressed board then enters the broke system (U12) as wet broke (F20). This is advantageous since the machine is able to continue operating whilst the drying section problem is resolved. The machine remains fed up until the press section and only the drying section needs to be fed when it is ready. This reduces the time required for machine start-up after a paper break thereby increasing productivity.

Process block: Drying (U7)

In this block the pressed sheet is further dried as it comes into contact with a series of steam heated cylinders. At first the sheet is supported by a dryer fabric, but as it dries it is able to support its own weight and the sheet is sent directly over the drying cylinders. The temperature profile though the drying cylinders is carefully controlled by adjusting the inlet steam pressure to each cylinder. The water thus evaporated (F22) is extracted using ventilation fans and discharged to atmosphere. The final dry product (F23) at a consistency of approximately 93% is sent to other finishing operations such as calendaring, winding and cutting. If there are any problems in these finishing operations the sheet can be broken at the drying section and the product sent to the broke system (U12) as dry broke (F24). The trim from the board also reports as dry broke.

Process block: Machine pit (U8)

In this block the surplus water from the approach flow (F14), the water pressed out of the sheet in the press section (F21), and the press section shower water (F17 and F18) are collected. This water (F25) is then pumped to the save-all (U9).

Process block: Save-all (U9)

In this block the machine water is treated by the save-all unit. This unit is essentially a thickener and operates in similar manner as described in the thickener process block description. The recovered fibre stream (F26) is sent to the broke system (U12). The reclaimed water (F27) is sent to the save-all water chest (U10) for storage.

Process block: Save-all water chest (U10)

In this block the water reclaimed from the save-all is stored and distributed. Water is sent to the filler waste plant (F38) for dilution; the clarification plant (F37) for water treatment; the broke system (F31) for dilution and the white water chest (F30) for further storage.

Process block: White water chest (U11)

In this block process water is stored for distribution. Save-all water chest water (F30) and the water removed from thickening (F8) are stored. This water is then used for refining dilution (F10) and the rest is sent to the filler waste plant for dilution (F6).

Process block: Underground system (U12)

In this block filler waste plant drains and surplus water is purged to the underground system (F32). The drain streams consist of tank overflows and floor washing water. This water is treated with vibrating screens to remove plastics, and then pressure screens in order to reclaim fibre. The fibre removed (F33) is sent to Board Machine 6 as recovered fibre for its broke system. The partially cleaned water (F34) is then sent to the clarification plant (U14) for further treatment.

Process block: Clarification (U14)

In this block the water from the underground system is treated in the clarifiers. Gravity sedimentation in the clarifiers allows solids to settle and be removed in the sludge stream (F35). This sludge is removed with waste skips and stored in the holding site before contractors remove it for composting to be used in the agricultural sector. Flocculants and coagulants are dosed in the clarifiers in order to assist the settling and removal of fibre. The cleaned clarifier overflow water is then sent back to the plant for broke system dilution (F40), and low pressure shower water (F15 and F17). The rest of the water is discharged to the municipality as an effluent stream (F39). This stream quality is carefully monitored since effluent discharge cost is dependent on water quality.

3.3 Super structure development

By defining Process unit mixers and splitters as shown in Figure 2-6 and allowing all possible network connections as shown in Figure 2-5, the water network *super structure* was developed. The water network super structure naming convention is presented in Table 3-1.

Table 3-1 Naming convention used in water network super structure

Name	Description
U1	Filler waste plant
U2	Thickening
U3	Refining
U4	Approach flow
U5	Forming
U6	Pressing
U7	Drying

Table 3-1 Naming convention used in water network super structure continued

Name	Description
U8	Machine pit
U9	Save-all
U10	Save-all water chest
U11	White water chest
U12	Broke system
U13	Underground system
U14	Clarification
MUi	Mixer for Process unit i
MUia	Mixer for high quality water to Process unit i
MUib	Mixer for low quality water to Process unit i
SUi	Splitter for Process unit i
SUiw	Splitter for water stream from Process unit i
SUif	Splitter for fibre stream from Process unit i

The splitter and mixer units represent the sources and sinks respectively. The connectivity matrix between sources and sinks for the existing water network structure is presented in Appendix B, Table B-1. The logical condition of 1 represents the existence of a network connection. A condition of 0 implies no connection exists. The case of process units with multiple input or output streams was also addressed. The Forming process unit (U5) has high pressure fresh water (F43) and low pressure regenerated water (F15) shower feed. Each system has different water quality requirements, and hence each one was designated an individual sink, namely MU5a and MU5b. The save-all (U9) produces a fibre stream (F26) and a water stream (F27). Individual sources for these process units were designated to differentiate between these streams, namely SU9f and SU9w.

3.4 Results

The Board Machine network structure was used to perform the material balance. Streams were identified by stream numbers presented in Figure 3-1. A steady-state operation was assumed since the Board Machine 3 generally runs a single product and grade for an extended period of time. This gives the system sufficient time to settle to the steady-state operation conditions.

Only disturbances caused by operator intervention, mechanical issues and product changes would cause a significant change from the normal steady-state operation. The material balance can be recalculated for changes in the process stream associated with product or grade changes.

Board Machine 3 is the older of the two machines at Springs mill, with very little automation or instrumentation. This resulted in a severe lack of available information. The little information that is manually recorded was used to calculate daily average material balance input values over a four month period, September – December 2010. This served to provide material balance output results that were representative of the average Board Machine 3 operation, rather than for a particular grade or product.

Although much of the material balance stream information was unknown, instead of undertaking an exhaustive sampling campaign to determine stream flow rates and compositions, a degree of freedom (DOF) analysis was performed. This provided the minimum number of stream specifications required to obtain a unique solution, which is confirmed by the process column degree of freedom (DOF) of zero. The DOF analysis technique is explained more fully in Felder and Rousseau (2000). The complete set of material balance specifications is presented in Appendix A, Table A1. The total set of stream specifications required could not be measured due to many streams being inaccessible. Also, some streams specifications were the daily average calculated over a four month period so a single point measurement would have resulted in inconsistent results. Therefore, assumptions about the average Board Machine operation were made. These assumptions are also presented in Appendix A, Table A1. A sensitivity analysis for these assumptions is shown in Table 3-9 in which the assumptions are ranked according to their impact on the material balance results.

In addition, stream properties such as the flow rate of streams F37 and F41 had to be assumed to meet the required number of stream specifications. The placement of these assumptions around process units was initially incorrectly chosen. Although the process column degree of freedom was zero for the system, there were process unit columns that were under-specified and other process unit columns that were over-specified. An under-specified unit would have a greater number of unknown material balance variables than independent equations relating them. In this situation the material balance around the unit has an infinite number of solutions. Conversely, an over-specified solution has fewer unknown material balance variables than independent equations relating them. Some information may be redundant or inconsistent. This did not permit a material balance solution. The assumed properties were shifted to different process units until the process and individual unit columns had a degree of freedom of zero.

The results of the DOF analysis for the complete system are shown in Appendix A, Table A3. This DOF analysis considered TSS and COD as contaminants and resulted in a process column degree of freedom of zero, indicating the existence of a unique material balance solution. However, no process unit columns had a degree of freedom of zero. Therefore, there was no starting point for the material balance calculation. This problem was resolved by considering the subsystem of TSS as the only contaminant. The DOF analysis for this system is presented in Appendix A, Table A4. A process column and dryer column degree of freedom of zero meant a unique solution and a starting point for the material balance calculation existed. By solving this subsystem, all the stream flow rates and TSS compositions were determined. This information was then used to calculate all the stream COD compositions.

The material balance solution was inherently implicit and the problem was solved in Excel 2007 with the Solver Add-on. At certain points in the solution procedure the value of a variable had to be guessed to permit further calculation. This variable could then be calculated later using other material balances. The deviation between the guessed and calculated variable was minimized using Excel's Solver, by changing the value of the guessed variable. The material balance is not a data reconciliation model because no redundant information is used.

Results are presented in Table 3-2 with specified information used to complete the material balance highlighted. The total fresh water usage is 819 t/d (F11, F18 and F43) which equates to a specific usage of 8.78 t/ton of pulp. This specific water usage is for BM3 alone and hence differs from the entire mill average of 9.2 t/ton of pulp as seen in Section 2.2. The steam stream (F2) is also a fresh water stream but is not included in the BM3 total fresh water usage since it originates from the Boiler house and is reported there. The Boiler house is outside the scope of the BM3 investigation and hence this stream (F2) is fixed and not available for later fresh water minimization.

Table 3-2 Material balance results

Stream Name	**Stream Number**	**Total Flow* tons/day**	**Composition TSS weight fraction [g TSS / g Stream]**		**COD weight fraction [g COD / g Stream]**	
Raw material	F1	106	x1	0.88	y1	2.95E-02
Steam	F2	50	x2	0	y 2	0
Cleaned stock	F3	12 670	x3	9.00E-03	y 3	1.47E-03
Rejects	F4	16	x4	0.2	y 4	1.47E-03
Broke	F5	3 298	x5	8.23E-03	y 5	1.42E-03
Dilution	F6	10 889	x6	1.03E-03	y 6	1.46E-03
Thick stock	F7	2 444	x7	0.042	y 7	1.47E-03
Thickener water	F8	10 226	x8	1.12E-03	y 8	1.47E-03
Refined stock	F9	2 947	x9	0.035	y 9	1.47E-03
Dilution	F10	504	x10	1.03E-03	y 10	1.46E-03
Chemicals	F11	202	x11	0	y 11	5.97E-02
Board Machine feed	F12	14 270	x12	9.00E-03	y 12	1.52E-03
Forming return water	F13	14 452	x13	2.67E-03	y 13	1.49E-03
Surplus water	F14	3 331	x14	4.00E-03	y 14	1.52E-03
Low pressure shower	F15	533	x15	1.50E-04	y 15	1.43E-03
Formed fibre mat	F16	599	x16	1.50E-01	y 16	1.52E-03
Low pressure shower	F17	646	x17	1.50E-04	y 17	1.43E-03
High pressure shower	F18	369	x18	0	y 18	0
Pressed fibre mat	F19	158	x19	0.53	y 19	1.52E-03
Wet broke	F20	8.3	x20	0.53	y 20	1.52E-03
Pressing water	F21	1 448	x21	1.31E-03	y 21	1.09E-03
Evaporation	F22	68	x22	0	y 22	0
Product	F23	81	x23	0.93	y 23	1.79E-02
Dry broke and Trim	F24	9	x24	0.93	y 24	1.79E-02
Machine water	F25	4 779	x25	3.18E-03	y 25	1.39E-03
Recovered fibre	F26	114	x26	0.12	y 26	1.39E-03
Save-all water	F27	4 665	x27	3.26E-04	y 27	1.39E-03
Save-all water	F28	2 332	x28	3.26E-04	y 28	1.39E-03
Save-all water	F29	2 332	x29	3.26E-04	y 29	1.39E-03

Table 3-2 Material Balance results continued

Save-all water	F30	1 167	x30	3.26E-04	y 30	1.39E-03
Dilution	F31	1 167	x31	3.26E-04	y 31	1.39E-03
Drains and water purge	F32	1 989	x32	7.33E-03	y 32	1.47E-03
Recovered fibre	F33	416	x33	0.0315	y 33	1.47E-03
Underground water	F34	1 573	x34	9.27E-04	y 34	1.47E-03
Sludge	F35	4.5	x35	0.35	y 35	1.43E-03
Clarifier overflow	F36	3 568	x36	1.50E-04	y 36	1.43E-03
Clarifier feed	F37	2 000	x37	3.26E-04	y 37	1.39E-03
Dilution	F38	332	x38	3.26E-04	y 38	1.39E-03
Effluent	F39	389	x39	1.50E-04	y 39	1.43E-03
Return water	F40	3 179	x40	1.50E-04	y 40	1.43E-03
Dilution	F41	2 000	x41	1.50E-04	y 41	1.43E-03
Shower water	F42	1 179	x42	1.50E-04	y 42	1.43E-03
High pressure shower	F43	248	x43	0	y 43	0

Notes:

(highlighted) Highlighted cells indicate specified information in the material balance calculation

* Total flow refers to the entire stream including water, TSS and COD

The material balance results provide mill management with information on previously unmeasured stream properties which will assist in the design of new process units and improve process control systems. Particular points of interest include:

- Quantification of steam losses by evaporation from the drying section (F22). The flow rate of 68 t/d will be useful in the design of the hood ventilation system and drying section performance investigation.
- Determination of shower flow rates (F15, F17, F18, F43). Indirect measurement method explained in Appendix A
- Chemical addition stream COD composition (y11).
- Soluble COD retention. Most of the starch added in the chemical addition stream adheres to the fibres to assist in mat formation. The fraction remaining in the water network (retained soluble COD) was calculated. This is important when considering different types of starches to assist formation.

- Raw material COD composition (y1). Could not be measured directly because of various raw material sources and the specific pulping conditions that affect soluble COD liberation.

The material balance also serves as a tool that can be used to investigate process modifications. For instance the effect on the water network COD loading if a raw material with a lower contaminant load were to be used. Also, the effect of a save-all fibre recovery as a function of the inlet consistency may be investigated. The save-all fibre recovery investigation will form part of the action plan pending the submission of this dissertation.

3.5 Material balance verification

The material balance provided a model for the prediction of stream properties. The validation of these predictions was performed by measuring the current operating conditions of the system for the material balance input variables. Accessible streams (F8, F10, F13, F25, and F32) were then sampled and the measured stream compositions compared to the calculated mass balance values. Correlation between the measured and calculated stream properties was investigated by performing a statistical t-test on the data. The following null hypothesis was made:

The sample mean of the compositions calculated by the mass balance is equal to the sample mean of the measured compositions, with 95% confidence.

3.5.1 Comparison between calculated and measured stream compositions

The input variables of raw material usage (F1), production rate (F23) and clarifier overflow water compositions (x40 and y40) were forced according to a daily measurement. The value of the variables is shown in Table 3-3. This information formed the basis of the material balance model.

Table 3-3 Values of input variables for material balance verification

Stream number	Stream name	Flow rate (t/d)	TSS weight fraction [g TSS / g Stream]	COD weight fraction [g COD / g Stream]
F1	Raw material	116.6	-	-
F23	Product	92.1	-	-
F32	Drains and water purge	-	2.80E-05	2.21E-03

A total of 5 streams were sampled and the measured compositions are presented in Table 3-4.

Table 3-4 Composition measurements of sampled streams for material balance verification

Sample number	Stream name	Stream number	TSS weight fraction [g TSS / g Stream]	COD weight fraction [g COD / g Stream]
1	Thickener water	F8	1.15E-03	2.86E-03
2	Dilution	F10	4.43E-03	2.95E-03
3	Forming return water	F13	1.42E-03	2.34E-03
4	Machine water	F25	1.59E-03	2.32E-03
5	Drains and water purge	F32	6.23E-03	2.39E-03

Under the conditions in Table 3-3, the material balance was evaluated and the calculated stream properties compared to the measured properties shown in Table 3-4. Figure 3-2 and Figure 3-3 show the results of this comparison.

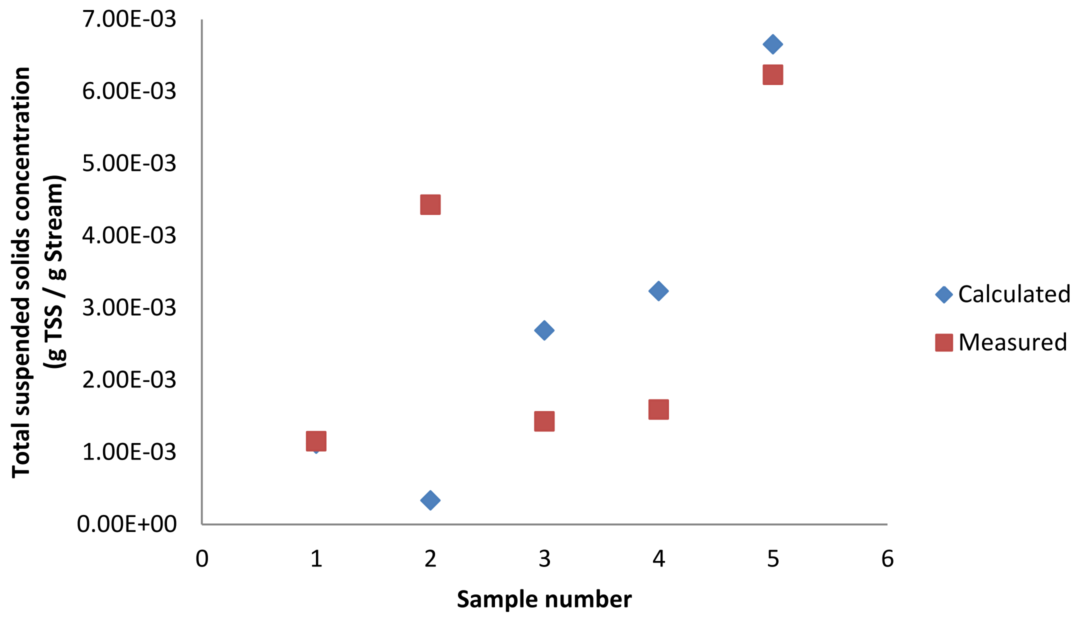

Figure 3-2 Comparison of calculated and measured TSS concentrations before model training

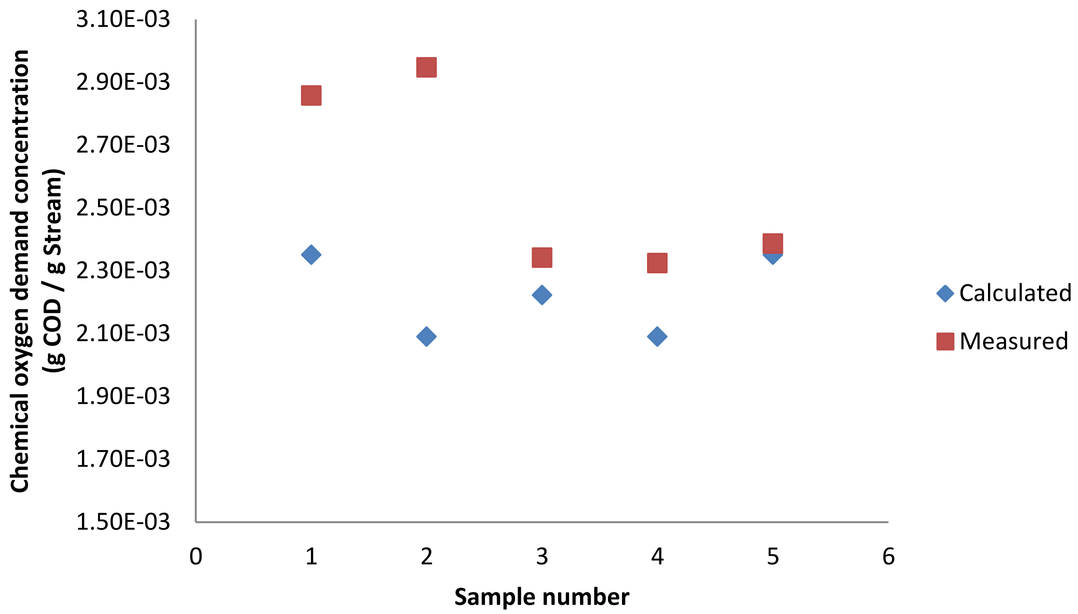

Figure 3-3 Comparison of calculated and measured COD concentrations before model training

These graphs show that there was a significant difference between the calculated and measured stream properties. This is most likely due to the material balance assumptions accounting for an average operation over a four month period. To accommodate this change, the Board Machine operating assumptions were adjusted. The adjustment of model parameters and relaxation of COD reduction was done by visual inspection of the resulting graphs shown in Figure 3-4 and Figure 3-5 that resulted in the smallest deviation between the data sets. This step can be viewed as model training and greatly improved the model's ability to predict the measured stream properties. The results of the trained model predictions are shown in Figure 3-4 and Figure 3-5. Furthermore, it was observed that oxygen is injected at the clarifiers which reduce the COD loading. Therefore, the constraint of no COD reduction across the clarifiers was relaxed until the model prediction of COD concentration was satisfactory. It was calculated that 1 t/d of COD is removed by oxygen injection.

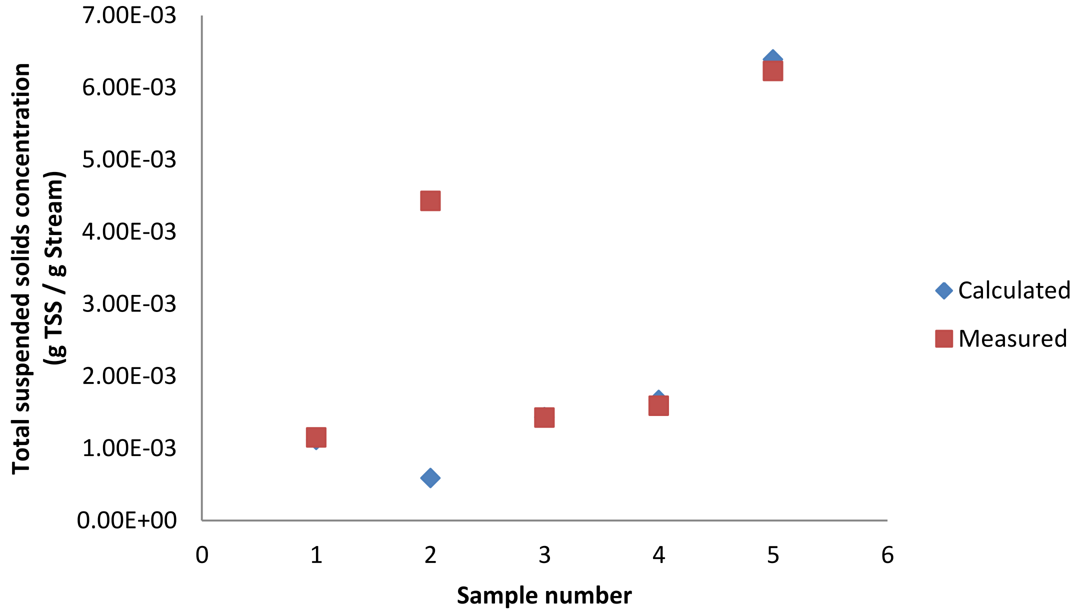

Figure 3-4 Comparison of calculated and measured TSS concentrations after model training

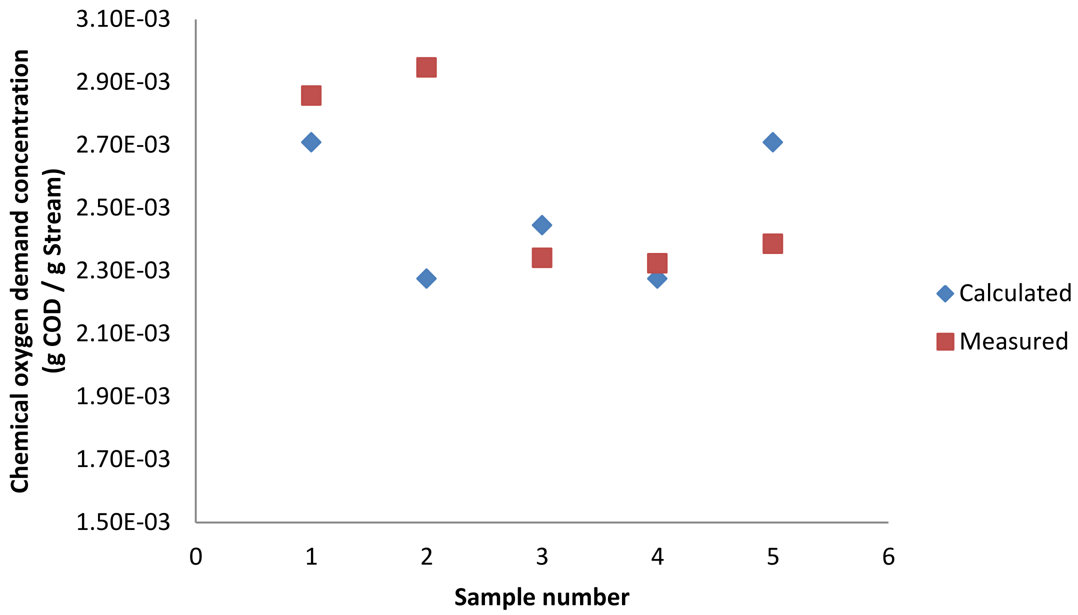

Figure 3-5 Comparison of calculated and measured COD concentrations after model training

The only sample point which could not be improved on, was sample 2 (Stream number 10). This stream is the water from the save-all water chest. The measured TSS concentration was approximately 7.5 times larger than the calculated value. This is most likely due to a mechanical problem with the save-all unit, such as holes in the drum or leaking seals, which allowed fibre into the water stream. The inaccuracy in the TSS concentration resulted in a similar inaccuracy in the COD concentration of stream 10. This is because the COD concentration depends on the TSS concentration.

3.5.2 Results of t-tests for TSS and COD concentrations

The t-test for two samples and assuming unequal variances was performed using the Excel 2007, Data analysis tool pack. The two-tail test was used to evaluate deviations on either side of the mean. The results for the TSS and COD data samples are presented in Table 3-5 and Table 3-6 respectively.

Table 3-5 t-Test result for comparison of calculated and measured TSS concentrations

	Calculated	**Measured**	**Units**
Mean	2.24E-03	2.96E-03	g TSS / g Stream
Variance	5.54E-06	5.09E-06	(g TSS / g Stream)^2
Observations	5	5	
Hypothesized Mean Difference	0		
df	8		
t Stat	-0.50		
P(T<=t) one-tail	0.32		
t Critical one-tail	1.86		
P(T<=t) two-tail	0.63		
t Critical two-tail	2.31		

Table 3-6 t-Test result for comparison of calculated and measured COD concentrations

	Calculated	**Measured**	**Units**
Mean	2.48E-03	2.57E-03	g COD / g Stream
Variance	4.75E-08	9.28E-08	(g COD / g Stream)^2
Observations	5	5	
Hypothesized Mean Difference	0		
df	7		
t Stat	-0.53		
P(T<=t) one-tail	0.31		
t Critical one-tail	1.89		
P(T<=t) two-tail	0.61		
t Critical two-tail	2.36		

Since the t-Stat is within the range defined by [-t Critical two-tail, +t Critical two-tail] for both the TSS and COD t-tests, the null hypothesis that the means for both the sample and measured data sets are equal can be accepted with 95% confidence. Therefore, it can be accepted that the material balance is able to successfully predict Board Machine process stream compositions.

3.6 Error and sensitivity analysis

The source of error in the material balance calculation can be attributed to measurement accuracy, assumed values of unit operation parameters and neglected streams. The Sartorius BP 2100 S electronic mass balance is accurate to 0.01g. It was used to calculate and confirm the mill specification of the total suspended solids concentration of streams. Since clarified water

(F36) has the lowest total suspended solids weight fraction, 150 ppm, the TSS measurement error is as high as 67%. For high consistency streams such as the final product stream (F23) the TSS measurement error is as low as 0.01%. The COD concentration of streams was measured using the HACH Spectrometer DR/2000, which has a precision of 24 ppm. This range was attached to the two measured COD concentrations (y11 and y36) and the mass balance recalculated at the high and low ends of the range. The resulting output range is shown in Figure 3-6. The average material balance COD concentration error was 1.67% shown as error bars on Figure 3-6. COD concentration of streams termed sources were plotted since this was necessary for later verification of the optimization results. The source numbers are explained in Table 3-7. The TSS and COD testing procedures and equipment used are discussed in Appendix A. Furthermore, the test method repeatability was evaluated according to the TAPPI standard T-1200 and the results presented in Table 3-8. The repeatability thus calculated is 'an estimate of the maximum difference which is expected 95% of the time between two test results obtained under the same testing conditions and from the same homogenous source of material' (TAPPI, 2000).

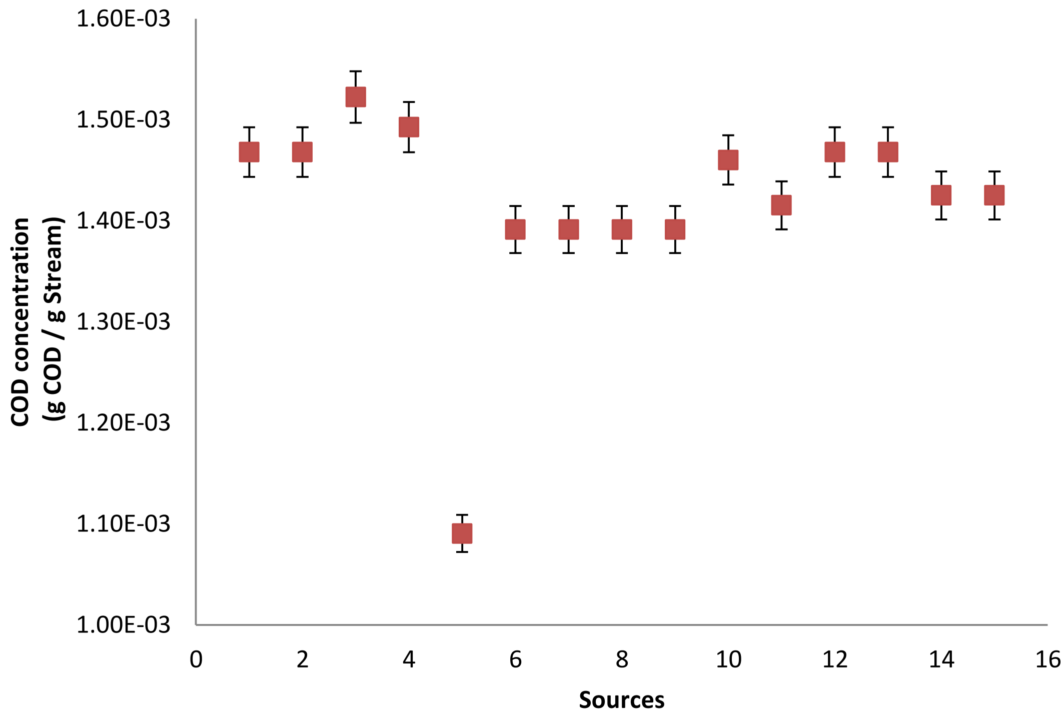

Figure 3-6 Sensitivity of COD measurement on calculated COD concentrations

Table 3-7 Source streams used in COD sensitivity analysis

Source number	Source name	TSS weight fraction [g TSS / g Stream]	COD weight fraction [g COD / g Stream]
1	SU1	7.33E-03	1.47E-03
2	SU2	1.12E-03	1.47E-03
3	SU4	4.00E-03	1.52E-03
4	SU5	2.67E-03	1.49E-03
5	SU6	1.31E-03	1.09E-03
6	SU8	3.18E-03	1.39E-03
7	SU9f	0.12	1.39E-03
8	SU9w	3.26E-04	1.39E-03
9	SU10	3.26E-04	1.39E-03
10	SU11	1.03E-03	1.46E-03
11	SU12	8.23E-03	1.42E-03
12	SU13f	0.0315	1.47E-03
13	SU13w	9.27E-04	1.47E-03
14	SU14f	0.35	1.43E-03
15	SU14w	1.50E-04	1.43E-03

Table 3-8 Test method repeatability results

	Consistency	COD (ppm)
Test Result 1	2.09%	2510
Test Result 2	1.87%	2640
Test Result 3	1.93%	2520
Test Result 4	2.14%	2630
Test Result 5	2.03%	2410

Table 3-8 Test method repeatability results continued

	Consistency	COD (ppm)
Laboratory Material Mean	2.01%	2542.00
Laboratory Material Standard Deviation	0.11%	95.24
Repeatability Standard Deviation	0.11%	95.24
Repeatability	0.3%	263.8
Repeatability Ratio	15.3%	10.4%

A sensitivity analysis was performed on the assumed unit operation parameters and the results shown in Table 3-9. The COD's of the streams were used since the COD balances include flow, TSS and COD terms; see Table 4-2, Equation 4.3. The average percentage change in the COD concentration across all the sources for a change in an assumed value was used to quantify the change in the material balance results. The range of the average change in COD concentration served to rank the assumptions according to its impact on the material balance and hence provide an order for investigating them.

Table 3-9 Assumed parameter sensitivity analysis and ranking

Assumptions	-5 %	5 %	Range	Rank
COD retention	-3.43E-02 %	3.43E-02 %	6.85E-02 %	1
Save-all fibre removal	-1.66E-02 %	1.76E-02 %	3.42E-02 %	2
Former retention	6.54E-03 %	-6.52E-03 %	1.31E-02 %	3
Save-all water chest to Waste plant and Clarification	-3.89E-03 %	4.17E-03 %	8.06E-03 %	4
Dry broke	-1.57E-03 %	1.59E-03 %	3.16E-03 %	5
Save-all water chest to White water chest	-2.24E-04 %	3.14E-04 %	5.39E-04 %	6
Wet broke	-2.65E-04 %	2.67E-04 %	5.32E-04 %	7
Press felt retention	-1.26E-04 %	1.26E-04 %	2.52E-04 %	8

The chemical addition stream (F11) consists of dissolved starch, which is a primary source of COD in the water network system. The other source of COD is the raw material, with the major contributors being the CMW and K4 due to the contamination of these sources. Most of the starch adheres to the fibres and reports to the final product, however some starch remains in the water network. The COD retention assumption refers to this portion of COD due to starch, which is retained in the water network. The material balance sensitivity was calculated by the variation in the COD concentration which is directly affected by the COD retention assumption. Therefore, this assumption would have the largest impact and rank first as seen in Table 3-8. However, for a 5% change in the assumed value, the material balance only changes by 0.034%. The lower ranking assumptions had a lesser effect on the material balance.

Although these changes are small, the assumptions play a critical role in reproducing the actual mill stream measurements, as seen by the model training in Section 3.5. The assumed values change depending on the product being produced and the plant set up. Therefore it is recommended that these assumptions are evaluated for different mill conditions to improve the material balance accuracy.

3.7 Concluding remarks

The Board Machine 3 mill structure was developed and its material balance successfully solved. The Degree of Freedom analysis was used to find a unique solution using the minimum number of stream specifications. The material balance was verified with 95% confidence by forcing the input variables to current operating conditions and comparing calculated and measured stream compositions. An error analysis on the measured COD concentrations revealed the confidence range of the material balance results. Also a sensitivity analysis ranked the assumed operating parameters according to their impact on the material balance results and hence provided an order of investigation. The sampling error for TSS and COD measurement was also quantified. The test method repeatability was evaluated according to the TAPPI standard T-1200, and a repeatability of 0.3% and 263.8 ppm was calculated for the TSS and COD measurements respectively. In the next chapter the mill structure will be optimized with respect to fresh water demand. The optimization code will initially be verified by reproducing the material balance results. The optimization will then be used to investigate the fresh water reduction as a function of the regenerated water quality.

4. Phase 2 – Optimization

In the previous chapter the material balance for Board Machine 3 was developed, solved and verified. In addition the results confidence range based on COD measurement error was determined. The assumed operating parameters were also ranked according to their impact on the material balance. In this chapter, the mill network structure is mathematically modelled and optimized with respect to fresh water demand using GAMS 20.7, and the MINOS solver. The GAMS code is provided on the attached CD-ROM and in Appendix D. The effect of varying regenerated water TSS concentration on the fresh water demand was also investigated.

4.1 The water network

At a pulp and paper mill there is no clear distinction between water network and process streams. Water may enter the process as steam to assist pulping or dilution of stock and chemicals. It may also leave the process when stock is thickened or fibre is recovered from waste water. The process is affected by many factors such as machine operability, type of product, production rates, and economic considerations. An optimization of the process with respect to fresh water demand minimization alone may adversely affect the above mentioned factors. So the distinction between process and water network streams was necessary since this project is an optimization of the water network only. By fixing the process stream conditions, shown in Table 4-1, the water network optimization can safely reduce the fresh water demand without affecting the process. Process streams were defined as the streams representing the flow of stock through the board machine, from raw material source to final product. The water network then consisted of the remaining streams. This is represented in Figure 4-1.

Table 4-1 Process stream specifications

Stream name	**Stream number**	**Total Flow tons/day**	**TSS weight fraction [g TSS / g Stream]**	**COD weight fraction [g COD / g Stream]**
Raw material	F1	106	0.880	0.030
Steam	F2	50	0	0
Cleaned stock	F3	-	9.00E-03	-
Rejects	F4	16	0.200	-
Thick stock	F7	-	0.042	-
Refined stock	F9	-	0.035	-

Table 4-1 Process stream specifications continued

Stream name	Stream number	Total Flow tons/day	TSS weight fraction [g TSS / g Stream]	COD weight fraction [g COD / g Stream]
Chemicals	F11	202	-	0.060
Board Machine feed	F12	-	9.00E-03	-
Formed fibre mat	F16	-	0.150	-
Pressed fibre mat	F19	-	0.530	-
Wet broke	F20	-	0.530	-
Product	F23	-	0.930	-
Dry broke and trim	F24	-	0.930	-
Recovered fibre	F33	-	0.032	-
Sludge	F35	-	0.350	-

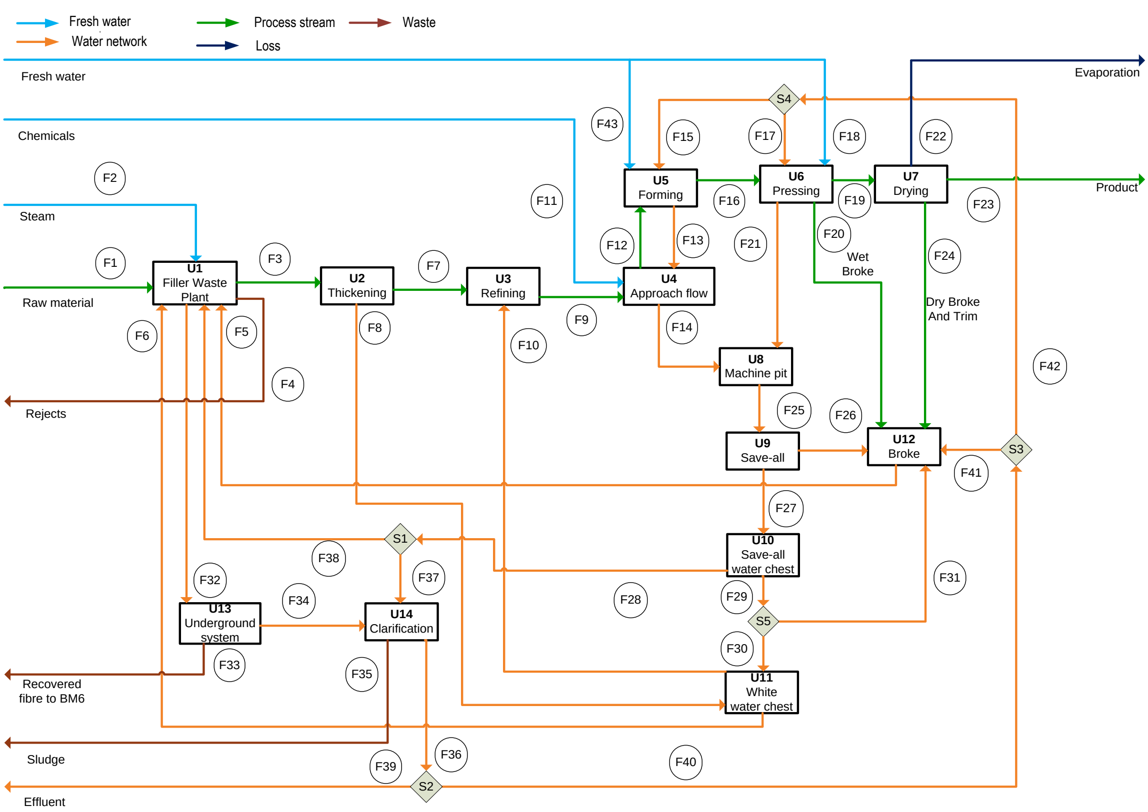

Figure 4-1 Mill network showing stream differentiation

4.2 GAMS Model formulation

The model is built by defining the material balances as equality constraints. The general equations are presented in Table 4-2. The complete model is shown in the GAMS program code in Appendix D. The GAMS model can be run from the attached CD-ROM.

Table 4-2 Material balance equations

Mixer		
Flow	$TotSink_h = \sum_i Flow_{h,i}$	4.1
Mixer		
TSS	$TotSink_h \times TotSinkComp_{h,TSS} = \sum_i Flow_{h,i} \times FlowComp_{h,i,TSS}$	4.2
COD	$TotSink_h \times (1 - TotSinkComp_{h,TSS}) \times TotSinkComp_{h,COD} = \sum_i Flow_{h,i} \times (1 - FlowComp_{h,i,TSS}) \times FlowComp_{h,i,COD}$	4.3
Process Unit		
Flow	$TotSink_h + Process_{in} = TotSource_i + Process_{out}$	4.4
TSS	$TotSink_h \times TotSinkComp_{h,TSS} + Process_{in} \times ProcessComp_{in,TSS} = TotSource_i \times TotSourceComp_{i,TSS} + Process_{out} \times ProcessComp_{out,TSS}$	4.5
COD	$TotSink_h \times (1 - TotSinkComp_{h,TSS}) \times TotSinkComp_{h,COD} + Process_{in} \times (1 - ProcessComp_{in,TSS}) \times ProcessComp_{in,COD} = TotSource_i \times (1 - TotSourceComp_{i,TSS}) \times TotSourceComp_{i,COD} + Process_{out} \times (1 - ProcessComp_{out,TSS}) \times ProcessComp_{out,COD}$	4.6
Splitter		
Flow	$TotSource_i = \sum_h Flow_{h,i}$	4.7
TSS	$TotSource_i \times TotSourceComp_{i,TSS} = \sum_h Flow_{h,i} \times FlowComp_{h,i,TSS}$	4.8
COD	$TotSource_i \times (1 - TotSourceComp_{i,TSS}) \times TotSourceComp_{i,COD} = \sum_h Flow_{h,i} \times (1 - FlowComp_{h,i,TSS}) \times FlowComp_{h,i,COD}$	4.9
Restriction	$TotSourceComp_{i,k} = FlowComp_{h,i,k}$	4.10

Where:

h – Sinks

i – Sources

k – Contaminants

TSS – Total suspended solids

COD – Chemical oxygen demand

4.3 Model verification

The material balance results and existing water network structure were used as the initial condition for optimization. The optimization code was verified by specifying the existing water network structure and comparing the calculated stream compositions to the material balance values shown in Figure 4-2. The comparison between COD concentrations was used to verify the GAMS code results. COD balance equations included flow and TSS variables as well, so any deviations in these terms will be reported in the COD concentration comparison. The GAMS code produces results which are lower than the material balance calculations. The material balance was solved sequentially using the Microsoft Excel Solver Add-in. The drawback of this approach is that the flow and TSS balances were first solved iteratively and thereafter these results were used in an iterative calculation to solve the COD balances. The Solver Add-in has a convergence limit after which the manipulated variable is accepted as a solution. Since the Solver never actually reached an objective value of zero (implying exact solution has been found) this slight error is propagated in the second iteration. The GAMS model however solves all variables simultaneously which avoids this error propagation at the cost of increased processing power. The largest relative error between the GAMS model concentrations and the material balance concentrations is 1.48%. This is less than the average material balance concentration error of 1.67% due to the COD measurement accuracy. Hence, the GAMS model was verified.

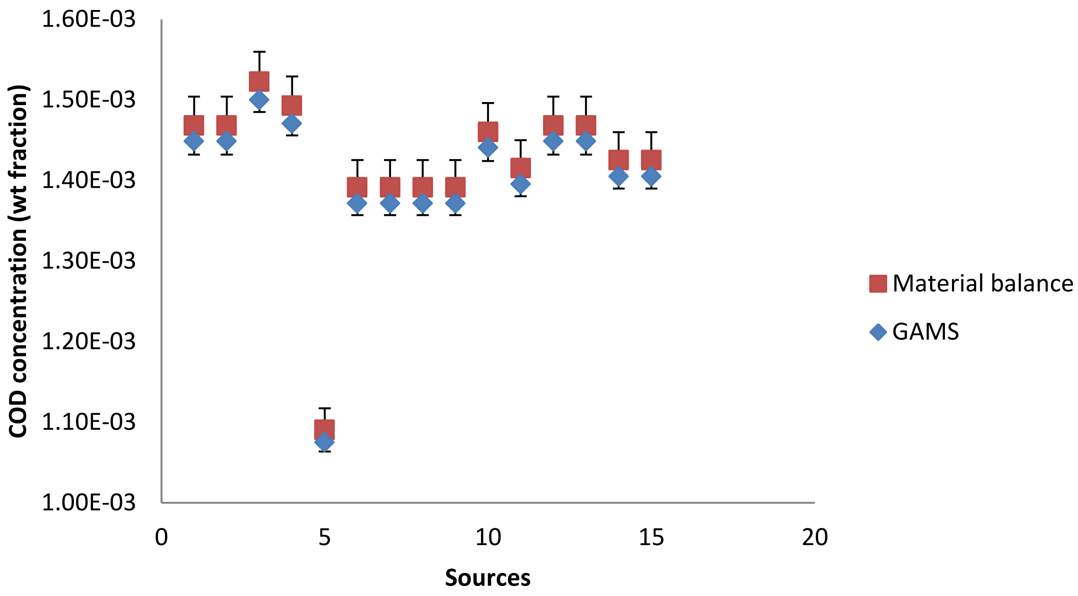

Figure 4-2 *General algebraic modelling system model verified by relative error being less than material balance accuracy*

4.4 Model quality constraints

The material balance equations, shown in Table 4-2, together with the connectivity matrix representing the network connections completely describe the system. The connectivity matrix representing the existing mill structure is presented in Appendix B, Table B-1. Optimization at this stage is possible, however the GAMS solver would completely recycle the effluent water to the fresh water users resulting in a zero effluent network. The theoretical minimum fresh water demand corresponding to a zero effluent network is 430 t/d. This situation does not consider the effect of water network contaminant build-up and therefore is impractical. The mill would not be able to operate with such poor water quality. To address this issue the acceptable water quality for individual process unit usage was investigated.

According to the Ekurhuleni Metropolitan Municipality, the acceptable discharge limit is 5 000 ppm (Ekurhuleni Metropolitan Municipality, 2013). However, the charge for 'treatment and conveyance' of industrial effluent is heavily weighted for COD concentration (Ekurhuleni Metropolitan Municipality, 2013). To minimize discharge costs the Mpact, Springs mill targets an effluent COD limit of 2 000 ppm. To comply with the target, this upper limit was imposed on the COD concentration in the GAMS model.

Machine shower manufacturer specifications provided the maximum allowable solids concentration (STAMM, accessed 23/07/2014):

High pressure showers TSS limit: 20 ppm

According to Starch manufactures, chemical dilution can only be performed with fresh water (Lloyd, 2014):

Chemical dilution TSS limit: 0 ppm

These concentration limits were interrogated by performing a sensitivity analysis, the results of which are presented in Figure 5-9.

The final model constraints were the fixing of the fresh water sinks' total flow rate. This was done to avoid the trivial solution of the solver minimizing the fresh water demand by not sending a flow rate to these sinks. By fixing the total sink demand, it forced the solver to replace fresh water with another water source as intended.

4.5 Model solution

The model was initially defined in terms of continuous flow and concentration variables as well as binary variables representing the existing system's network configuration. Although the total flow material balances are linear, the TSS balances contain bi-linear terms and the COD balances contain tri-linear terms. A bi-linear term arises from the multiplication of two linear variables such as flow and TSS concentration, and is non-linear. Similarly, tri-linear terms are the product of 3 linear terms such as flow, TSS concentration and COD concentration and are also non-linear. These terms greatly contribute to the non-linearity of the model. To solve this type of model, a Mixed-Integer Non-Linear Programming (MINLP) solver is required. The mixed-integer aspect caters for the binary variable.

The GAMS DICOPT solver is able to handle MINLP and was therefore the first choice. It based on the following 3 concepts (Grossmann et al., accessed 06/12/2011):

1. Outer Approximation
2. Equality Relaxation
3. Augmented Penalty

For a full description of the DICOPT solver mechanics, please refer to the GAMS solver manual (Grossmann et al., accessed 06/12/2011). The solver effectively relaxes model equality constraints into inequality constraints by adding positive slack variables, known as augmented penalties. These linear approximations are accumulated during iterations and increase the lower bound of the objective function for a minimization problem; effectively guiding the solver towards the solution. The DICOPT solver first relaxes the integer variables and solves the Relaxed Mixed-Integer Linear Programming (RMINLP) problem. Thereafter, the solver alternates between solving the Mixed-Integer Programming (MIP) problem and the NLP problem for a fixed set of binary variables on each iteration. The DICOPT solver terminates when it detects that the objective function is worsening.

The DICOPT solver could not successfully optimize the water network problem. Figure 4-3 shows the error message of model infeasibility that was produced. The DICOPT solver was not able to complete the first step of solving the RMINLP problem. The DICOPT solver manual suggests this may be due to scaling, the choice of starting point or addition of bounds (Grossman et. al., accessed 06/12/2011). Although the CONOPT solver used to solve the NLP aspect of the problem has an in-built scaling step, Figure 4-3 indicates that the model infeasibility was not improved during this step. This indicates that a more rigorous manual scaling implementation is necessary. The choice of starting point cannot be the problem, since the existing network configuration was used to initialize the binary variables, and the material balance solved successfully for this structure. The addition of bounds refers to the addition of constraints to prevent non-linear functions that may become undefined, such as a lower limit of $x = 0.001$ on a function $f(x) = \log(x)$ (Grossman et. al., accessed 06/12/2011). The material balance equations defining the model do not have such non-linear functions.

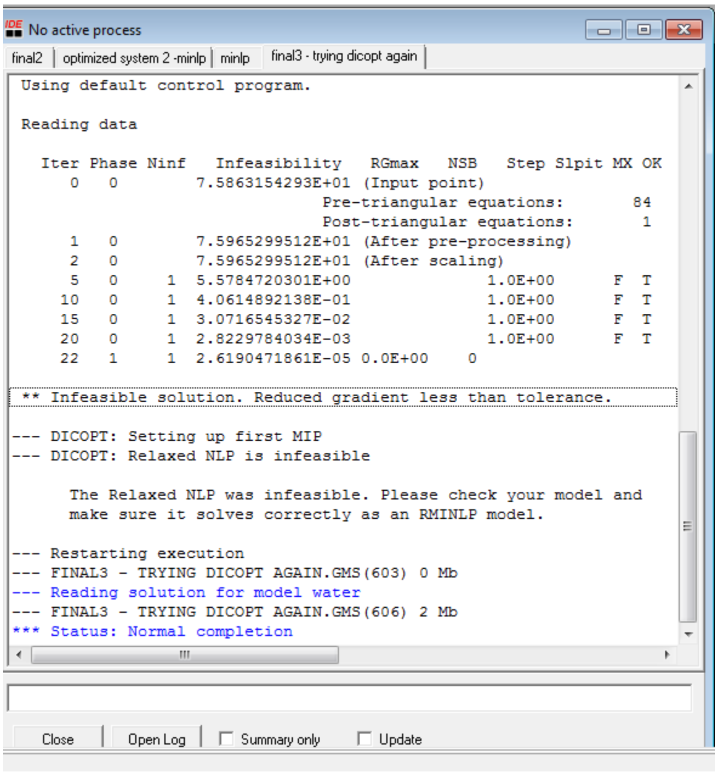

Figure 4-3 General algebraic modelling system output for DICOPT solver run

For this reason the binary variable representing the network connections was removed and replaced with fixed parameters. The user could manipulate the network configuration prior to solving the model and investigate the effect of network structure on the fresh water demand. To decide on the next network connection to be allowed or disallowed, another flow condition was added to the model. For all non-existent network connections, it forced the corresponding flow rate to zero. Although this may seem trivial, since connections that don't exist would not have a flow rate, it was done to extract the *marginal value* information. The subset of all model constraints that are limiting the objective variable are termed *active constraints*. Active constraints have a property termed marginal value or shadow cost. It quantifies the change in the objective variable should the constraint's bound be changed by one unit. So, using the results of the first model run with the existing mill structure, the marginal values associated with non-existent connections were investigated. The connections with the largest negative marginal value would result in the greatest reduction in the objective variable. Using this information network changes were made manually and the model re-run to obtain improved fresh water reduction. This process was repeated until the improvements between runs were negligible. The termination criterion of fresh water reduction improvement of less than 5% between sequential runs was imposed. The final network structure that met this criterion was recorded as well as the final reduced fresh water demand. The results of this optimization procedure is presented in Table 5-1.

By removing the binary variable the model was simplified to a constrained non-linear problem. GAMS solvers such as MINOS and CONOPT, as well as the fmincon function in Matlab, became applicable. According to the GAMS website the MINOS and CONOPT solvers are the most applicable for non-linear problems (GAMS, accessed 27/09/2011). Both solvers are based on different mathematical algorithms and should be tested to improve model solutions reliability. Generally CONOPT is more appropriate for models with very non-linear constraints and few degrees of freedom.

CONOPT is based on the reduced gradient algorithm (Drud, accessed 30/11/2011). By selecting a set of basic variables, the solver calculates a direction for steepest descent that will result in the greatest reduction in the objective function. A step is then made in this direction and the basic variables are updated. This process is iterated until the reduced gradient calculated becomes small, indicating the slow convergence of iteration solutions. The set of variables corresponding to this point is reported as the optimized solution. The CONOPT solver also failed to optimize the model, due to the same scaling problems experienced when using the DICOPT solver.

The MINOS solver was however successful by employing a project Lagrangian algorithm (Murtagh et al., accessed 30/11/2011). This is different from CONOPT since it ‘does not apply the reduced gradient algorithm directly to the problem, but rather uses it to solve a linearly constrained subproblem to find the next step’(More and Wright, 1993).

4.6 Program algorithm

The GAMS code logic is presented in Figure 4-4. The first step defines the sources, sinks and contaminants sets. The set elements are then defined as the types of contaminants and specific sources and sinks belonging to the process units. In the second step the variables such as flows and composition; as well as parameters like network connections are defined. Variables are manipulated by the solver to improve the object variable, whereas parameters are constants used to build the model. The third step involves the initialization of the model using stream data calculated by the material balance. The existing mill water network configuration is used to initialize the first run. This is an important step because it provides the solver a starting point from which to perform the optimization. The MINOS solver can only provide local optimum solutions and cannot guarantee global optimality. A solution strategy to overcome this limitation is the testing of various starting points. However, since the optimization of the existing mill structure is the main concern and global optimality is unnecessary with a preliminary investigation, it was decided that a single starting point and the resulting local optimum would be sufficient. The purpose of this project is to establish a mathematical model and method for multiple contaminant water network optimization. Global optimality can be addressed once the BM6 machine is included and various treatment units are tested. The next stage in the program algorithm is the definition of material balance equations and concentration constraints that define the model; see Sections 4.2 and 4.4. These constraints will be used by the solver to optimize the model. The fully modelled system is now transferred to the MINOS solver. The mechanics of the MINOS solver are fully discussed in the solver manual found on the GAMS website (Murtagh et al., accessed 30/11/2011). The solver results are then analysed. Network structure marginal values were investigated to improve the objective variable. The suggested network changes were made in the Excel input matrix and the model was repeatedly run until the termination criterion was met. The final solver result is then accepted as the reduced fresh water demand for the model. The corresponding water network structure was recorded as the fresh water reduction strategy.

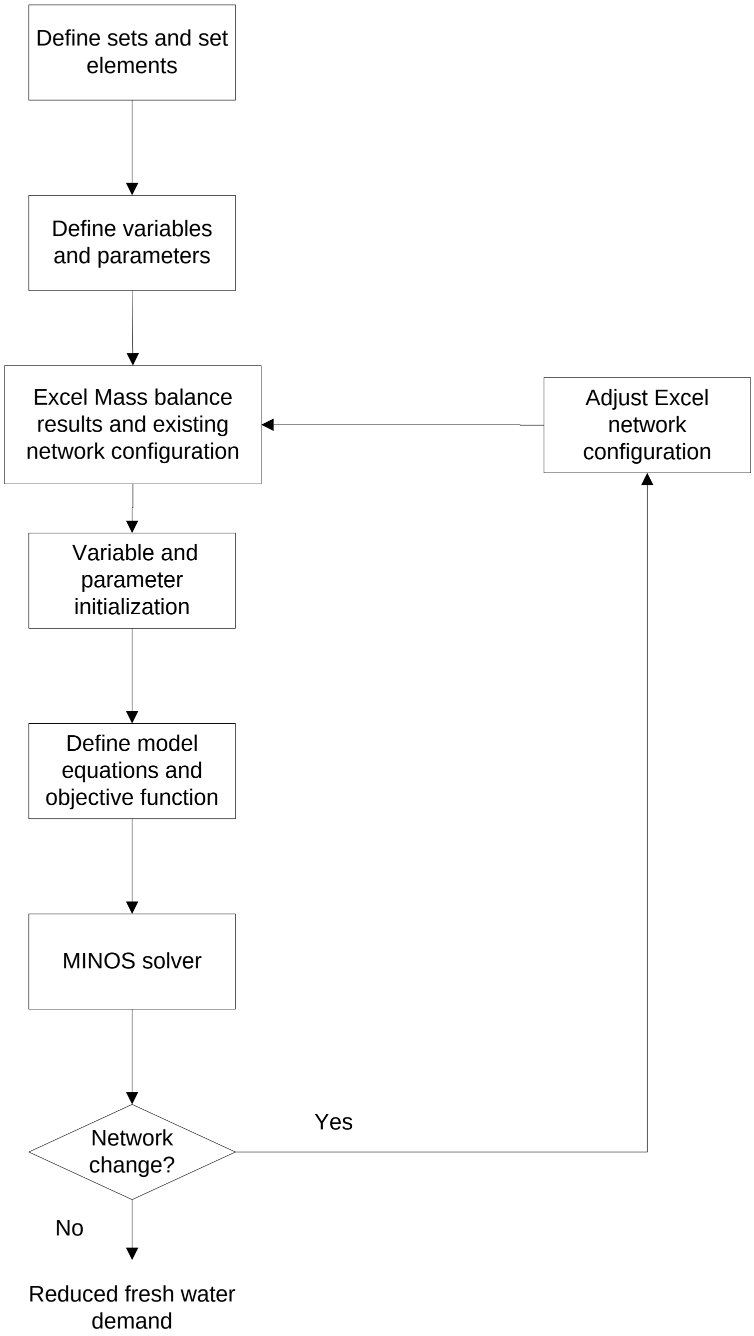

Figure 4-4 General algebraic modelling system code logic based on Gianadda (2002)

4.7 Concluding remarks

The GAMS model reproduced the source stream concentrations within the material balance error margin. This verified the GAMS model. The MINLP problem could not be successfully solved, but was addressed indirectly by defining a constrained NLP model and manually adjusting network connections according to its marginal value. The model was successfully optimized using the MINOS solver and a reduced fresh water demand subject to water quality constraints was recorded. In the next chapter the results of model optimization at varying regenerated water TSS concentrations is presented and discussed. The BM3 fresh water reduction potential is identified and water treatment technology necessary to achieve this level of network closure is discussed.

5. Results and Discussion

In the previous chapter the model formulation and choice of GAMS solver was discussed. The optimization was also verified by reproducing the material balance results within the measurement error. In this chapter the verified optimization is used to determine the reduced fresh water demand as a function of the regenerated water TSS concentration. Regenerated water refers to the clarifier overflow water that is available for re-use on the Board Machine. Also, the regions of the fresh water demand curve is analysed. Finally the significance of the results is discussed, possible control implementation strategy is proposed and the concentration constraint sensitivity is determined.

5.1 Regenerated water TSS concentration

The daily regenerated water TSS concentration data for 2011, consisting of 169 measurements, is presented in Figure 5-1. The concentration values are spread without a clearly discernible normal operating concentration. The mean concentration is 150 ppm and shown on Figure 5-1. This data was then represented in a frequency histogram shown in Figure 5-2. Most of the TSS concentration measurements are below the mean. This can be seen by the taller bars in the lower concentration ranges. This type of distribution is a right skewed normal distribution. This was confirmed by performing a Chi-square test for normality on the sample data.. The null hypothesis was: The sample data is normally distributed. At a significance level of 0.05, the calculated Chi-square statistic was 71.3. This corresponds to a cumulative probability of 2.73E-08. Since this probability is less than the significance level of 0.05, the null hypothesis of the sample data being normally distributed was rejected with at least 95% confidence.

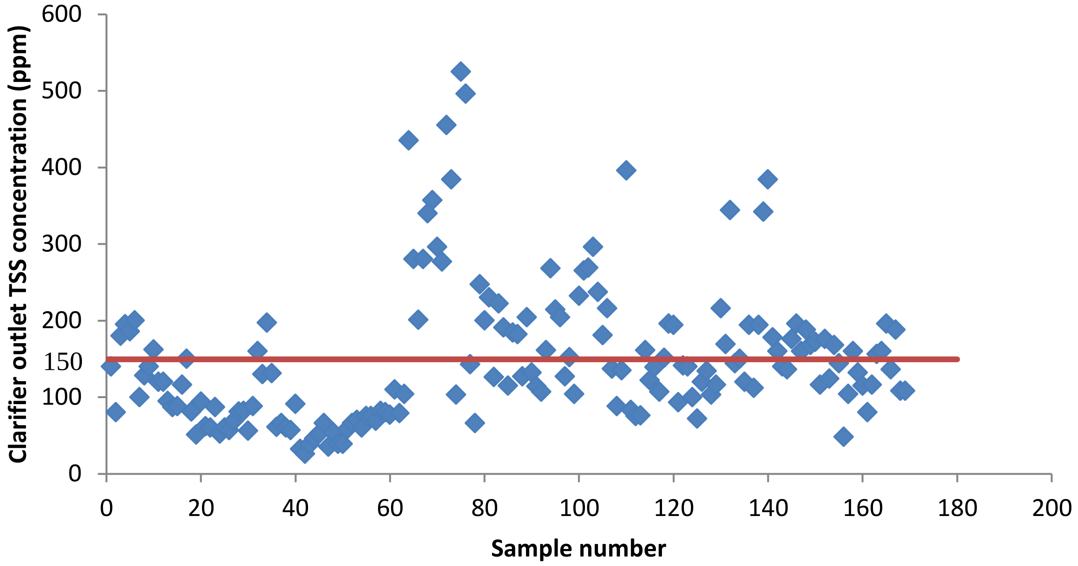

Figure 5-1 Scatter plot of regenerated water TSS concentration showing data spread

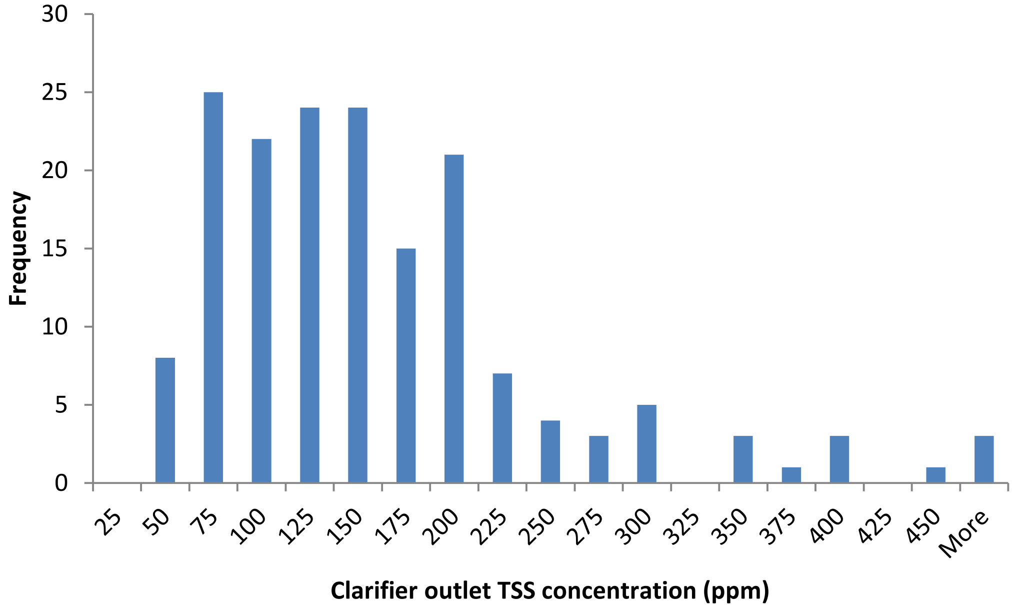

Figure 5-2 Frequency histogram of regenerated water TSS concentration showing the skewed normal distribution

Figure 5-2 shows that most samples are within the 75 ppm to 200 ppm concentration range, representing normal operation. Concentrations above this range would be caused by poor clarifier performance. This could be caused by high fibre loading from the Board Machines due to tank overflows being washed to drain, the clarifier rake becoming jammed by high sludge levels, or the sludge pumps tripping. Concentrations below this range would be due to individual Board Machine shuts. During this time there is no flow from the Board Machine to the clarifier thereby reducing the fibre loading.

Since the model was developed for steady state normal operation it was assumed the clarifier operates with a fixed regenerated water TSS concentration of 150 ppm, corresponding to the data mean. This assumption was required because the regenerated water TSS concentration is a function of many variables. These variables include:

1. Volumetric flow rate of water sent to the clarifier from the Board Machines
2. TSS concentration of water sent to the clarifier from the Board Machines
3. Dosing quantity of flocculants and coagulants used by clarification operators in order to facilitate solids settling
4. Clarification plant equipment reliability

Although the trend data is available to determine the correlation between the regenerated water TSS concentration and variables 1, 2 and 3; variable 4 could not be modelled. If any sludge pump, clarifier rake or save-all trips due to high current, the clarification plant would no longer operate normally. This kind of equipment failure could not be incorporated into the model and hence a fixed overflow TSS concentration was used. This also facilitated in linearizing the clarification unit operation in the model formulation. It is recommended that this assumption be investigated to determine the actual clarifier operation and improve model accuracy.

5.2 BM3 water network optimization

Initially the model was optimized using the mean regenerated water TSS concentration of 150 ppm. Using Equation 2.3 in Section 2.3.1, discussed by Parthasarathy and Krishnagopalan (2001), the fresh water stream flow rate will be minimized by either reducing the difference between the source concentration and the sink demand concentration; or by maximizing the difference between the fresh water concentration and the sink demand concentration. The latter cannot be achieved since both the fresh water and the sink demand concentrations are fixed. The largest fresh water reduction corresponds to the use of a source stream with a concentration nearest the fresh water sink demand concentration. This resulted in the source stream with the lowest TSS concentration becoming the first choice for replacement of fresh water. From Table 3-7, the regenerated water TSS concentration (SU14w) was the lowest and therefore the connection between this source and the high pressure showers were allowed. This confirmed the optimization algorithm could be successfully applied; and a fresh water demand reduction of 10% from 819 t/d to 734 t/d was obtained at a regenerated water TSS concentration of 150 ppm. The resulting network configuration is shown in Figure 5-3.

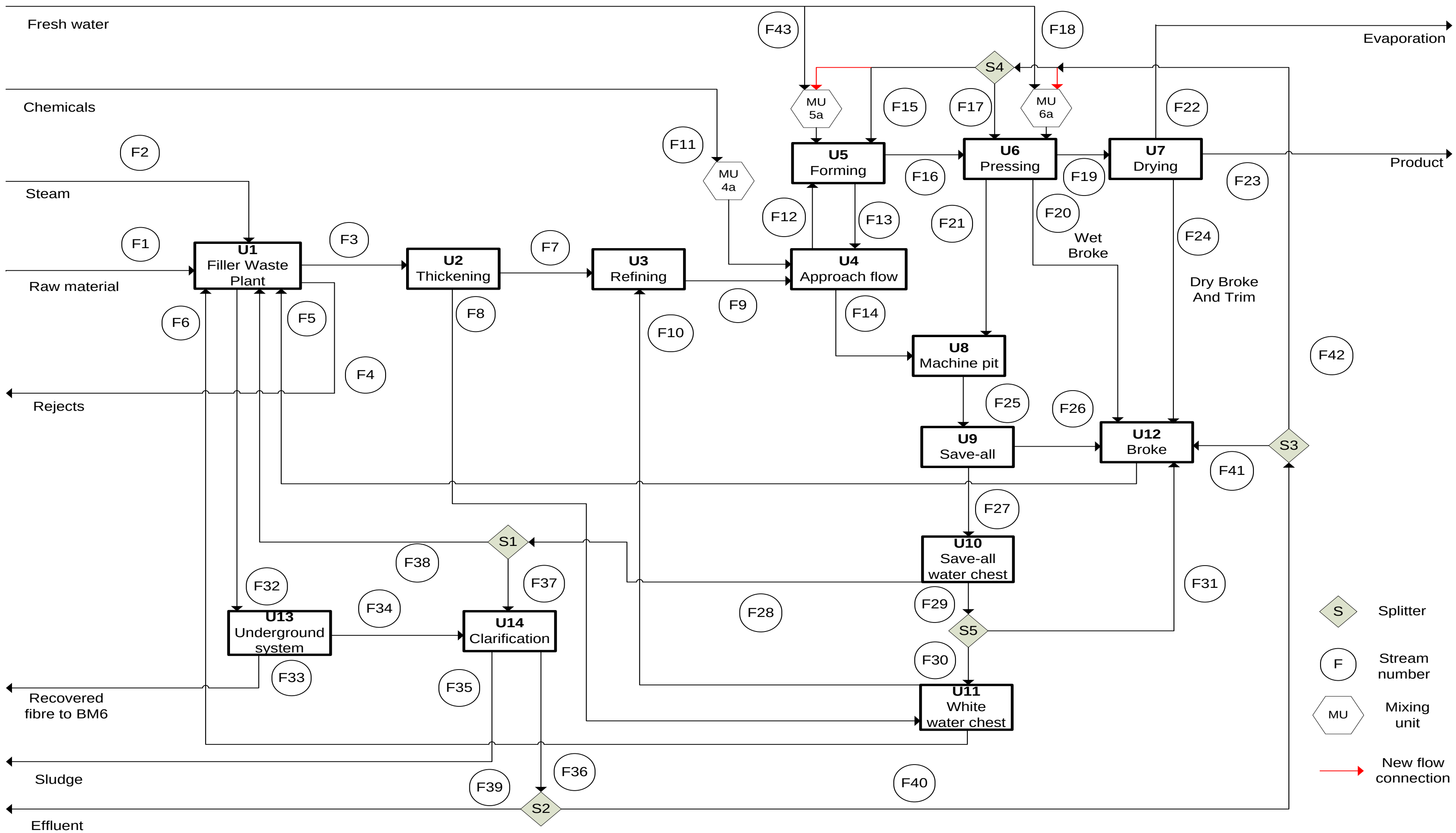

Figure 5-3 Optimized BM3 process flow diagram at a regenerated water TSS concentration of 150 ppm

Although this is a promising result for the mill, its applicability was further investigated by varying the regenerated water quality.

5.3 Fresh water demand curve

The cumulative distribution for the regenerated water TSS concentration data, shown in Figure 5-4, revealed that 61% of the time the TSS concentration is the mean of 150 ppm or lower. The mean does not correspond to a cumulative probability of 50% because the data is not normally distributed. Since the network was optimized for this quality of water, this results in a 61% concentration constraint compliance. The rest of the time, the water is worse than the sinks can accept. Problems such as shower head clogging and improper felt cleaning will occur. This is unacceptable in terms of mill operation.

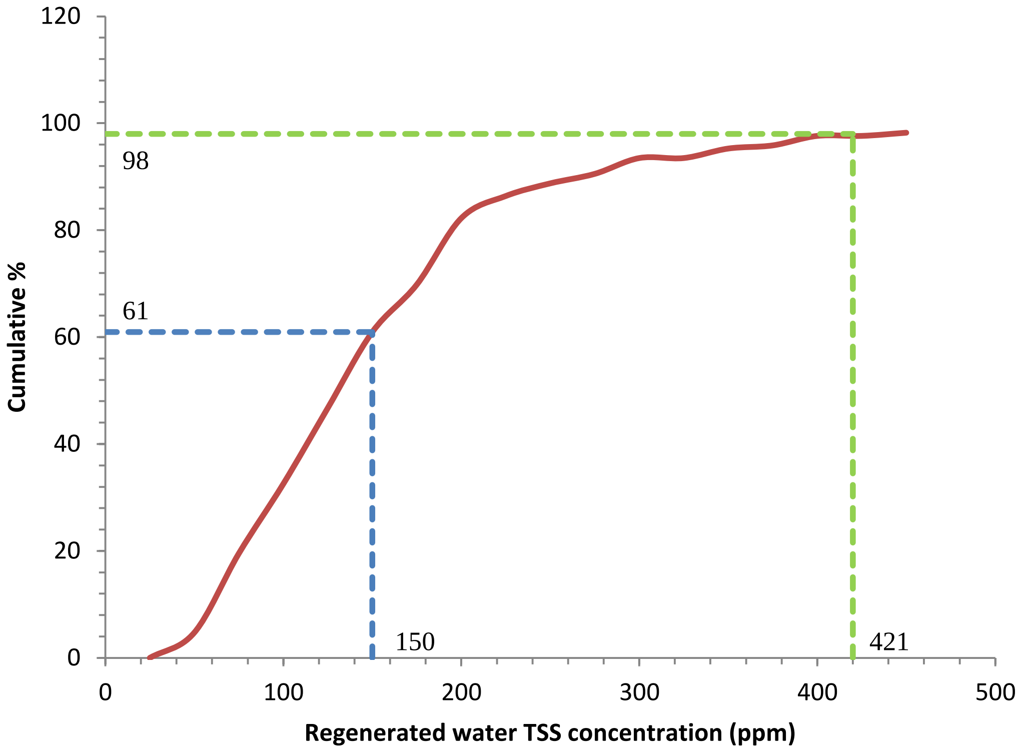

Figure 5-4 Cumulative distribution of regenerated water total suspended solids concentration data

A range of TSS concentration constraint compliance values were evaluated using the corresponding regenerated water concentrations from Figure 5-4. For each regenerated water quality, the water network was optimized and the fresh water demand recorded. The existing network configuration was used to start the optimization, and thereafter the marginal values associated with active constraints were used to improve on the objective variable. No clear network change recommendations were seen on the first iteration since all marginal values were either 0 or -1. Therefore the source stream with the lowest TSS concentration was used as the first choice for replacement of water in the fresh water sinks. The model was then solved again and the marginal values re-evaluated. Negative marginal values indicated allowing the connection would improve the objective variable. The magnitude of the marginal value is directly proportional to the magnitude of improvement. The connection with the largest negative marginal value was allowed and the model solved. This was repeated until a network change yielded an improvement on the previous objective variable of less than 5%. This was the termination criterion. Improvements of less than 5% requiring installation of additional piping and valves may be economically infeasible, depending on the distance between the source and sink. An investigation of the cost versus benefit of additional network connections is recommended in order to interrogate the selection of the 5% value of the termination criterion. The results of the optimization for each regenerated water concentration are presented in Table 5-1.

From Table 3-7, the save-all water chest water has a TSS concentration of 326 ppm. Therefore, save-all water chest water (SU10) was allowed for fresh water replacement for regenerated water TSS concentrations above this value. Decreasing regenerated water TSS concentration did not reduce the fresh water demand since it was not allowed for fresh water replacement until the concentration was below 326 ppm. However, the save-all water chest water replacement option resulted in a fresh water reduction less than the 5% termination criterion. Therefore this network suggestion was rejected. Thereafter, the fresh water demand reduces with decreasing regenerated water TSS concentration until the COD concentration limit of 2 000 ppm is reached.

The COD concentration limit was found by specifying TSS regenerated water concentrations and using an interval halving technique until the COD concentration limit was reached. The regenerated water TSS concentration thus found was at 28 ppm and the concentration compliance was 0.59%. This corresponds to a fresh water demand of 569 t/d and a fresh water reduction of 30.54%. Oxygen dosage at the clarifiers reduces COD but since this method promotes the growth of microbial organisms it was not considered a viable option for COD reduction. Furthermore, the mill does not have water treatment units to remove COD loading. Therefore further reduction in the regenerated water TSS concentration does not result in a reduction in the fresh water demand.

Table 5-1 Optimization and termination criterion results

Clarifier overflow TSS Concentration (ppm)	**Concentration constraint compliance (%)**	**Network change**	**Fresh water demand (t/d)**	**Reduction (%)**	**Status**
450	98	Save-all water chest (SU10) to high pressure showers	781.10	4.62	Rejected
350	95	Save-all water chest (SU10) to high pressure showers	781.10	4.62	Rejected
250	89	Regenerated water (SU14w) to high pressure showers No further changes suggested	769.64	6.02	Accepted
200	82	Regenerated water (SU14w) to high pressure showers No further changes suggested	757.30	7.53	Accepted
150	61	Regenerated water (SU14w) to high pressure showers No further changes suggested	734.00	10.38	Accepted
100	33	Regenerated water (SU14w) to high pressure showers No further changes suggested	695.60	15.07	Accepted
75	20	Regenerated water (SU14w) to high pressure showers No further changes suggested	654.47	20.09	Accepted
45	4	Regenerated water (SU14w) to high pressure showers No further changes suggested	583.94	28.70	Accepted

Table 5-1 Optimization and termination criterion results continued

Clarifier overflow TSS Concentration (ppm)	Concentration constraint compliance (%)	Network change	Fresh water demand (t/d)	Reduction (%)	Status
35	2	Regenerated water (SU14w) to high pressure showers No further changes suggested	574.71	29.83	Accepted
28	1	Regenerated water (SU14w) to high pressure showers No further changes suggested	568.88	30.54	Accepted
25	0	Regenerated water (SU14w) to high pressure showers No further changes suggested	568.88	30.54	Accepted
5	0	Regenerated water (SU14w) to high pressure showers No further changes suggested	568.88	30.54	Accepted

The fresh water demand after network optimization is shown in Figure 5-5. The theoretical minimum fresh water demand of 430 t/d corresponding to the zero effluent condition, in which the network is completely closed, is also shown. Since the current fresh water usage for Board Machine 3 is 819 t/d; a completely closed network would result in a 47% fresh water usage reduction. This possible reduction is supported by McDonald (2004) when he stated '...there is some opportunity to reduce water usage by about half...' at the Mpact, Springs mill. The economic feasibility of a zero water discharge network at a paper mill was addressed by Koppol et. al. (2003). They found that the treated water outlet concentration determined the type of physical treatment required and hence had a strong influence on the network operating cost.

The TSS concentration constraint compliance represents the percentage of time the water quality is acceptable for use in the fresh water sinks. When the water is of a poorer quality than the concentration constraint, then shower blockage and improper felt cleaning will result. Machine down time due to these problems is not recorded and hence an acceptable mill TSS concentration constraint compliance could not be determined. If for instance, machine downtime due to these causes was 10% of the total machine downtime, then the TSS concentration compliance would be 90%. A conservative assumption of 95% constraint compliance was used to avoid fresh water reductions at the cost of machine operability. From Table 5-1 this option was rejected since the fresh water reduction did not meet the termination criterion. Constraint compliance of less than 95% would require further water treatment units to reach the acceptable 95% condition.

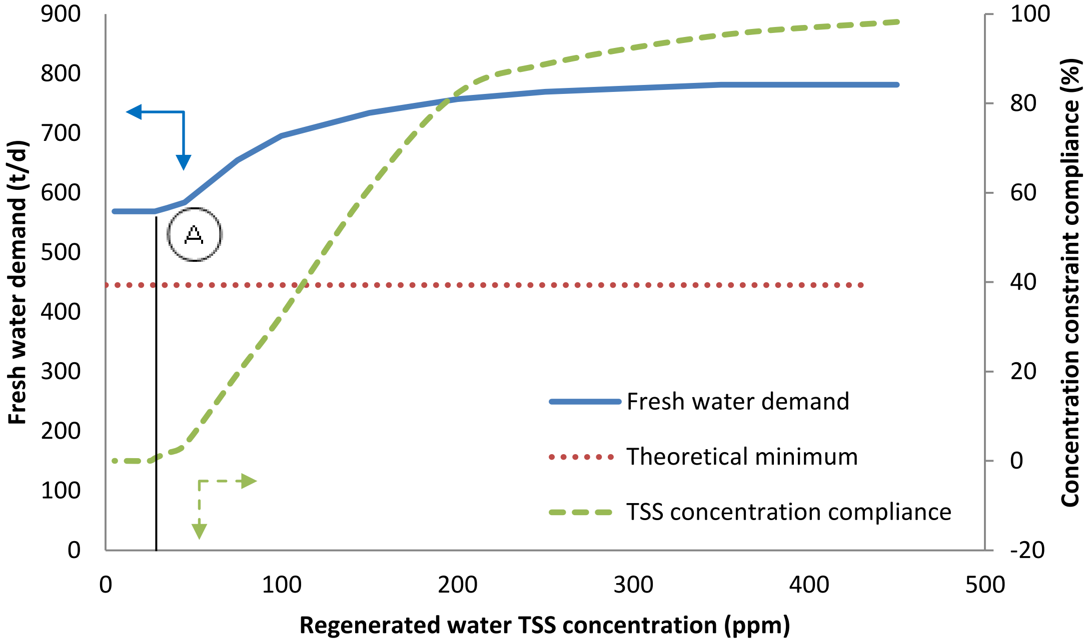

Figure 5-5 Fresh water demand curve with corresponding TSS concentration constraint compliance

From Figure 5-5, it is seen that a critical point at regenerated water TSS concentration of 28 ppm exists at point A, below which further reduction in the suspended solids loading does not reduce the fresh water demand. At this point the maximum COD concentration constraint has become limiting.

The increase in COD concentration as the fresh water demand is reduced is illustrated in Figure 5-6. The graph ends abruptly on the left since the fresh water demand cannot be reduced below 569 t/d because the imposed COD concentration limit of 2 000 ppm cannot be exceeded. The graph also ends abruptly on the right since, for clarifier overflow TSS concentration greater than 326 ppm, the save-all water chest water (SU10) is used for fresh water replacement. This water source concentration cannot be adjusted because it depends on the save-all fibre removal fraction which is constant in the model. Because only one source TSS concentration is possible, the optimization will yield a single fresh water demand, thereby truncating the curve in Figure 5-6. The save-all fibre removal fraction assumption is shown in Appendix A, Table A1.

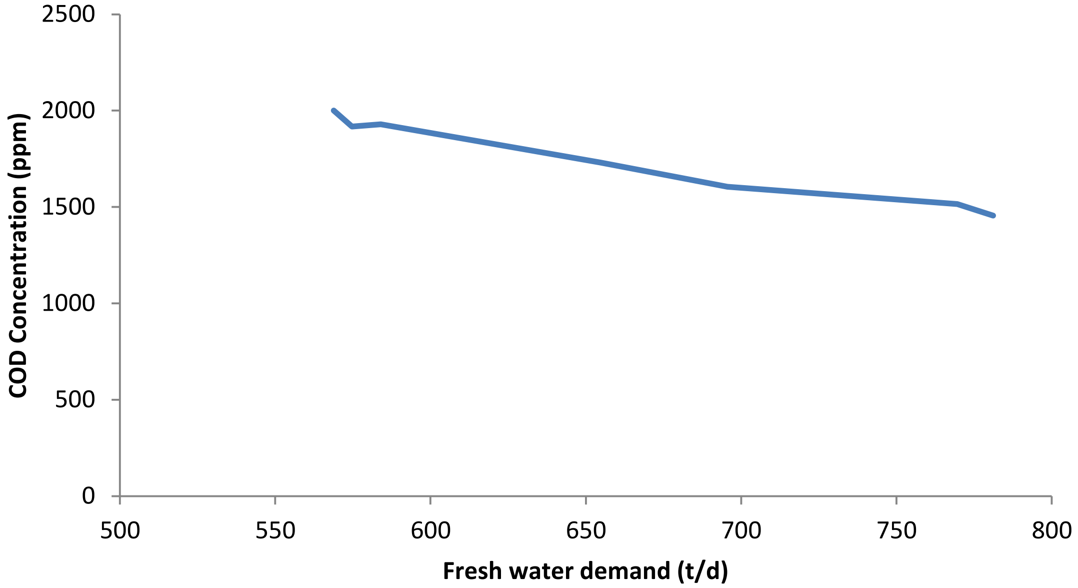

Figure 5-6 Impact of water network closure on the COD concentration

To further reduce the fresh water demand, the COD in the system needs to be removed. Currently the mill handles the slime caused by microbial growth by dosing biocide. Microbial growth increases with increasing COD concentration. The critical point at a regenerated water TSS concentration of 28 ppm then represents the greatest fresh water demand reduction possible without the addition of water treatment units to remove COD. As this would most likely be of the most interest to the mill, it is reported as the final optimized solution for this investigation. This corresponds to a fresh water demand of 569 t/d and a reduction of 31%. This reduction would require the installation of piping to replace fresh water with regenerated water. Also TSS removal water treatment units would need to be installed to ensure the regenerated water remained below the critical TSS concentration at least 95% of the time.

The optimized network structure for a regenerated water TSS concentration of 28 ppm is the same as the network presented in Figure 5-3 since the same network change suggestions were made. The logical network representation is shown in Appendix B, Table B-2.

5.4 Implementation of results at the Mpact, Springs mill

The Fresh Water Demand (FWD) curve can be divided into 3 distinct regions, shown in Figure 5-7.

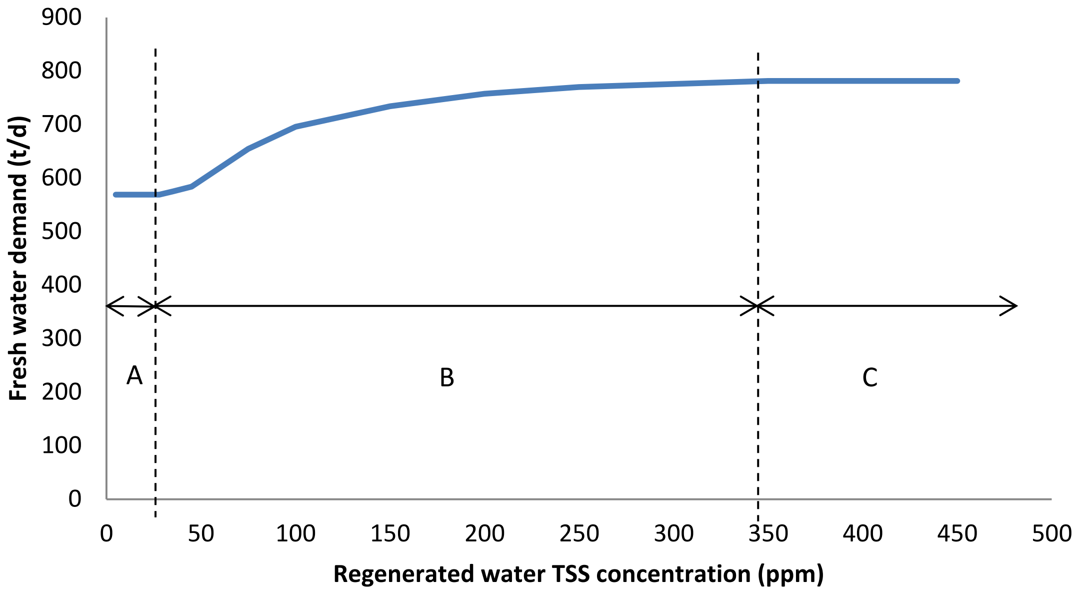

Figure 5-7 Fresh water demand curve regions

In region A, no further reduction in the fresh water demand is possible without removing the COD loading in the system. The installation of aerobic and/or anaerobic treatment units would be required to achieve this. Region B covers the regenerated water TSS concentration range that requires further solids removal to meet the 95% concentration constraint compliance. Installation of solids removal treatment units would be required. Discussion of treatment units for regions A and B is addressed in Section 5.4.1. The poorest water quality with TSS exceeding 350 ppm has concentration constraint compliance greater than 95%, and is described by region C. The piping required for the network changes is the connection of the save-all water chest water (SU10) to the fresh water users, ie: high pressure showers (MU5a and MU6a). However, from Table 5-1, it can be seen that this network connection does not provide a fresh water reduction exceeding the termination criterion of 5%. Therefore, Region C is not applicable since this network connection was rejected.

Furthermore, the risk of using save-all water chest water for fresh water replacement is that the TSS concentration may vary greatly because of Board Machine operability. Essentially the solids loading in this stream consists of fines which are very small fibre particles that have passed through the wire in the Former section (U5). In the mass balance a Former retention of 70% was assumed, see Appendix A, Table A1. However, in operation this retention is affected by the amount of retention aid chemical added which may vary for different products; as well as the refining intensity in the refiners (U3). Other mechanical problems in the save-all (U9) such as leaking seals or holes in the drum will allow these fines to report to the save-all water chest water. In the mass balance a save-all fibre removal of 90% was assumed, see Appendix A, Table 1. If the save-all water chest water (SU10) quality deteriorates then the amount of possible fresh water replacement would be reduced. For these reasons there is a high risk attached to the network changes proposed in Region C.

Therefore, fresh water reduction on Board Machine 3 would require the installation of TSS removal water treatment units to achieve operating conditions in Region B; as well as COD removal water treatment units to achieve operating conditions in Region A.

5.4.1 Water treatment technology

Different water treatment technologies are available to remove water stream contaminants. Screening may be used to remove large particles that would otherwise block or damage more intensive contaminant removal operations (Smook, 1992). The Mpact, Springs mill uses vibrating screens and rotating drum screens to remove plastics and metal staples from the water network. Pressure screens are also used to treat process water in order to recover useable fibre and reduce the solids loading on the clarifiers.

The most common primary treatment methods at pulp and paper mills are gravity sedimentation and dissolved air flotation (Smook, 1992). Smook (1992) explains that dissolved air flotation processes ‘are generally more efficient in removing solids’ than gravity sedimentation processes. However, clarifiers which are a type of gravity sedimentation process can remove up to 95% of solids able to settle (Sappi, 2012). The Mpact, Spings mill uses clarifiers to treat the process water by removing the suspended solids. The sludge stream produced cannot be recycled back to the board machine as a raw material substitute because of the high ash content. The high ash content is due to boiler house grit arrestor water and ash cooling water which are also sent to the clarification plant for treatment.

Other treatment methods include membrane separation techniques such as micro-filtration, ultra-filtration, and reverse osmosis. The applicability of these treatment units depend on the quality of inlet water, desired outlet concentration and the capital investment available. To achieve the desired critical concentration, a combination of treatment units may be required. The optimal removal strategy with respect to fresh water minimization should be investigated.

Secondary treatment units include aerobic and anaerobic units which remove COD loading. The most common aerobic processes are aerated stabilization basins and activated sludge treatment. The introduction of microorganisms, oxygen and inorganic nutrients such as phosphorus and nitrogen allow the biodegradation of soluble organic matter in the waste water stream. Temperature and pH are important factors affecting microorganism function (Smook, 1992). These operations can reduce COD by 50% to 90% (Sappi, 2012). Anaerobic treatment is performed in the absence of oxygen and the microorganisms produce methane and hydrogen sulphide products (Smook, 1992). The installation of these technologies will make fresh water demand reduction past the critical point possible. However, capital investment is a major concern as well as space availability. Aerated stabilization basins typically have detention times of between 5 to 10 days (Smook, 1992). The Mpact, Springs mill would not have sufficient space to build such a large water treatment operation to treat the required volume of process water. The activated sludge process does not require as much space and hence should be considered as a secondary treatment option.

5.4.2 Control scheme for fresh water replacement

Due to the variation in the regenerated water TSS concentration, the fresh water replacement must be controlled to ensure the water sent to the high pressure showers does not exceed the concentration limit. A consistency control loop will not be appropriate since the consistency transmitters used at the mill have a measurement range of 1-6% consistency. The target consistency of 20 ppm will be too low for the instrument to measure thus preventing control.

An alternative solution is to assume a regenerated water TSS concentration that can be achieved by a TSS removal treatment unit. If for instance 50 ppm is assumed and a 20% safety factor is attached, then the regenerated water concentration would be 60 ppm. The fresh water replacement ratio (FWRR) can then be calculated as shown in equation 5.1:

$$Target\ TSS = Fresh\ water\ TSS \times (1 - FWRR) + Regenerated\ water\ TSS \times FWRR \qquad \text{Equation 5.1}$$

For a Target TSS of 20 ppm, the FWRR is 33%, assuming fresh water TSS is 0 ppm. A cascade level and flow control loop can be used as shown in Figure 5-8. The remote set point sent to each flow controller is calculated based on the FWRR inputted by the operator.

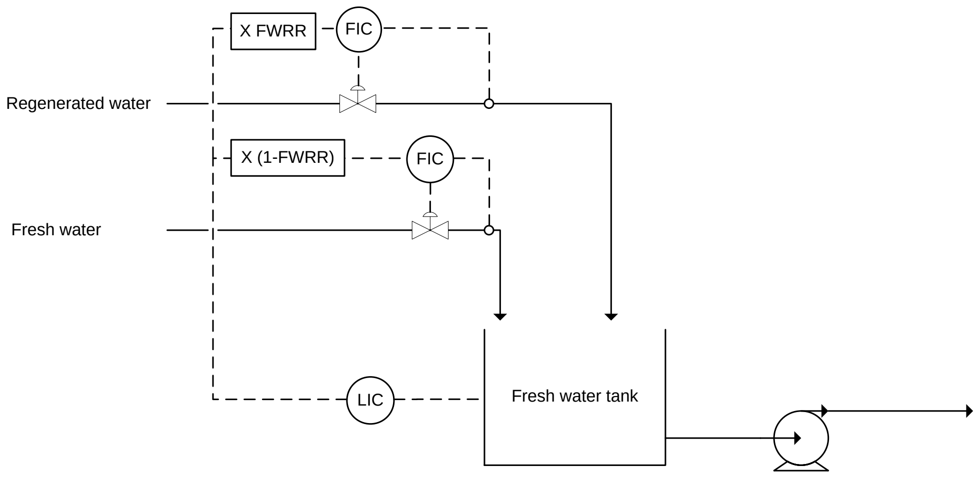

Figure 5-8 Fresh water replacement control scheme

5.4.3 Accumulation of dissolved solids in water network

Dissolved ionic species in the mill water network are responsible for operational problems. Chlorides cause corrosion whilst calcium causes scaling. Additionally, the wet-end chemistry is especially sensitive to ionic speciation. The major source of these contaminants is the fresh water and raw materials. Although fresh water to the boiler system is de-ionised, this is not done for fresh water supplied to the rest of the mill. Fibre raw materials are the greatest contributor to dissolved solids loading in the system, due to the dirty nature of the recycled paper. Since the recycled paper is sorted, an investigation into the contaminant loading of the different types is suggested.

To address the dissolved ionic species, chemical speciation models need to be developed for the mill water network. The current GAMS code is unable to do this and the Water Quality Management Tool software that is being developed by the UKZN Pollution Research Group is suggested to perform the modelling.

5.5 Significance of results

The scope of the investigation was for a single product, namely Ndicore 400. This product is a high strength board product used for the manufacture of cores. Cores are used to wind paper for distribution. Ndicore 400 makes up approximately 50% of the Board Machine production. The optimization output depends on the material balance results since process stream data are fixed in the model formulation. A sensitivity analysis on the process stream specifications was also proposed. The purpose of this was to assess the uncertainty of the optimization output using Monte Carlo simulations. However, the process design specifications are fixed since they would be controlled for production of Ndicore 400. The sensitivity analysis on these specifications was therefore disregarded. The single product scope also fixes the fresh water requirement for chemical dilution since, the starch requirement and dilution factor is known.

The optimisation result is purely the fresh water demand of the board machine. Because the fresh water sink demand and concentration limits are fixed by the unit operation, only the quality of the regenerated water affects the amount of fresh water substitution possible. Any variability in the material balance inputs would be noticed in the water network streams because the process streams are held constant. The change in the clarifier inlet solids loading should affect the outlet concentration and hence the fresh water reduction possible. However, all other input variables are effectively decoupled from the optimization result by the fixing of the regenerated water quality on each model run. The variability in these other input variables is seen in the sludge stream as it handles the changing inlet solids load. The constant regenerated water concentration assumption prevents the analysis of material balance input variability on the optimization result.

The concentration constraints used in the optimization were investigated in a sensitivity analysis, presented in Figure 5-9. The high pressure shower concentration limits were investigated at a regenerated water TSS concentration of 100 ppm where these constraints are limiting. The maximum COD concentration limit was investigated at a regenerated water TSS concentration of 5 ppm where it is limiting. The fresh water optimization is most sensitive to the maximum COD concentration limit and least sensitive to the fresh water shower concentration limit. This is because of the relative magnitudes of the concentration limits. The TSS concentration limit is 20 ppm, therefore a 5% change is just a 1 ppm limit change. This will have a small effect on the fresh water demand. However, the COD concentration limit is 2 000 ppm, therefore a 5% change is a 100 ppm limit change. A much larger effect on the fresh water demand will be achieved as seen in Figure 5-9.

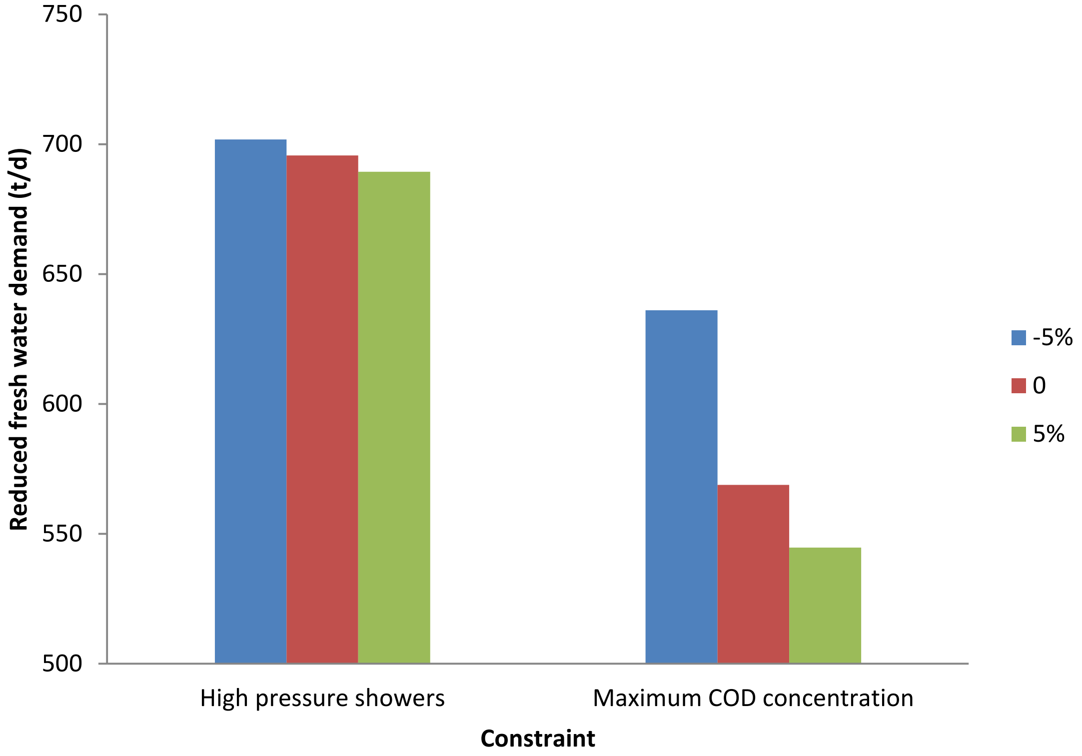

Figure 5-9 Concentration constraints sensitivity results

5.6 Concluding remarks

The GAMS model was successfully optimized to produce the network structure shown in Figure 5-3. The only network change necessary is to allow regenerated water to the high pressure showers. New water treatment units will have to be installed to ensure the regenerated water quality meets the TSS concentration limits at least 95% of the time. Additional network changes could not improve fresh water reduction more than the 5% termination criterion. The critical point where COD becomes limiting, at a TSS concentration of 28 ppm, is reported as the final accepted solution for this first stage investigation. It corresponds to a fresh water reduction of 31% and a fresh water usage of 569 t/d.

The project results will be used as a bench mark for investigations considering the scaling risk of a closed water circuit; the chemical speciation of the water system and how network closure affects wet-end chemistry, as well as the effect of changing paper grades and raw material types on the contaminant loading of the system. Only once the system is fully understood and all variables can be quantitatively accounted for in terms of machine operability, product quality and utility costs should the objective function become economic in nature.

6. Conclusions

- The Board Machine 3 material balance was successfully developed and solved using Excel 2007 with the Solver add-on
- The Board Machine 3 material balance was able to successfully predict measured stream properties
- The mill water network was successfully optimized using the verified GAMS model
- The critical regenerated water TSS concentration of 28 ppm, at which COD becomes limiting resulted in a fresh water reduction of 31% and a fresh water demand of 569 t/d
- The model uncertainty could not be quantified however the concentration constraint compliance sensitivity, Figure 5-9, indicated the fresh water demand is most sensitive to the COD concentration limit

7. Recommendations

- Install TSS removing water treatment technology and supply high pressures showers with regenerated water, Section 5.4
- Investigate mass balance structure low flow limit of 50 t/d, Section 3.2
- Interrogate mass balance assumptions for different mill conditions in the order presented in Table 3-9, Section 3.6
- Interrogate concentration limits based on results presented in Figure 5-9, Section 5.5
- Investigate other water treatment technologies for TSS removal to improve regenerated water quality, Section 5.4.1
- Investigate save-all operation as a function of feed consistency, Section 3.4
- Investigate clarifier operation for GAMS modelling purposes, Section 5.1
- Investigate the effect of changing product grades on the contaminant loading of the water network, Section 5.4.3
- Investigate contaminant loadings in the various types of recycled paper raw material, Section 5.4.3
- Include chemical speciation to account for dissolved solids in water network using Water Quality Management Tool, Section 5.4.3
- Perform an economic feasibility study to assess the selected network structure termination criterion of 5%, Section 5.3
- Perform this water network optimization for Board Machine 6, Section 3.2

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9. Appendices

A. Board Machine 3 material balance

A.1 Stream specifications and Degree of Freedom Analysis

Stream specifications used to solve the material balance are shown in Table A-1.

Table A-1 Material balance specifications

Stream Flow	(t/d)
F1	106
F2	50
F4	16
F11	202
F15	533
F17	646
F18	369
F23	81
F37	2000
F41	2000
F43	248
Stream TSS composition	**(wt fraction)**
x1	0.88
x3	0.009
x4	0.2
x7	0.042
x9	0.035
x12	0.009
x14	0.004
x16	0.15
x19	0.53
x20	0.53
x23	0.93
x24	0.93
x26	0.12
x33	0.0315
x35	0.35

Table A-1 Material balance specifications continued

Stream COD composition	(wt fraction)
x36	1.50E-04
y36	1.43E-03
y11	0.0597
y18	0
Assumptions	
Dry broke	0.1
Wet broke	0.05
Former retention	0.7
Thickener fibre recovery	0.9
Save-all fibre recovery	0.9
Save-all Water Chest to Waste plant fraction	0.6
Save-all Water Chest to White Water chest and Broke split	0.5
Press felt retention	0.98
COD retention	0.0743

Using these stream specifications and assumptions the degree of freedom (DOF) analysis for the Board Machine 3 system was performed. The method is illustrated by performing DOF analysis on the Filler Waster Plant. Figure A-1 shows the streams entering and leaving the process block; and the specified information for this block is presented in Table A-2.

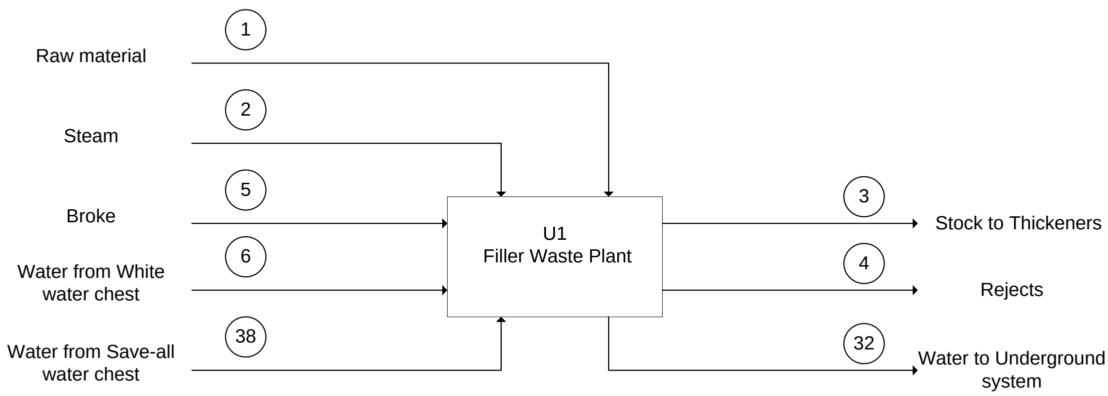


Figure A-1 Block diagram of Filler Waste Plant for DOF analysis

Table A-2 Specified information for Filler Waste Plant

Stream number	Flow rate (t/d)	TSS weight fraction [g TSS / g Stream]	COD weight fraction [g COD / g Stream]
1	106	0.88	-
2	50	N/A	N/A
3		0.009	-
4	16	0.2	-
5	-	-	-
6	-	-	-
32	-	-	-
38	-	-	-

Note: dashes (‘-‘) indicate the stream property is not specified

Each stream has four variables of which any combination of three variables is independent. This is because the sum of the individual component balances (water, TSS and COD) yield the total flow balance. The special case is the steam stream (stream 2) because it comprises only of water. Therefore it has only one variable, namely flow rate. The total number of stream specifications is six. The number of independent variables for the process block is the sum of the independent variables in each stream. Each stream has three independent variables except stream 2 which has one independent variable.

Number of independent variables = 7 Streams * (3 independent variables) + Stream 2 * (1 independent variable)

= 22

Next, the number of independent balances that can be written is three since the total flow balance can also be written as the sum of the individual component balances.

Splitter restrictions apply to units or pipeline splits in which the exiting streams have the same composition. The number of splitter restrictions is calculated as:

Number of splitter restrictions = (Number of outlet branches – 1) * (Number of stream components – 1)

The splitter restrictions do not apply to the Waste plant process block. However, the COD in the exiting streams were assumed equal since all the operations within the Filler waste plant block only affect the TSS and not the COD dissolved in the water. Therefore:

Number of COD restrictions on process unit = (Number of outlet branches – 1) * (Number of stream components – 1)

= (3 – 1)*(2 – 1)

= 2

The other material balance assumptions do not involve any of the streams in the Filler Waste Plant process block and therefore do not apply. The degree of freedom is then calculated as:

DOF = Number of independent variables – Number of independent balances

– Number of specifications – Number of Splitter restrictions

– Number of COD restrictions on process unit – Number of applicable assumptions

= 22 – 3 – 6 – 0 – 2 – 0

= 11

Table A-3 Degree of freedom analysis for complete system (TSS and COD)

		Filler Waste plant	**Thickening**	**Refining**	**Approach Flow**	**Former**	**Press**	**Dryer**	**Machine pit**	**Save-all**	**Save-all water chest**
Number of independent variables		22	9	9	14	13	16	10	9	9	9
Number of independent balances		3	3	3	3	3	3	3	3	3	3
Specifications	**Flow**	3	0	0	1	2	2	1	0	0	0
	Composition	3	2	2	4	2	3	3	1	1	0
Splitter restrictions		0	0	0	0	0	0	0	0	0	0
TSS restriction on process units		0	0	0	0	0	0	0	0	0	1
COD restrictions on process units		2	1	0	1	0	2	1	0	1	1
Assumptions	SA fibre recovery	0	0	0	0	0	0	0	0	1	0
	Thickener fibre recovery	0	1	0	0	0	0	0	0	0	0
	COD retention	0	0	0	1	0	0	0	0	0	0
	SAWC to WP	0	0	0	0	0	0	0	0	0	1
	SAWC to WWC and Broke	0	0	0	0	0	0	0	0	0	0
	Dry broke	0	0	0	0	0	0	1	0	0	0
	Wet broke	0	0	0	0	0	1	0	0	0	0
	Press felt retention	0	0	0	0	0	1	0	0	0	0
	Former retention	0	0	0	0	1	0	0	0	0	0
DOF		**11**	**2**	**4**	**4**	**5**	**4**	**1**	**5**	**3**	**3**

Table A-3 Degree of freedom analysis for complete system (TSS and COD) continued

		White water chest	Broke	Underground system	Clarification	S1	S2	S3	S4	S5	Process
Number of independent variables		12	18	9	12	9	9	9	9	9	120
Number of independent balances		3	3	3	3	3	3	3	3	3	57
Specifications	**Flow**	0	1	0	1	1	0	1	2	0	11
	Composition	0	3	2	5	1	2	0	0	0	18
Splitter restrictions		0	0	0	0	2	2	2	2	2	10
TSS restriction on process units		1	0	0	0	0	0	0	0	0	2
COD restrictions on process units		1	0	1	1	0	0	0	0	0	12
Assumptions	SA fibre removal	0	0	1	0	0	0	0	0	0	2
	Thickener fibre recovery	0	0	0	0	0	0	0	0	0	1
	COD retention	0	0	0	0	0	0	0	0	0	1
	SAWC to WP	0	0	0	0	0	0	0	0	0	1
	SAWC to WWC and Broke	0	0	0	0	0	0	0	0	1	1
	Dry broke	0	0	0	0	0	0	0	0	0	1
	Wet broke	0	0	0	0	0	0	0	0	0	1
	Press felt retention	0	0	0	0	0	0	0	0	0	1
	Former retention	0	0	0	0	0	0	0	0	0	1
DOF		**7**	**11**	**2**	**2**	**2**	**2**	**3**	**2**	**3**	**0**

Table A-4 Degree of freedom analysis for subsystem (TSS only)

		Filler Waste plant	Thickening	Refining	Approach Flow	Former	Press	Dryer	Machine pit	Save-all	Save-all water chest
Number of independent variables		15	6	6	9	9	11	7	6	6	6
Number of independent balances		2	2	2	2	2	2	2	2	2	2
Specifications	**Flow**	3	0	0	1	2	2	1	0	0	0
	Composition	3	2	2	3	2	3	3	1	1	0
Splitter restrictions		0	0	0	0	0	0	0	0	0	0
TSS restriction on process units		0	0	0	0	0	0	0	0	0	1
Assumptions	SA fibre removal	0	0	0	0	0	0	0	0	1	0
	Thickener fibre recovery	0	1	0	0	0	0	0	0	0	0
	SAWC to WP	0	0	0	0	0	0	0	0	0	1
	SAWC to WWC and Broke	0	0	0	0	0	0	0	0	0	0
	Dry broke	0	0	0	0	0	0	1	0	0	0
	Wet broke	0	0	0	0	0	1	0	0	0	0
	Press felt retention	0	0	0	0	0	1	0	0	0	0
	Former retention	0	0	0	0	1	0	0	0	0	0
DOF		**7**	**1**	**2**	**3**	**2**	**2**	**0**	**3**	**2**	**2**

Table A-4 Degree of freedom analysis for subsystem (TSS only) continued

		White water chest	Broke	Underground system	Clarification	S1	S2	S3	S4	S5	Process
Number of independent variables		8	12	6	8	6	6	6	6	6	81
Number of independent balances		2	2	2	2	2	2	2	2	2	38
Specifications	**Flow**	0	1	0	1	1	0	1	2	0	11
	Composition	0	3	1	2	0	1	0	0	0	16
Splitter restrictions		0	0	0	0	1	1	1	1	1	5
TSS restriction on process units		1	0	0	0	0	0	0	0	0	2
Assumptions	SA fibre removal	0	0	1	0	0	0	0	0	0	2
	Thickener fibre recovery	0	0	0	0	0	0	0	0	0	1
	SAWC to WP	0	0	0	0	0	0	0	0	0	1
	SAWC to WWC and Broke	0	0	0	0	0	0	0	0	1	1
	Dry broke	0	0	0	0	0	0	0	0	0	1
	Wet broke	0	0	0	0	0	0	0	0	0	1
	Press felt retention	0	0	0	0	0	0	0	0	0	1
	Former retention	0	0	0	0	0	0	0	0	0	1
DOF		**5**	**6**	**2**	**3**	**2**	**2**	**2**	**1**	**2**	**0**

A.2 Excel material balance spreadsheet

Instructions for using the material balance spreadsheet developed in Excel are as follows:

1. Open Excel file 'MaterialBalance', sheet 'mass bal'.
2. Adjust input data in cells B2:B10; B12; E2:E12; U3 or U11.
3. Open the solver tool in the Data tab.
4. Solve cell 'Q34' to a target value of zero by manipulating cell 'P21'.
5. Open the solver tool in the Data tab.
6. Solve cell 'S39' to a target value of zero by manipulating cells 'Y13:Y14' subject to condition that cell 'Y17' equals zero.

A.3 Data acquisition

The lack of stream information prevented the solution of the material balance. An information gathering campaign was undertaken to obtain the necessary flow and composition data. Various sources were used such as clarifier reports; production reports; communications with mill technicians; independent sampling as well as physical inspection.

Clarifier reports provided historical data on stream information entering and leaving the clarification unit. Information regarding pH, temperature and concentrations of TDS, TSS, COD and H_2S are included. Production reports provided information on raw material usage, final production rate and product grade making plan. Process stream specifications were obtained from mill technicians and later confirmed by sampling. Results are presented in Table A-5.

Table A-5 Sampling campaign to confirm mill specification for total suspended solids

	Units	**2012**			**Average**	**Standard deviation**	**Mill specification**
		31/01	**01/02**	**02/02**			
Cleaned stock	wt %	0.973	0.661	0.647	0.761	0.184	0.900
Thickened stock	wt %	4.263	4.100	3.840	4.068	0.213	4.200

From Table A-5 the mill specification falls within one standard deviation of the average TSS % calculated. This was sufficient evidence to accept the mill specification for the stream TSS %.

The sampling methods used for consistency and COD measurement are outlined as follows:

Consistency test:

Apparatus:

- Electronic mass balance – Sartorius BP 2100 S, accuracy of 0.01g
- Buchner funnel and vacuum flask
- Sampling bottles
- Vacuum source
- Hot plate for drying samples
- Oven
- Filter paper

Procedure:

1. Weigh sample bottle before and after sample collection to obtain sample mass by difference.
2. Weigh filter paper that has been dried previously in an oven at 100 °C to 105 °C.
3. Filter the sample under vacuum using dried weighed filter paper.
4. When filtered, fold and dry the paper and pulp mat on a hot plate, dry to constant mass.
5. When dry, weigh the filter paper.
6. Pulp mass = (Mass filter paper and pulp) less (Mass filter paper)
7. Consistency = (Pulp mass/Sample mass)*100%

COD test:

Apparatus:

- Buchner funnel and vacuum flask
- Sampling bottles
- Vacuum source
- Filter paper
- Beaker
- 10 ml pipette
- High Range Plus COD vials (0 – 15 000 ppm), manufacturer is CHEMetrics
- COD vial heating block
- HACH Spectrometer DR/2000

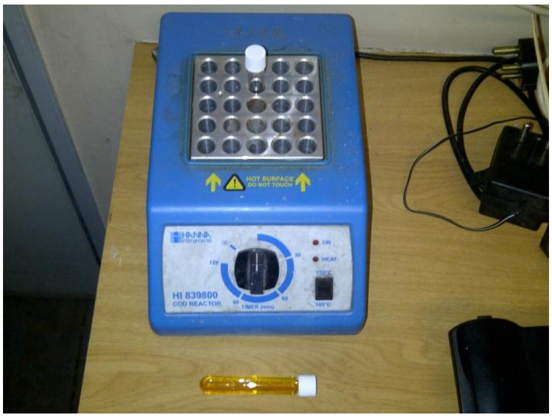
Procedure:

1. Empty and clean vacuum flask.
2. Filter the sample under vacuum using filter paper.
3. Collect filtrate in beaker.
4. Prepare pipette with de-ionized water followed by filtered sample.
5. Pipette 6 ml of filtered sample into HR+ COD vial.
6. Close lid and invert to ensure solution completely mixed.
7. Incubate vial for 3 h in the heating block at 150 °C.
8. Remove vial from heating block and allow to cool.
9. Insert blank COD vial into spectrometer to calibrate the device.
10. Insert COD sample vial and record COD measurement.

(a)

(b)

(c)



(d)

(e)

Figure A-2 Experimental apparatus:

(a) Büchner funnel and vacuum flask

(b) Hot plate

(c) Electronic mass balance

(d) COD heating block and COD vial

(e) Spectrometer

The procedure had to be adjusted for the chemical stream (F11) COD measurement. The HR+ vials have a maximum COD concentration of 150 000 ppm. This was exceeded by the chemical stream due to the high starch content and resulted in the spectrometer reporting an over-range error. Hence, the chemical stream sample was diluted with de-ionized water in a 1:9 ratio. The reported COD was then corrected by this ratio.

The forming and press section shower water stream flow rates were important to determine since these were fresh water users. Since the streams were not measured mill technicians could not provide information on the flow rates and the streams were not measured either. The subsequent investigation to determine the shower flow rates revealed that there were two types of showers. High pressure showers use fresh water, whilst low pressure showers use regenerated water. From physical inspection of the Board Machine the number of shower heads in each section was counted. The water line supplying the shower heads was traced and the pressure determined from the pressure gauge. Nozzle size was found by consulting with the Stores Department. This information was used together with the nozzle manufacturer data sheet to determine the flow per nozzle. High pressure showers have a 0.9 mm nozzle size and 20 bar line pressure. Low pressure showers have a 2 mm nozzle size and 6 bar line pressure. The Stamm showers supplier data sheet is presented in Appendix C, Table C-1 accessed 27/09/2011). The results of this investigation are presented in Table A-6.

Table A-6 Results of shower flow rate investigation

Section	Shower type	No. Nozzles	Flow per nozzle (l/min)	Total Flow (t/d)
Forming	HP	157	1.58	248
	LP	125	4.4	553
Press	HP	162	1.58	369
	LP	102	4.4	646

These shower flow rates were then set as constants in the optimization since they are fixed flow rate applications required to clean the felts and wire. The optimization should not reduce the fresh water demand by reducing flow rates. Rather a replacement of fresh water should occur.

B. Network connectivity matrix

Table B-1 Logical representation of existing mill network configuration

	Fresh	**SU1**	**SU2**	**SU4**	**SU5**	**SU6**	**SU8**	**SU9f**	**SU9w**	**SU10**	**SU11**	**SU12**	**SU13f**	**SU13w**	**SU14f**	**SU14w**
MU1	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0	0
MU3	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0
MU4a	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MU4b	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0
MU5a	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MU5b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
MU6a	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MU6b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
MU8	0	0	0	**1**	0	**1**	0	0	0	0	0	0	0	0	0	0
MU9	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0
MU10	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0
MU11	0	0	**1**	0	0	0	0	0	0	**1**	0	0	0	0	0	0
MU12	0	0	0	0	0	0	0	**1**	0	**1**	0	0	0	0	0	**1**
MU13	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MU14	0	0	0	0	0	0	0	0	0	**1**	0	0	0	**1**	0	0
BM6recov	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0
Sludge	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0
Effluent	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**

Table B-2 Logical representation of optimized mill network configuration

	Fresh	**SU1**	**SU2**	**SU4**	**SU5**	**SU6**	**SU8**	**SU9f**	**SU9w**	**SU10**	**SU11**	**SU12**	**SU13f**	**SU13w**	**SU14f**	**SU14w**
MU1	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0	0
MU3	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0
MU4a	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MU4b	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0
MU5a	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
MU5b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
MU6a	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
MU6b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
MU8	0	0	0	**1**	0	**1**	0	0	0	0	0	0	0	0	0	0
MU9	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0
MU10	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0
MU11	0	0	**1**	0	0	0	0	0	0	**1**	0	0	0	0	0	0
MU12	0	0	0	0	0	0	0	**1**	0	**1**	0	0	0	0	0	**1**
MU13	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MU14	0	0	0	0	0	0	0	0	0	**1**	0	0	0	**1**	0	0
BM6recov	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0
Sludge	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0
Effluent	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**

C. Shower water flow rate information

Table C-1 Supplier information for shower nozzle flow rate

Water consumption in l/min per nozzle:															
Nozzle size e	Water pressure (bar)														
	1	**2**	**3**	**4**	**6**	**8**	**10**	**15**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
0.6	0.16	0.22	0.27	0.31	0.36	0.44	0.49	0.60	0.70	0.85	0.90	1.10	1.20	1.30	1.39
0.7	0.20	0.28	0.34	0.40	0.48	0.56	0.63	0.77	0.89	1.06	1.25	1.40	1.53	1.66	1.77
0.8	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.10	1.30	1.60	1.80	2.00	2.20	2.40	2.50
0.9	0.35	0.50	0.61	0.71	0.87	1.00	1.12	1.37	1.58	1.94	2.24	2.50	2.74	2.96	3.17
1.0	0.50	0.70	0.90	1.00	1.20	1.40	1.60	2.00	2.20	2.70	3.10	3.50	3.80	4.20	4.40
1.2	0.60	0.90	1.30	1.50	1.60	1.80	2.00	2.50	2.90	3.50	4.00	4.50	4.90	5.30	5.70
1.5	1.00	1.40	1.70	2.00	2.40	2.80	3.00	3.80	4.30	5.30	6.10				
2.0	1.80	2.50	3.10	3.60	4.40	5.00	5.60	6.90	7.90	9.70	11.20				
2.5	2.80	4.00	4.90	5.60	6.90	7.90	8.90	10.80	12.60	15.50	17.90				
3.0	4.50	6.30	7.80	9.00	11.00	12.50	14.10	17.50	20.00	24.00	28.00				
4.0	7.20	10.10	12.40	14.30	17.50	20.20	22.70	27.60	32.00	39.00					
5.0	11.20	15.80	19.40	22.40	27.40	31.50	35.40	42.70	50.00	60.00					
6.0	17.80	25.00	31.00	35.80	43.80	50.40	56.60	68.30	80.00	95.00					
7.0	22.30	31.20	39.00	45.00	55.00	63.00	72.00	87.00	102.00	120.00					
8.0	26.00	40.00	49.00	56.00	69.00	79.00	89.00	107.50	126.00	149.00					

D. GAMS program code

Code commenting is provided in red text.

Ensure the Excel source data files FinalResult.xls and MaterialBalance.xls are saved in the GAMS directory folder.

Unit abbreviations:

U1 = Filler waste plant

U2 = Thickening

U3 = Refining

U4 = Approach flow

U5 = Forming

U6 = Pressing

U7 = Drying

U8 = Machine pit

U9 = Save-all

U10 = Save-all water chest

U11 = White water chest

U12 = Broke system

U13 = Underground system

U14 = Clarification

S,M prefix indicates unit splitter and mixer respectively

Ma,Mb prefix indicates multiple water streams entering a unit (a = HP system, b = LP system)

option decimals = 8;

Sources, sinks, process streams and contaminants are defined as sets. Dissolved contaminants are defined as a subset of the contaminant set.

Sets

```
      h   sinks        / MU1
                         MU3
                         MU4a
                         MU4b
```

MU5a

MU5b

MU6a

MU6b

MU8

MU9

MU10

MU11

MU12

MU13

MU14

BM6recov

Sludge

Effluent/

i	sources	/ Fresh
		SU1
		SU2
		SU4
		SU5
		SU6
		SU8
		SU9f
		SU9w
		SU10
		SU11
		SU12
		SU13f

SU13w

SU14f

SU14w/

j process streams / RM

Steam

Rejects

Product

Evap

U1U2

U2U3

U3U4

U4U5

U5U6

U6U7

U6U12

U7U12

Chem/

k contaminants /TSS

COD/

l(k) dissolved contaminant /COD/

;

Process stream flow rates are defined as parameters since the value is fixed by the material balance. Chem represents the solid chemicals to be dissolved and added to system

Parameter PF(j) Process flow rates

/ RM 106

Steam	50
Rejects	16
Product	81
Evap	67.9245283019
U1U2	12655.42856
U2U3	2440.689793
U3U4	2943.696013
U4U5	14270.3698
U5U6	599.3555317
U6U7	157.9245283019
U6U12	8.3118172790
U7U12	9
Chem	12.0594

/

;

The logical condition of whether a network connection exists is accounted for by a parameter rather than a binary variable. This is done to avoid the mixed integer aspect of the optimization. This allowed a solution to be found. Different network connection were evaluated according to the method discussed in Section 4.5.

```
Parameter    A(h,i)         Allowable connections
```

Information imported from Excel file.

```
$LIBinclude XLimport A FinalResult.xls newconn!a1:q19
```

Continuous variables defined.

```
variable

        TotSource(i)              Total flow from  source i

        TotSourceComp(i,k)        Composition of total flow from source i

        Flow(h,i)                 Flow from source i to sink h

        TotSink(h)                Total flow to sink h

        TotSinkComp(h,k)          Composition of total stream entering sink h
```

FlowComp(h,i,k)		Compositions of flows

PC(j,k)		Process stream composition

positive variable TotSource, TotSourceComp, Flow, TotSink, TotSinkComp, FlowComp, PC;

Parameter CODret		COD retention percentage from chemical addition

;

CODret = 0.0742810214438532;

Variables cannot be directly initialized by importing tabular information. A parameter needs to be set up first and replacement performed to achieve the initialization.

Parameter	F(h,i)		Flows

$LIBinclude XLimport F MaterialBalance.xls flowrates!a1:q19

;

```
Flow.l(h,i) = F(h,i);
```

Fixing the water flow rates coming into the system since these water streams are constant flow applications.

```
TotSink.fx('MU4a') = 202;

TotSink.fx('MU5a') = 248;

TotSink.fx('MU6a') = 369;

TotSink.fx('MU5b') = 553;

TotSink.fx('MU6b') = 646;


TotSource.l(i) = sum(h, F(h,i));

TotSink.l(h) = sum(i, F(h,i));
```

Initializing the stream compositions.

```
Parameter TSC(i,k)      total source compositions
```

```
$LIBinclude XLimport TSC MaterialBalance.xls compositions!a2:c18

;



TotSourceComp.l(i,k) = TSC(i,k);

TotSourceComp.fx('Fresh','TSS') =  TSC('Fresh','TSS');

FlowComp.l(h,i,k) = TSC(i,k);

TotSinkComp.l(h,'TSS') = (sum(i, Flow.l(h,i)*FlowComp.l(h,i,'TSS')))/TotSink.l(h);

TotSinkComp.l(h,l) = (sum(i, Flow.l(h,i)*(1-FlowComp.l(h,i,'TSS'))*FlowComp.l(h,i,l)))/TotSink.l(h);

TotSinkComp.up(h,k) =  1;

TotSourceComp.up(i,k) =  1;

FlowComp.up(h,i,k) =  1;
```

Initializing the process stream compositions

```
Parameter C(j,k)       process stream compositions
```

```
$LIBinclude XLimport C MaterialBalance.xls compositions!e3:g17

;

PC.l(j,k) = C(j,k);

PC.fx(j,'TSS') = C(j, 'TSS');

PC.fx('RM',k) = C('RM', k);

PC.fx('Evap',k) = 0;

PC.fx('Steam',k) = 0;

PC.fx('Chem',k) = C('Chem', k);
```

Defining the material balance equations and model constraints.

```
Equation

    MixerFlow(h)          'mixer flow balances'

    MixerTSS(h,k)         'mixer TSS balances'

    MixerDS(h,l)          'mixer DS balances'
```

SplitterFlow(i)	'splitter flow balances'
SplitterTSS(i,k)	'splitter TSS balances'
SplitterDS(i,l)	'splitter DS balances'
SplitterRes(h,i,k)	'splitter restrictions'
FlowBalU1	'unit1 flow balance'
FlowBalU2	'unit2 flow balance'
FlowBalU3	'unit3 flow balance'
FlowBalU4	'unit4 flow balance'
FlowBalU5	'unit5 flow balance'
FlowBalU6	'unit6 flow balance'
FlowBalU7	'unit7 flow balance'
FlowBalU8	'unit8 flow balance'
FlowBalU9	'unit9 flow balance'
FlowBalU10	'unit10 flow balance'

FlowBalU11	'unit11 flow balance'
FlowBalU12	'unit12 flow balance'
FlowBalU13	'unit13 flow balance'
FlowBalU14	'unit14 flow balance'
TSSBalU1	'unit1 TSS balances'
TSSBalU2	'unit2 TSS balances'
TSSBalU3	'unit3 TSS balances'
TSSBalU4	'unit4 TSS balances'
TSSBalU5	'unit5 TSS balances'
TSSBalU6	'unit6 TSS balances'
TSSBalU7	'unit7 TSS balances'
TSSBalU8	'unit8 TSS balances'
TSSBalU9	'unit9 TSS balances'

TSSBalU10	'unit10 TSS balances'
TSSBalU11	'unit11 TSS balances'
TSSBalU12	'unit12 TSS balances'
TSSBalU13	'unit13 TSS balances'
TSSBalU14	'unit14 TSS balances'

DSBalU1	'unit1 DS balances'
DSBalU2	'unit2 DS balances'
DSBalU3	'unit3 DS balances'
DSBalU4	'unit4 DS balances'
DSBalU5	'unit5 DS balances'
DSBalU6	'unit6 DS balances'
DSBalU7	'unit7 DS balances'
DSBalU8	'unit8 DS balances'

DSBalU9	'unit9 DS balances'
DSBalU10	'unit10 DS balances'
DSBalU11	'unit11 DS balances'
DSBalU12	'unit12 DS balances'
DSBalU13	'unit13 DS balances'
DSBalU14	'unit14 DS balances'

U9FR	'fibre recovery of U9 save-all'
U13FR	'fibre recovery of U13 save-all'
U14FR	'Clarifier fibre removal'

DSResU1a	'unit1 DS restriction'
DSResU1b	'unit1 DS restriction'
DSResU2	'unit2 DS restriction'

DSResU4	'unit4 DS restriction'
DSResU5	'unit5 DS restriction'
DSResU6a	'unit6 DS restriction'
DSResU6b	'unit6 DS restriction'
DSResU7	'unit7 DS restriction'
DSResU9	'unit9 DS restriction'
DSResU13	'unit13 DS restriction'
DSResU14	'unit14 DS restriction'
Flow2(h,i)	'zero flowrate condition on non-existant flows'
MU5aTSSMax	'upper bound on contaminant concentration entering deckle sprays'
MU5bTSSMax	'upper bound on contaminant concentration entering felt showers'
MU6aTSSMax	'upper bound on contaminant concentration entering press HP showers'

```
MU6bTSSMax            'upper bound on contaminant concentration entering press LP showers'

TotSourceCODMax       'COD maximum concentration in any stream'


FreshCOD              'Condition for fresh water inlet COD concentration'

FreshTSS              'Condition for fresh water inlet TSS concentration'

BM6recov              'minimum fibre concentration in recovered stream'

;
```

Additional condition that forces flow rates in a non-exist connection to be zero.

```
Flow2(h,i)$(A(h,i)=0) ..    Flow(h,i) =e= 0;


MixerFlow(h) ..           TotSink(h) =e= sum(i, Flow(h,i));

MixerTSS(h,'TSS') ..      TotSink(h)*TotSinkComp(h,'TSS') =e= sum(i,(Flow(h,i)*FlowComp(h,i,'TSS')));

MixerDS(h,l) ..           TotSink(h)*(1-TotSinkComp(h,'TSS'))*TotSinkComp(h,l) =e= sum(i, (Flow(h,i)*(1-
                          FlowComp(h,i,'TSS'))*FlowComp(h,i,l)));

SplitterFlow(i) ..        TotSource(i) =e= sum(h, Flow(h,i));
```

```
SplitterTSS(i,'TSS') ..      TotSource(i)*TotSourceComp(i,'TSS') =e= sum(h, (Flow(h,i)*FlowComp(h,i,'TSS')));

SplitterDS(i,l) ..           TotSource(i)*(1-TotSourceComp(i,'TSS'))*TotSourceComp(i,l) =e= sum(h, (Flow(h,i)*(1-
                             FlowComp(h,i,'TSS'))*FlowComp(h,i,l)));

SplitterRes(h,i,k) ..        FlowComp(h,i,k) =e= TotSourceComp(i,k);


FlowBalU1 ..                 TotSink('MU1') + PF('RM') + PF('Steam') =e= TotSource('SU1') + PF('U1U2') + PF('Rejects');

FlowBalU2 ..                 PF('U1U2')=e= TotSource('SU2') + PF('U2U3');

FlowBalU3 ..                 PF('U2U3') + TotSink('MU3') =e= PF('U3U4');

FlowBalU4 ..                 PF('U3U4') + PF('Chem') + TotSink('MU4a') + TotSink('MU4b')=e= PF('U4U5') + TotSource('SU4');

FlowBalU5 ..                 PF('U4U5') + TotSink('MU5a')+ TotSink('MU5b') =e= PF('U5U6') + TotSource('SU5');

FlowBalU6 ..                 PF('U5U6') + TotSink('MU6a') + TotSink('MU6b') =e= PF('U6U7') + TotSource('SU6') + PF('U6U12');

FlowBalU7 ..                 PF('U6U7') =e= PF('Evap') + PF('Product') + PF('U7U12');

FlowBalU8 ..                 TotSink('MU8') =e= TotSource('SU8');

FlowBalU9 ..                 TotSink('MU9') =e= TotSource('SU9f')+ TotSource('SU9w');

FlowBalU10 ..                TotSink('MU10') =e= TotSource('SU10');
```

```
FlowBalU11 ..     TotSink('MU11') =e= TotSource('SU11');

FlowBalU12 ..     TotSink('MU12') + PF('U6U12') + PF('U7U12')=e= TotSource('SU12');

FlowBalU13 ..     TotSink('MU13') =e= TotSource('SU13f')+ TotSource('SU13w');

FlowBalU14 ..     TotSink('MU14') =e= TotSource('SU14f')+ TotSource('SU14w');


TSSBalU1 ..       TotSink('MU1')*TotSinkComp('MU1','TSS') + PF('RM')*PC('RM','TSS') + PF('Steam')*PC('Steam','TSS') =e=
                  TotSource('SU1')*TotSourceComp('SU1','TSS') + PF('U1U2')*PC('U1U2','TSS') + PF('Rejects')*PC('Rejects','TSS');

TSSBalU2 ..       PF('U1U2')*PC('U1U2','TSS')=e= TotSource('SU2')*TotSourceComp('SU2','TSS') + PF('U2U3')*PC('U2U3','TSS');

TSSBalU3 ..       PF('U2U3')*PC('U2U3','TSS') + TotSink('MU3')*TotSinkComp('MU3','TSS') =e= PF('U3U4')*PC('U3U4','TSS');

TSSBalU4 ..       PF('U3U4')*PC('U3U4','TSS')+ PF('Chem')*PC('Chem','TSS') + TotSink('MU4a')*TotSinkComp('MU4a','TSS') +
                  TotSink('MU4b')*TotSinkComp('MU4b','TSS') =e= PF('U4U5')*PC('U4U5','TSS') +
                  TotSource('SU4')*TotSourceComp('SU4','TSS');

TSSBalU5 ..       PF('U4U5')*PC('U4U5','TSS') + TotSink('MU5a')*TotSinkComp('MU5a','TSS')+
                  TotSink('MU5b')*TotSinkComp('MU5b','TSS') =e= PF('U5U6')*PC('U5U6','TSS') +
                  TotSource('SU5')*TotSourceComp('SU5','TSS');
```

```
TSSBalU6 ..      PF('U5U6')*PC('U5U6','TSS') + TotSink('MU6a')*TotSinkComp('MU6a','TSS') +
                 TotSink('MU6b')*TotSinkComp('MU6b','TSS') =e= PF('U6U7')*PC('U6U7','TSS') +
                 TotSource('SU6')*TotSourceComp('SU6','TSS') + PF('U6U12')*PC('U6U12','TSS');

TSSBalU7 ..      PF('U6U7')*PC('U6U7','TSS') =e= PF('Evap')*PC('Evap','TSS') + PF('Product')*PC('Product','TSS') +
                 PF('U7U12')*PC('U7U12','TSS');

TSSBalU8 ..      TotSink('MU8')*TotSinkComp('MU8','TSS') =e= TotSource('SU8')*TotSourceComp('SU8','TSS');

TSSBalU9 ..      TotSink('MU9')*TotSinkComp('MU9','TSS') =e= TotSource('SU9f')*TotSourceComp('SU9f','TSS') +
                 TotSource('SU9w')*TotSourceComp('SU9w','TSS');

TSSBalU10 ..     TotSink('MU10')*TotSinkComp('MU10','TSS') =e= TotSource('SU10')*TotSourceComp('SU10','TSS');

TSSBalU11 ..     TotSink('MU11')*TotSinkComp('MU11','TSS') =e= TotSource('SU11')*TotSourceComp('SU11','TSS');

TSSBalU12 ..     TotSink('MU12')*TotSinkComp('MU12','TSS') + PF('U6U12')*PC('U6U12','TSS') + PF('U7U12')*PC('U7U12','TSS')=e=
                 TotSource('SU12')*TotSourceComp('SU12','TSS');

TSSBalU13 ..     TotSink('MU13')*TotSinkComp('MU13','TSS') =e= TotSource('SU13f')*TotSourceComp('SU13f','TSS')+
                 TotSource('SU13w')*TotSourceComp('SU13w','TSS');

TSSBalU14 ..     TotSink('MU14')*TotSinkComp('MU14','TSS') =e= TotSource('SU14f')*TotSourceComp('SU14f','TSS')+
                 TotSource('SU14w')*TotSourceComp('SU14w','TSS');
```

```
U9FR ..        TotSource('SU9f')*TotSourceComp('SU9f','TSS') =e= 0.9*TotSink('MU9')*TotSinkComp('MU9','TSS');

U13FR ..       TotSource('SU13f')*TotSourceComp('SU13f','TSS') =e= 0.9*TotSink('MU13')*TotSinkComp('MU13','TSS');

U14FR ..       TotSourceComp('SU14w','TSS') =e= 131e-6;


DSBalU1(l) ..  TotSink('MU1')*(1-TotSinkComp('MU1','TSS'))*TotSinkComp('MU1',l) + PF('RM')*(1-PC('RM','TSS'))*PC('RM',l) +
               PF('Steam')*(1-PC('Steam','TSS'))*PC('Steam',l) =e= TotSource('SU1')*(1-
               TotSourceComp('SU1','TSS'))*TotSourceComp('SU1',l) + PF('U1U2')*(1-PC('U1U2','TSS'))*PC('U1U2',l) +
               PF('Rejects')*(1-PC('Rejects','TSS'))*PC('Rejects',l);

DSBalU2(l) ..  PF('U1U2')*(1-PC('U1U2','TSS'))*PC('U1U2',l)=e= TotSource('SU2')*(1-
               TotSourceComp('SU2','TSS'))*TotSourceComp('SU2',l) + PF('U2U3')*(1-PC('U2U3','TSS'))*PC('U2U3',l);

DSBalU3(l) ..  PF('U2U3')*(1-PC('U2U3','TSS'))*PC('U2U3',l) + TotSink('MU3')*(1-TotSinkComp('MU3','TSS'))*TotSinkComp('MU3',l)
               =e= PF('U3U4')*(1-PC('U3U4','TSS'))*PC('U3U4',l);

DSBalU4(l) ..  PF('U3U4')*(1-PC('U3U4','TSS'))*PC('U3U4',l) + (PF('Chem')*(1-PC('Chem','TSS'))*PC('Chem',l))*CODret +
               TotSink('MU4a')*(1-TotSinkComp('MU4a','TSS'))*TotSinkComp('MU4a',l) + TotSink('MU4b')*(1-
               TotSinkComp('MU4b','TSS'))*TotSinkComp('MU4b',l) =e= PF('U4U5')*(1-PC('U4U5','TSS'))*PC('U4U5',l) +
               TotSource('SU4')*(1-TotSourceComp('SU4','TSS'))*TotSourceComp('SU4',l);
```

DSBalU5(l) .. PF('U4U5')*(1-PC('U4U5','TSS'))*PC('U4U5',l) + TotSink('MU5a')*(1-TotSinkComp('MU5a','TSS'))*TotSinkComp('MU5a',l)+ TotSink('MU5b')*(1-TotSinkComp('MU5b','TSS'))*TotSinkComp('MU5b',l) =e= PF('U5U6')*(1-PC('U5U6','TSS'))*PC('U5U6',l) + TotSource('SU5')*(1-TotSourceComp('SU5','TSS'))*TotSourceComp('SU5',l);

DSBalU6(l) .. PF('U5U6')*(1-PC('U5U6','TSS'))*PC('U5U6',l) + TotSink('MU6a')*(1-TotSinkComp('MU6a','TSS'))*TotSinkComp('MU6a',l) + TotSink('MU6b')*(1-TotSinkComp('MU6b','TSS'))*TotSinkComp('MU6b',l) =e= PF('U6U7')*(1-PC('U6U7','TSS'))*PC('U6U7',l) + TotSource('SU6')*(1-TotSourceComp('SU6','TSS'))*TotSourceComp('SU6',l) + PF('U6U12')*(1-PC('U6U12','TSS'))*PC('U6U12',l);

DSBalU7(l) .. PF('U6U7')*(1-PC('U6U7','TSS'))*PC('U6U7',l) =e= PF('Evap')*(1-PC('Evap','TSS'))*PC('Evap',l) + PF('Product')*(1-PC('Product','TSS'))*PC('Product',l) + PF('U7U12')*(1-PC('U7U12','TSS'))*PC('U7U12',l);

DSBalU8(l) .. TotSink('MU8')*(1-TotSinkComp('MU8','TSS'))*TotSinkComp('MU8',l) =e= TotSource('SU8')*(1-TotSourceComp('SU8','TSS'))*TotSourceComp('SU8',l);

DSBalU9(l) .. TotSink('MU9')*(1-TotSinkComp('MU9','TSS'))*TotSinkComp('MU9',l) =e= TotSource('SU9f')*(1-TotSourceComp('SU9f','TSS'))*TotSourceComp('SU9f',l) + TotSource('SU9w')*(1-TotSourceComp('SU9w','TSS'))*TotSourceComp('SU9w',l);

DSBalU10(l) .. TotSink('MU10')*(1-TotSinkComp('MU10','TSS'))*TotSinkComp('MU10',l) =e= TotSource('SU10')*(1-TotSourceComp('SU10','TSS'))*TotSourceComp('SU10',l);

DSBalU11(l) .. TotSink('MU11')*(1-TotSinkComp('MU11','TSS'))*TotSinkComp('MU11',l) =e= TotSource('SU11')*(1-TotSourceComp('SU11','TSS'))*TotSourceComp('SU11',l);

DSBalU12(l) .. TotSink('MU12')*(1-TotSinkComp('MU12','TSS'))*TotSinkComp('MU12',l) + PF('U6U12')*(1-PC('U6U12','TSS'))*PC('U6U12',l) + PF('U7U12')*(1-PC('U7U12','TSS'))*PC('U7U12',l)=e= TotSource('SU12')*(1-TotSourceComp('SU12','TSS'))*TotSourceComp('SU12',l);

DSBalU13(l).. TotSink('MU13')*(1-TotSinkComp('MU13','TSS'))*TotSinkComp('MU13',l) =e= TotSource('SU13f')*(1-TotSourceComp('SU13f','TSS'))*TotSourceComp('SU13f',l)+ TotSource('SU13w')*(1-TotSourceComp('SU13w','TSS'))*TotSourceComp('SU13w',l);

DSBalU14(l) .. TotSink('MU14')*(1-TotSinkComp('MU14','TSS'))*TotSinkComp('MU14',l) =e= TotSource('SU14f')*(1-TotSourceComp('SU14f','TSS'))*TotSourceComp('SU14f',l)+ TotSource('SU14w')*(1-TotSourceComp('SU14w','TSS'))*TotSourceComp('SU14w',l);

DSResU1a(l) .. TotSourceComp('SU1',l) =e= PC('Rejects',l);

DSResU1b(l) .. TotSourceComp('SU1',l) =e= PC('U1U2',l);

DSResU2(l) .. TotSourceComp('SU2',l) =e= PC('U2U3',l);

DSResU4(l) .. TotSourceComp('SU4',l) =e= PC('U4U5',l);

DSResU5(l) .. PC('U4U5',l) =e= PC('U5U6',l);

```
DSResU6a(l) ..        PC('U5U6',l) =e= PC('U6U7',l);

DSResU6b(l) ..        PC('U5U6',l) =e= PC('U6U12',l);

DSResU7(l) ..         PC('Product',l) =e= PC('U7U12',l);

DSResU9(l) ..         TotSourceComp('SU9f',l) =e= TotSourceComp('SU9w',l);

DSResU13(l)..         TotSourceComp('SU13f',l) =e= TotSourceComp('SU13w',l);

DSResU14(l) ..        TotSourceComp('SU14f',l) =e= TotSourceComp('SU14w',l);


FreshCOD ..           TotSourceComp('Fresh','COD') =e= 0;

FreshTSS ..           TotSourceComp('Fresh','TSS') =e= 0;


MU5aTSSMax ..         TotSinkComp('MU5a', 'TSS') =l=  2e-5;

MU5bTSSMax ..         TotSinkComp('MU5b', 'TSS') =l=  5e-4;

MU6aTSSMax ..         TotSinkComp('MU6a', 'TSS') =l=  2e-5;

MU6bTSSMax ..                 TotSinkComp('MU6b', 'TSS') =l=  5e-4;
```

```
    TotSourceCODMax(i,k) ..        TotSourceComp(i,'COD') =l= 2e-3;

    BM6recov ..                    TotSinkComp('BM6recov','TSS') =g= 0.03;
```

The model will be optimized with respect to the following objective variable.

```
free variable

    FreshWater                objective variable

;
```

The objective variable is initialized with the current fresh water usage before optimization.

```
    FreshWater.l = 819;

equation

    Fresh                    objective function;

    Fresh   ..               FreshWater =e= sum(h, Flow(h,'fresh'));
```

The model is defined as the set of all equalities and inequalities conditions previously defined.

```
model    water   'a water network optimization'  /all/;
```

The solver type is chosen with the option statement.

```
option NLP = MINOS;
```

The model is solved by the chosen non-linear problem solver.

```
Solve water minimizing FreshWater using NLP ;
```

Specific solver output results are displayed for ease in results interpretation.

```
display Flow2.m;

display TotSourceComp.l;
```