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Application of membrane bioreactors in the pulp and paper industry

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ABSTRACT

Application of membrane bioreactors in the pulp and paper industry

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The increasing water scarcity of the world, along with increasing requirements for both municipal and industrial wastewater treatment quality, has created a need for new and improved wastewater treatment technologies. One of the new technologies that have gained attention is that of membrane bioreactor (MBR) technology, integrating conventional biotreatment and membrane filtration. MBR technology allows high sludge age, low hydraulic retention time and a higher biomass concentration than the commonly used conventional activated sludge (CAS) technology. Subsequent advantages include almost total retention of suspended solids, high organic matter removal, low footprint and the possibility of reduced sludge production.

This study aimed to present MBR technology and its applications, with special focus on the pulp and paper industry. The study was performed by means of a literature study and a case study on the Swedish pulp and paper mill Korsnäs. The literature study showed MBR technology to be a feasible wastewater treatment for both municipal and industrial wastewaters, and the application of MBR in the pulp and paper industry was supported by numerous scientific studies, which all indicated feasibility.

In the case study, calculations on MBR performance and costs were compared to that of implementation of CAS, as well as the present wastewater treatment. Calculations of MBR were performed on three flows; a fibrous flow, a bleaching process effluent flow and an evaporator condensate flow. None of the presented MBR alternatives showed feasibility as compared to the CAS, and were thus not recommended for Korsnäs. General application of MBR technology in the pulp and paper industry however, proved promising. While the case study showed MBR not to be feasible for implementation at Korsnäs, the potential of using MBR in other pulp and paper applications proved promising in the literature study.

Keywords: Membrane Bioreactor, MBR, wastewater treatment, pulp and paper industry.

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REFERAT

Tillämpning av membranbioreaktorer i massa- och pappersindustrin

Thérèse Johansson

Vattenbristen i världen har, tillsammans med ständigt ökande reningskrav på utsläpp, ökat efterfrågan på mer effektiva vattenreningsmetoder. En metod som uppmärksammats är membranbioreaktorer (MBR), där biologisk vattenrening kombineras med membranfiltrering, vilket möjliggör upprätthållandet av hög slamålder, låg hydraulisk retentionstid och hög biomassakoncentration. Jämfört med konventionell aktivslamteknik (AS) uppnås en högre reduktionsgrad av organiskt material och suspenderade ämnen, samtidigt som MBR ofta är mer kompakt.

Studien ämnade att genom litteraturstudier redogöra för MBR-teknikens funktion och tillämpningar inom både kommunal och industriell vattenrening, med speciell fokus på massa- och pappersindustrin. Utöver litteraturstudien utfördes en fallstudie för det svenska massa- och pappersbruket Korsnäs, där effekten och kostnaden av MBR-tillämpning beräknades och utvärderades.

Litteraturstudien visade att MBR är en lämplig teknik för både kommunal och industriell vattenrening, och att den har potential för tillämpning inom massa- och pappersindustrin.

I fallstudien beräknades implementering av MBR för tre olika processflöden, ett ifrån fiberlinjer, ett blekeriavlopp och ett flöde framför allt bestående av kondensat från indunstning. Beräkningar av prestanda och kostnader för de tre procesströmmarna jämfördes med implementering av AS på blekeriavloppet och den nuvarande reningsanläggningen. AS-alternativet var att föredra framför de tre MBR-alternativen, varför MBR inte rekommenderades för Korsnäs.

Trots att MBR inte var aktuellt vid Korsnäs tyder litteraturstudien på att metoden är lämplig för applikation i massa- och pappersindustrin.

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PREFACE

This master's thesis is written as a part of the environmental and aquatic civil engineering program at Uppsala University. It has been carried out at ÅF Industry AB, Forest department (ÅF), in Stockholm during 2012, and constitutes 30 university credits.

Senior process consultant Åsa Sivard was my mentor at ÅF, subject examiner was Bengt Carlsson at The Department of Information Technology at Uppsala University and final examiner was Allan Rodhe at The Department of Earth Sciences, also at Uppsala University. The master's thesis work was sponsored by ÅF.

I would like to express my uttermost gratitude towards Åsa Sivard for her guidance and encouragement throughout the thesis. I also want to give thanks to Bengt Carlsson for supporting me in the process of writing and planning the thesis.

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Lastly, am very grateful for the support I have received from my beloved friends and family, as well as from my colleagues at ÅF Forest department. Thank you all!

Thérèse Johansson

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Tillämpning av membranbioreaktorer i massa- och pappersindustrin

Thérèse Johansson

Under det senaste århundradet har konsumtionen av vatten fördubblats i världen. Den ökade efterfrågan globalt har, på vissa platser, bidragit till ökade kostnader för vattenuttag. Många industrier världen över använder i dagsläget stora mängder vatten, för interna processer och kylning, vilket kan komma att bli kostsamt att upprätthålla i framtiden. Samtidigt som vattenanvändningen kan bli kostsamma, får många industrier skärpta krav på deras utsläpp till vatten.

En av de viktigaste industrierna i Sverige, massa- och pappersindustrin, använder stora mängder vatten för produktion och kylning, och släpper följaktligen ut stora mängder föroreningar i närliggande vatten. Vattenanvändning är för närvarande inte betraktat som ett problem i Sverige, då tillgången till färskvatten är hög. Däremot orsakar utsläpp från massa- och pappersindustrin övergödning och rubbar akvatiska ekosystem i och runt Sverige, varför krav på utgående vattenkvalitet är höga.

De vanligaste teknikerna för avloppsvattenrening inom massa- och pappersindustrin, såsom biologisk rening i luftade dammar och sedimentering av föroreningar i bassänger, är inte alltid tillräckligt effektiva för att uppnå de höga kraven, varför nya metoder efterlyses.

En av de nya metoderna på marknaden är membranbioreaktorteknik (MBR), där biologisk rening kombineras med membranfiltrering. MBR har visat sig vara pålitlig inom såväl kommunal som industriell avloppsvattenrening, och fanns år 2008 installerat i över 400 länder. De senaste åren har intresset för MBR-teknik ökat snabbt inom den industriella sektorn, där fler än 50 nya anläggningar byggts varje år sedan 2002.

Kombinationen med biologisk rening och membranfiltrering möjliggör en hög reningsgrad även för avloppsvatten som tidigare betraktats som svårrenade. Membranet håller tillbaks stora partiklar i den biologiska reningen, bland annat de mikroorganismer som utför själva reningen, medan andra mindre partiklar tillåts passera. Då produceras en ström med rent vatten, och en koncentrerad vätska som innehåller de föroreningar som önskas tas bort och som konsumeras av mikroorganismerna. Barriären som membranet utgör gör att reningsprocessen kan styras med avseende på uppehållstid för vattnet och mikroorganismerna.

Fördelar med MBR-teknik jämfört med andra biologiska reningstekniker är att mikroorganismerna kan koncentreras för att få samma reningsgrad på mindre yta, att mikroorganismernas flockstruktur och sammansättning inte påverkar avskiljningen och att produktionen av mikroorganismer kan styras för att erhålla en mindre mängd överskottsslam.

Studien syftade till att undersöka MBR-teknikens funktion och tillämpningar, med extra fokus på massa- och pappersindustrin, genom litteraturstudier och en fallstudie av ett svenskt massa- och pappersbruk. Litteraturstudie visade att MBR-tekniken är väl beprövad inom de flesta industrier, och att ett fåtal fullskaleanläggningar för rening av vatten från massa- och pappersbruk redan är i bruk. I nuläget i Sverige har MBR-tekniken inte fått något stort genomslag, men med sjunkande investeringspriser på MBR och ökade krav på reningsgrader av avloppsvatten kan det komma att bli aktuellt.

I fallstudien beräknades den totala reningseffekten av tillämpning av MBR på tre olika processflöden i produktionen, en från fiberlinje, en från massablekeriet och en från indunstningen. De jämfördes med tillämpning av en annan typ av biologisk rening, aktivslamprocessen (AS). Två av alternativen, där MBR tillämpades på fiberlinje- och indunstningsavloppsvatten, visade sig inte uppnå tillräcklig rening i slutavloppet. Tillämpningen av MBR på blekeriavloppsvatten visade liknande resultat i slutavloppet som tillämpningen av AS, som också tillämpades på blekeriavloppet. I en ekonomisk utvärdering visade sig dock MBR vara dyrare än AS, för både investering och driftskostnader, varför MBR inte ansågs vara lämpligt för de undersökta processflödena för det aktuella bruket.

Studien pekar på att MBR är lämpligt för användande inom massa- och pappersindustrin, men då framförallt vid små flöden, så att både investerings- och driftskostnader kan minimeras. Då små flöden oftast inte påverkar slutavloppets kvalitet nämnvärt, kan det vara lämpligt att använda MBR för att rena små flöden för återanvändning inom processen. MBR-tekniken är robust och klarar rening av vatten med hög temperatur, vilket är fördelaktigt inom industriella sammanhang, då processvattnet ofta är varmt, och kostnader för kylning kan reduceras.

Avslutningsvis kan sägas att MBR är en väl beprövad reningsteknik, som med stor sannolikhet kommer att vinna mark inom industriell tillämpning även i Sverige.

TABLE OF CONTENTS

GENERAL ABBREVATIONS

AOX	Halogenated organic compounds
BAT/BREF	Best available technology/ BAT reference document
BOD	Biological oxygen demand
CAS	Conventional activated sludge
CFV	Crossflow velocity
COD	Chemical oxygen demand
ECF	Elementary chlorine free
EPS	Extracellular polymeric substances
F:M	Food to microorganism ratio
FS	Flat sheet
HF	Hollow fiber
HRT	Hydraulic retention time
IPPC	Integrated pollution prevention and control
LMH	Liter permeate transported per square meter of membrane area and hour
MBR	Membrane bioreactor
MF	Microfiltration
MLSS	Mixed liquor suspended solids
N	Nitrogen
NF	Nanofiltration
P	Phosphorus
RO	Reverse osmosis
TCF	Totally chlorine free
TS	Total solids
TSS	Total suspended solids
UF	Ultrafiltration
VSS	Volatile suspended solids

ABBREVATIONS FOR CASE STUDY

AL	Aerated lagoon
AOR	Actual oxygen transfer rate
BL	Bleach process flow
BLP	Bleach effluent pipe
C	Primary clarification basin (C1, C2, C3, C4)
C & R	Causticizing and resin treatment process flow
CAS	Conventional activated sludge
CT	Collection tank process flow
ECF	Elementary chlorine free
EV	Evaporation process flow
FC	Final clarification basin
FL	Fiber line process flow
FLP	Fiber line pipe
FS	Flat sheet
HF	Hollow fiber
HRT	Hydraulic retention time
MIXP	Mixed pipe
MLP	Miscellaneous pipe
MT	Microtubular
NVV	Naturvårdsverket
PM	Paper machine process flow
SAD_m	Specific aeration demand
SOTR	Standard oxygen transfer rate
WP	Wood preparation process flow

1 INTRODUCTION

During the twentieth century the population of the world has three folded, while the utilization of water has six folded. Globally, irrigation is the largest user of water, followed by industrial use and domestic use (Cosgrove and Rijsberman, 2000). Meeting the increased demand for water, whilst keeping the fresh water eco systems of the world intact, is considered to be one of the biggest challenges of this century. One solution that has been discussed is to increase the reuse of water (Postel, 2000).

In Sweden, the largest use for water is for industrial use (SCB, 2011). Due to high availability and fast regeneration of fresh water, providing water for industrial and domestic use is not a hot topic in Sweden. However, keeping the impact on natural eco systems at a minimum is of high importance. Out of all the industries in Sweden, the pulp and paper mill industry is by far the largest user of water (SCB, 2011), and thus releases the largest amounts of wastewater.

The pulp and paper industry of Sweden does not suffer from the world water scarcity, but would benefit from further development of wastewater treatment. Benefits could include reduced costs, higher recirculation possibilities or meeting environmental demands from the authorities. To encourage the reuse and further treatment of water, new cost-efficient alternatives for wastewater treatment must be introduced (Asano and Levine, 1996).

This study aims to investigate the use of membrane bioreactors (MBRs) as a cost-efficient alternative to conventional wastewater treatment in the pulp and paper mill industry. MBRs have been developed over the last two decades and are primarily used for treatment of municipal wastewater. Advantages of MBR compared to conventional wastewater treatment include space saving and a higher removal of suspended matter. The main disadvantages are higher maintenance and operation costs. To further evaluate the implementation of MBR in the pulp and paper industry, this study will include dimensioning of, and economic calculations for Korsnäs, a Swedish pulp and paper mill.

If MBR can be considered cost-efficient for utilization in the pulp and paper mill industry, it would not only be beneficial for Swedish industries, but might open new doors for further reuse of water globally.

2 PURPOSE OF STUDY

The purpose of this study was, by means of literature and personal contacts with manufacturers and suppliers, to compile information about membrane bioreactors (MBR) and account for their function, application and feasibility for treating wastewater from the pulp and paper industry. To include cost-efficiency and sizing of an MBR, a case study was performed for an existing conventional pulp and paper wastewater treatment plant.

2.1 LIMITATIONS

The study covers only the treatment of water from pulp and paper mills. The sawmill industry is not included in the study. Air emissions are not addressed in the study; neither is waste or sludge from outside the external treatment, such as green liquor sludge from the recovery cycle.

3 METHODS

This study was conducted by means of literature studies and personal contacts with manufacturers and suppliers. Contacts with manufacturers and suppliers were conducted via e-mail correspondence, phone conversations and study visits. The literature study includes scientific papers, printed and electronic literature. Search engines such as Elsevier ScienceDirect, SpringerLink and Google Scholar were used to obtain academic research reports.

A case study was performed, where the effects and costs of implementation of MBR technology on different process flows treated by the external wastewater treatment at Korsnäs pulp and paper mill in Sweden. Calculations were performed using data supplied by Korsnäs to ÅF in 2008 and 2012, information obtained from the literature study and standard calculation values from ÅF.

Methods for performing the technical and economical evaluations in the case study are further described in chapter 6.2

4 THE PULP AND PAPER INDUSTRY

On account of the large raw material resources, the forest industry and especially the pulp and paper industry has long been of great importance for the Swedish economy. In 2009, the Swedish pulp and paper industry was the third largest in Europe and the fourth largest exporter in the world (Skogsindustrierna, 2011). Of the pulp types, kraft is the most prominent (Figure 1).

Figure 1. Swedish pulp production (1000 ton/year) 2005-2010 (Skogsindustrierna, 2010)

4.1 PROCESS DESCRIPTION

Wood consists mainly of cellulose fibers and lignin. The cellulose fibers are bound together by lignin. In the pulping process, logs are debarked and cut into wood chips. The wood chips are then treated to separate the cellulose fibers from lignin, which makes the fibers join together in a network. Depending on further usage of the pulp it can be followed by one or more bleaching stages. Methods for uncovering the cellulose fibers from lignin are divided into two categories: mechanical and chemical (Hultman, 1998). The two methods generate different properties to the finished pulp due to their different approaches.

For the bleaching process it is of importance to identify the amount of lignin in the produced pulp, as lignin affects the color. The amount of lignin is generally described by a value, where a low Kappa (χ) value indicates low lignin content and bright pulp and vice versa. When the pulp, depending of the Kappa value and desired brightness, has been bleached, its final color is described by an ISO value from 0 - 100%. The lighter the material is, the higher is its ISO value (Hultman, 1998).

Readily treated pulp is diluted and formed into sheets using moulds or wires (Hultman, 1998). If the pulp and paper processes are undertaken on the same site, the mill is referred to as integrated. Kraft pulp mills can be found both integrated and non-integrated, while sulphite pulp mills and mechanical pulp mills usually are integrated (IPPC, 2001).

4.1.1 Chemical pulping

In chemical production of pulp, wood chips and cooking liquor are cooked at an elevated temperature in a pressure vessel. The choice of cooking liquid determines, amongst other things, which features the pulp will have. The two most common treatments are the alkaline kraft process and the acidic sulphite process (Hultman, 1998).

The kraft process

In the kraft process wood chips are cooked with white liquor. White liquor is strongly alkaline cooking liquor; the active chemicals include sodium hydroxide (NaOH) and sodium sulfide (Na_2S) (Pokhrel and Viraraghavan, 2004). It also contains non-active chemicals such as sodium carbonate (Na_2CO_3), sodium sulphate (Na_2SO_4), sodium sulphite (Na_2SO_3) and sodium thiosulphate ($Na_2S_2O_3$) (Pokhrel and Viraraghavan, 2004). The kraft process produces a strong pulp and spent liquor which contains lignin, carbohydrates and cooking chemicals, referred to as black liquor. The black liquor passes through a recycling process, resulting in white and green liquor. Most types of wood can be used in the kraft process and approximately 44% of the wood substance is made into pulp (Hultman, 1998).

The sulphite process

In the sulphite process wood chips are cooked together with acidic or neutral cooking liquor, containing a mixture of sulfurous acid (H_2SO_3) and bisulphide ions (HSO_3^-) (Pokhrel and Viraraghavan, 2004). For the sulphite process spruce, birch, beech and aspen can be used and approximately 50% of the wood substance is made into pulp (Hultman, 1998).

4.1.2 Mechanical pulping

Pulp may also be prepared by decomposing wood and processing fibers mechanically. It is an energy consuming process, but has the advantage of converting up to 96% (Hultman, 1998) of the wood substance into pulp, which includes a considerable amount of lignin. The quality of mechanical pulp however, is lower than that of chemical pulp and it has a darker color (Pokhrel and Viraraghavan, 2004).

Refiner process

By grinding wood chips in disc refiners refiner pulp is produced. The wood chips are defibrated between rotating discs where they are heated and processed to pulp. The refining is carried out both under high pressure and under atmospheric pressure (Hultman, 1998). If the raw materials are pretreated by steaming before undergoing the refining process the produced pulp is referred to as thermo-mechanical (TMP). If the pretreatment also includes impregnation with chemicals, the pulp produced is referred to chemi-thermomechanical (CTMP). If only pretreated with chemicals it is referred to as chemo-mechanical (CMP) (Pokhrel and Viraraghavan, 2004). The impregnation chemical used for producing CMP and CTMP is sodium sulphite (Hultman, 1998).

Groundwood process

When manufacturing groundwood pulp, wood is pressed against a grinding stone and sprayed with water. The heat generated by friction softens the lignin and allows cellulose fibers to be sorted out from the wood and to form a new network (Hultman, 1998).

4.1.3 Recycled pulp

Pulp can also be made from recycled papers, which are processed into pulp and deinked prior to further usage. Fibers from recycle pulp are not as strong as in newly produced pulp, why they are mostly used to produce cardboard and corrugated paper (Hultman, 1998).

4.1.4 Pulp bleaching

When chemical pulp is produced, a large proportion of the original lignin is removed from the wood chips. The lignin content of the pulp however, is still approximately 3 – 5 %. Since the residual lignin gives color to the pulp, the content is often further reduced by bleaching. The first step of bleaching is conducted by the adding of oxygen while the following steps utilize chemicals such as chlorine dioxide (ClO_2), chelating agents and peroxides and/or ozone in various combinations until the desired ISO value is achieved (Hultman, 1998).

In the production of mechanical pulp, most of the lignin from the wood chips is retained in the pulp. Bleaching chemicals that modify lignin, rather than remove it, are used (Hultman, 1998).

4.2 WASTEWATER FROM THE PULP AND PAPER INDUSTRY

Worldwide, the overall industry uses a significant amount of water and Sweden is no exception. Out of all the water used in Sweden in 2010, 69% was for industrial use. Of the water used for industrial purposes, 1.7 billion cubic meters was fresh water and 0.6 billion cubic meters was seawater (SCB, 2011). The predominant industrial user of water was the pulp and paper industry, followed by the chemical industry and thirdly the steel and metal industry (Figure 2).

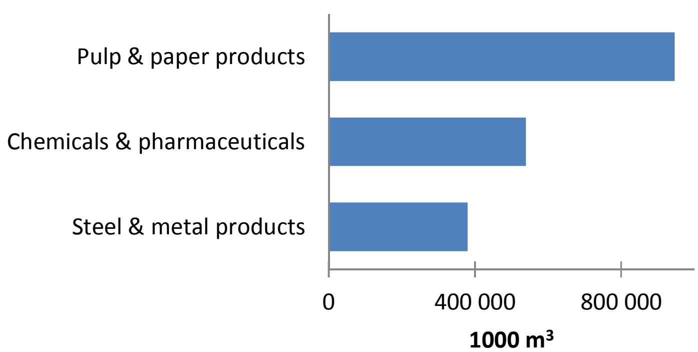


Figure 2. Water use per industrial section in Sweden, year 2010 (SCB, 2011)

The pulp and paper industry alone had a total withdrawal of 0.95 billion cubic meters of water, primarily from surface waters (SCB, 2011). With the large withdrawal of water follows large discharges. Approximately 0.86 billion cubic meters of polluted water was discharged in

2010 (SCB, 2011). Pulp and paper wastewater is considered one of the major sources of water pollution from the industries (Carmichael and Strzepek, 1987) and is of great importance to improve.

The most prominent pollutants in pulp and papermaking wastewater are suspended solids and organic matter. There are also inorganic salts, organic halogen compounds and chlorate in the effluents, and the discharges are in some cases colored. Typical pollution per production can be seen in Table 1.

Table 1. Typical pollution load per ton of pulp production. Total suspended solids (TSS) and organic matter expressed as biological oxygen demand (BOD) (Springer, 2000; Pokhrel and Viraraghavan, 2004).

Process	**Unit**	**SS**	**BOD**
Wood preparation	*kg/ton*	3.8	1
Pulping	*kg/ton*	14	5
Bleaching	*kg/ton*	6	16
Papermaking	*kg/ton*	31	11

Wastewater produced in the pulp and papermaking processes vary greatly in properties, why methods for treating it also vary. On behalf of the European Commission, the Integrated Pollution Prevention and Control (IPPC) have compiled information on best available techniques (BAT) for the pulp and paper industry compiled in a BAT reference document (BREF). Concerning wastewater the BREF states desired BAT emission levels (Table 2) and BAT for the pulping and papermaking processes.

Table 2. BAT emission levels to water that are associated with the use of sustainable combination of these techniques (IPPC, 2001). Parameters are expressed per air dry ton (Adt) pulp.

Parameter	**Unit**	**Bleached kraft**	**Unbleached kraft**	**Bleached sulphite**	**Non-integrated CTMP**	**Integrated mechanical**
Flow	*m^3/Adt*	30-50	15-25	40-55	15-20	12-20
COD	*kg/Adt*	8-23	5-10	20-30	10-20	2.0-5.0
BOD	*kg/Adt*	0.3-1.5	0.2-0.7	1-2	0.5-1.0	0.2-0.5
TSS	*kg/Adt*	0.6-1.5	0.3-1.0	1.0-2.0	0.5-1.0	0.2-0.5
AOX	*kg/Adt*	<0.25	-	-	-	<0.01
Tot-N	*kg/Adt*	0.1-0.25	0.1-0.2	0.15-0.5	0.1-0.2	0.04-0.1
Tot-P	*kg/Adt*	0.01-0.03	0.01-0.02	0.02-0.05	0.005-0.01	0.004-0.01

Common BAT for the different pulping processes include dry debarking, ECF or TCF bleaching, recirculation of water and chemicals, spill monitoring, stripping and reuse of condensate, reuse of cooling water and prevention of unnecessary loading and upsets in the external effluent treatment (IPPC, 2001).

For all above mentioned pulping processes, primary and biological treatment is considered BAT (IPPC, 2001). For mechanical pulp production flocculation and chemical precipitation are also recommended in some cases.

For paper making, the BAT for reducing emissions to water include minimizing of water usage, reducing frequency and effects of accidental discharge, collection and reuse of cooling water, substitution of potentially harmful substances and effluent treatment. The BAT of the paper process is thus primary treatment followed by biological treatment and in some cases chemical precipitation or flocculation (IPPC, 2001).

While all the above stated information is valid at time of writing, it should be born in mind that the IPPC are in the process of updating the cited BREF and that the requirements of performance will likely be raised.

4.2.1 Wastewater in pulp and paper processes

The water that is withdrawn for usage in the pulp and paper industry is mainly used as process water. The most water-consuming processes are cooking and bleaching where the water becomes contaminated by contact of raw materials, by-products and residues (Carmichael and Strzepek, 1987). Pulping is the largest source of pollution in the papermaking process (Pokhrel and Viraraghavan, 2004), and produces wastewater in each part of the process (Figure 3). Pulping produces wastewater that contains wood debris and soluble wood materials, while bleaching generally generates toxic substances (Pokhrel and Viraraghavan, 2004). Spill water can also occur within and between the production steps, but were not addressed as ordinary discharge.

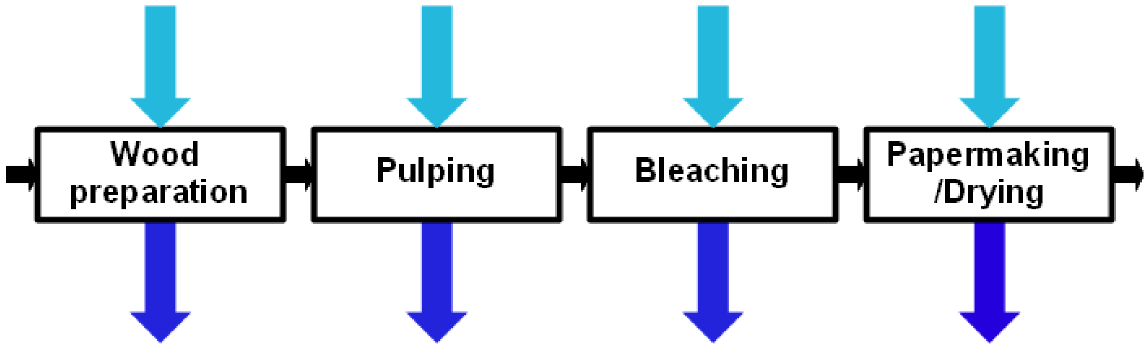


Figure 3. A schematic overview of the water flows in the process of making pulp and paper. Black arrows represent the direction of the process, while the light blue and dark blue arrows represent fresh water and waste water respectively.

The quantity of water discharged depends on the level of recycling within the production chain, while the quality mainly depends on the choice of processing and bleaching techniques. Wastewater characteristics are thus affected by the method used for pulp production and how closed the process is.

Chemical pulping

To prepare the raw wood for the kraft process and the sulphite process the wood is debarked and ground into chips. From the wet barking and chip washing, wastewater containing mainly organic material, suspended solids and other impurities are generated (Pokhrel and Viraraghavan, 2004).

In the kraft process, wood chips are cooked in white liquor and water and the remaining aqueous solution is black liquor. The black liquor mainly contains chemicals and lignin, and is supplied via the black liquor evaporation into incineration and chemicals recycling in a recovery boiler. The condensate from the evaporation contains organic matter, mainly in the shape of methanol. After cooking, the pulp is washed, and wastewater containing resins, fatty acids, organic matter and chlorinated organic compounds (AOX) (Pokhrel and Viraraghavan, 2004). Bleaching occurs in several steps, each followed by washing of the pulp. In the process of oxygen bleaching, lignin is oxidized and flushed out with the wash water. The wastewater thus contains large amounts of organic matter and suspended solids. The subsequent bleaching steps are carried out either with chemicals containing chlorine (ECF) or totally chlorine free chemicals (TCF) (Hultman, 1998). If ECF is used, the final effluent contains, in addition to organic matter and suspended matter, AOX and inorganic chlorine compounds, such as chlorate.

The water from sulphite cooking and subsequent washing mainly contains cooking chemicals and lignin. As sulphite pulp is, compared to kraft pulp, easy to bleach, it requires only few steps and is normally performed without chlorine, using TCF (Hultman, 1998). The wash water thus mainly contains organic matter and suspended solids.

Mechanical pulping

Similarly to the preparation of raw wood material of the chemical processes, the wood is debarked and then ground into wood chips, where water is polluted with organic matter, suspended solids and other impurities. The wood chips are then preheated with steam, which is captured and purified using heat exchangers. In the refining process water polluted with organic matter and suspended solids is generated. In the bleaching steps and subsequent washing, further organic matter and suspended solids are released (Hultman, 1998).

The groundwood process is free of chemicals until the bleaching steps, and until then thus only produces wastewater containing various amounts of organic matter and suspended solids.

Recycled pulp

Water used for deinking is mainly recirculated and is internally treated using microflotation, a process where suspended materials are adsorbed to air bubbles and rise to form a removable surface layer. The discharge from the recycled pulp process contains large amounts of organic matter, and is usually treated with biological wastewater treatment (Hultman, 1998).

Paper making

The last step in pulp and papermaking is the actual paper making, where large quantities of water are used for process and cooling water (IPPC, 2001). Wastewater from paper making contains particular waste, inorganic dyes and glue, and organic matter (Pokhrel and Viraraghavan, 2004; Hultman, 1998).

4.2.2 Water quality parameters

For the monitoring of wastewater quality several parameters are taken into account. The most important parameters for pulp and paper process wastewater are solids, organic matter, chlorinated organic matter, chlorate and nutrient content. Other wastewater parameters, such as pH, alkalinity and temperature are also important, but will not be further explained.

Solids content

The solid content is the most important physical characteristic of wastewater, and describes, as the name suggests, amount of suspended or dissolved matter in wastewater. The solid content parameters of importance for this study are settleable solids, total solids (TS), total suspended solids (TSS) and volatile suspended solids (VSS) (Metcalf and Eddy, 1991).

The settleable solids in a sample are measured as the amount of solids deposited at the bottom of an Imhoff cone after one hour. Only gravitational force is used to separate the solids from the sample (Metcalf and Eddy, 1991).

Total solids (TS) are measured by the adding of external heat to evaporate the liquids. The sample is heated to 103 or 105°C, and the remaining solids classified as TS. TS are further subcategorized through filtration, where solids are either filterable or non-filterable. TSS are non-filterable, which means that they do not pass through the 1.2 µm pore size filter. The expression "mixed liquor suspended solids" (MLSS) is used for samples containing both regular wastewater TSS, and also additional microorganisms from activated sludge processes. Further classification of the TSS is conducted to determine the organic and inorganic content. The SS is heated to 550 ± 50 °C, which will lead the organic matter to oxidize and vaporize. This fraction is thus classified as VSS (Metcalf and Eddy, 1991).

Organic matter content

Organic matter, along with nutrients and other dissolved matter, is part of the solids content, but is measured individually due to its high pollutant value. Organic matter content is usually measured by the three following methods; biological oxygen demand (BOD), chemical oxygen demand (COD) or total organic carbon (TOC) (Metcalf and Eddy, 1991).

BOD is a parameter that describes the amount of dissolved oxygen used by microorganisms in the process of oxidizing organic matter. Nutrients, microorganisms and dissolved oxygen are added to the wastewater to be tested, and the mixture is then incubated. After five (BOD_5) or seven (BOD_7) days, the used amount of dissolved oxygen is measured and the biodegradable organic matter content is calculated (Metcalf and Eddy, 1991).

COD is a parameter for the organic matter content, which can be chemically oxidized. An acidic medium and an oxidizing chemical are added to the wastewater sample, the oxidizing chemical commonly being dichromate. The sample is then heated to 150°C during two hours, after which the used amount of oxygen is measured. Due to the shorter time required for measuring COD compared to BOD, it is advantageous to find a correlation between the two and then only measure COD (Metcalf and Eddy, 1991).

TOC is a parameter for measurement of the wastewater carbon content by incineration or chemical oxidizing. A known quantity of wastewater is exposed to the oxidizing environment where carbon is transformed into carbon dioxide (CO_2). The produced amount of CO_2 is then measured using an infrared analyzer (Metcalf and Eddy, 1991).

Halogenated organic matter content

AOX is a parameter used for measuring the amount of halogenated organic matter, which in the pulp and paper industry mainly consists of chloro-organic compounds produced in the bleaching processes (Springer, 2000). Firstly, activated carbon is used to absorb halogens from a sample of wastewater. The activated carbon is then washed with a nitrate solution that removes chloride ions, while the carbon and organic compounds still adsorbed are burned, so that gas containing hydrochloride acid can be scrubbed, and chloride ions finally isolated using microcoulometric titration (Springer, 2000).

Chlorate

In the bleaching of pulp using chlorine, lignin is oxidized into several smaller compounds; amongst them is chlorate (Solomon, 1996). Chlorate has toxic effects on algae, and can therefore cause disturbance of the balance in the aquatic ecosystems (Solomon, 1996). The removal of chlorate is dependent on an even temperature, low oxygen concentration, pH ranging from 7 to 8, and a sufficient amount of easily degradable organic matter (BOD) in the wastewater. Chlorate can be measured using ion chromatography, where the charged chlorate ion is retained in a stationary phase by ionic interaction. The chlorate is then eluted and measured by conductivity.

Nutrient content

All living organisms require certain nutrients for cell growth and repair. The major nutrients of importance are nitrogen (N) and phosphorus (P). Other nutrients are required only in trace quantities. Nitrogen appears in aqueous solutions as ammonia (NH_4^+/NH_3), nitrite (NO_2^-), nitrate (NO_3^-) or organic nitrogen (Org-N). Nitrogen can either be represented individually, by Kjeldahl nitrogen (KN), total Kjeldahl nitrogen (TKN) or total nitrogen (Tot-N) (Metcalf and Eddy, 1991).

Ammonia is measured by shifting the NH_4^+/NH_3-balance towards NH_4^+ by raising the pH value of the sample. The sample is then boiled and distilled, and NH_4^+ content measured colorimetrically, titrimetrically or with specialized ion electrodes. Nitrite is an unstable compound, which is quickly oxidized into nitrate. Both nitrite and nitrate contents are determined colorimetrically (Metcalf and Eddy, 1991).

KN is a parameter for measuring biochemically degradable org-N. The sample is firstly boiled to drive off any dissolved NH_4^+. The sample then undergoes digestion, where organic nitrogen is transformed to NH_4^+, which is then measured. Only the organically bound nitrogen is thus measured using KN. TKN is a measurement of the org-N and NH_4^+ content, without pre-boiling the sample. The total nitrogen parameter (Tot-N) includes org-N, NH_4^+, NO_3^- and NO_2^- (Metcalf and Eddy, 1991).

Phosphorus appears as orthophosphate (PO_4^{3-}), polyphosphate and organically bound phosphate (org-P). Polyphosphate is slowly hydrolyzed into orthophosphate, which is available for bio-metabolism and therefore of interest to measure. A substance is added to the sample, which forms a colored complex with PO_4^{3-}, and thus indicates concentration. To measure the total phosphate content, org-P and polyphosphate are digested by the adding of an acid before measuring PO_4^{3-} (Metcalf and Eddy, 1991).

5 MEMBRANE BIOREACTORS

5.1 INTRODUCING MBR

Membrane bioreactor (MBR) is a term used for processes that integrate biotreatment with semi-permeable membrane filtration (Figure 4). The process is based on suspended growth of microorganisms, with continuous feeding of wastewater, and can be operated under aerobic, anaerobic or anoxic conditions.

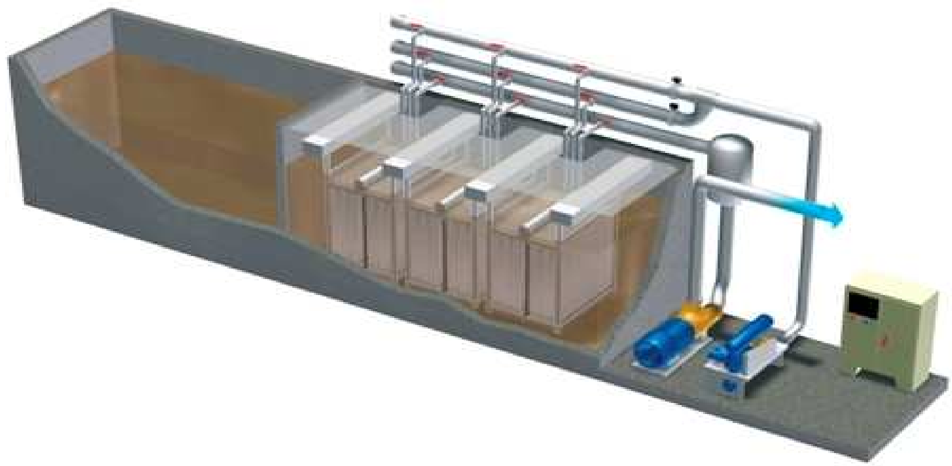


Figure 4. An overview of a submerged MBR equipped with ZeeWeed® membranes (GE Water & Process Technologies, 2012).

5.1.1 Past and present

MBRs have been utilized in the treatment of municipal water since the 70s, firstly gaining popularity in Japan and then continuing on to the global market (Radjenovic et al., 2007). The first type of MBR on the market was designed to have an external membrane module, to which water was pumped from a bioreactor. The external membrane module MBR was mainly used for domestic wastewater, in space-limited sites. In 1991, the first submerged MBR was introduced (Judd, 2011). The membrane module was submerged directly into the bioreactor, and water removed using vacuum pressure or shear forces induced by air scouring. The submerged design quickly evolved, and was used for both domestic and industrial wastewater treatment (Judd, 2011). The first full-scale MBR plant for municipal wastewater was built in the UK in 1998 (Le-Clech, 2010). A trend towards using membrane processes and MBRs was seen in 2005 (Wintgens et al., 2005) due to the globally increased interest in water reuse. In 2008, MBR systems had been built in more than 200 countries (Judd, 2011).

Another trend to be noted is the increased installation of MBR systems for industrial use (Figure 5). Continued growth of the MBR market is predicted in most countries due to decreasing capital and operating costs, and faster realization of large-scale implementation (Judd, 2011).

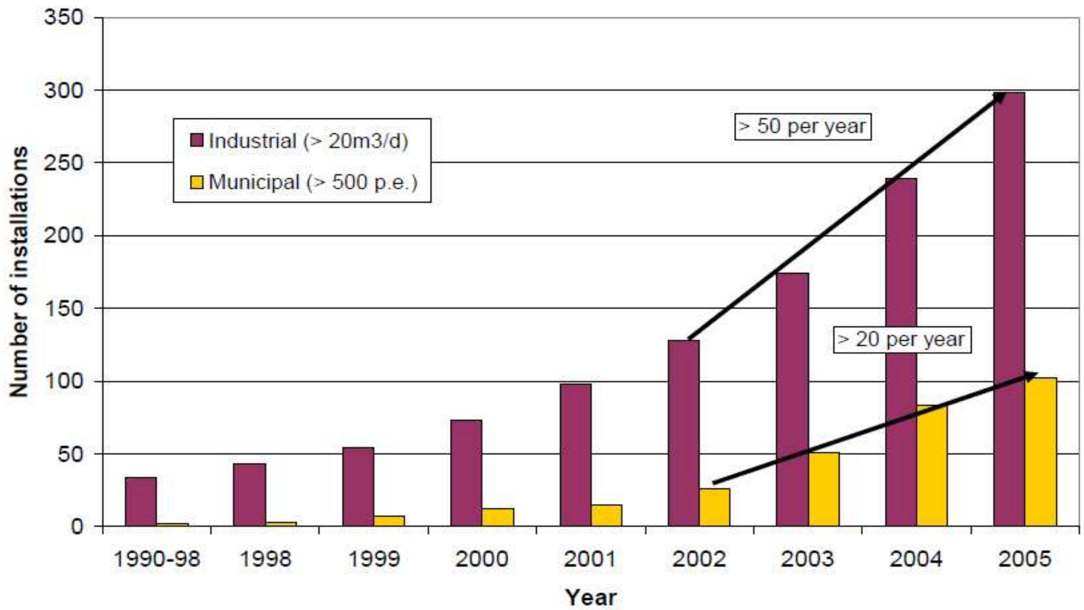


Figure 5. Development of industrial and municipal MBR markets (Lesjean and Huisjes, 2007).

5.1.2 Advantages and disadvantages

As any technology, MBR technology has its advantages and disadvantages. The most frequently mentioned properties (Van Dijk and Roncken, 1997; Melin et al., 2006; Radjenovic et al., 2007; Judd, 2011; Lin et al., 2012) are summarized in Table 3.

Table 3. Advantages and disadvantages of MBR. Properties are not sorted in order of significance.

Advantages	Disadvantages
Low footprint	Pretreatment required
Allows high biomass (MLSS) concentration	Membrane monitoring required
Sludge age decoupled with HRT	High energy costs
High quality effluent	Staff education required
Low sludge yield possible	Membrane maintenance required
Expanding capacity	

The evaluation of MBR performance and feasibility is often compared to that of the commonly implemented wastewater treatment technology conventional activated sludge (CAS). As an opposite to the MBR systems, where microorganisms are removed from the liquid phase by membrane filtration (Melin et al., 2006), CAS requires a sedimentation or flotation step (Figure 6).

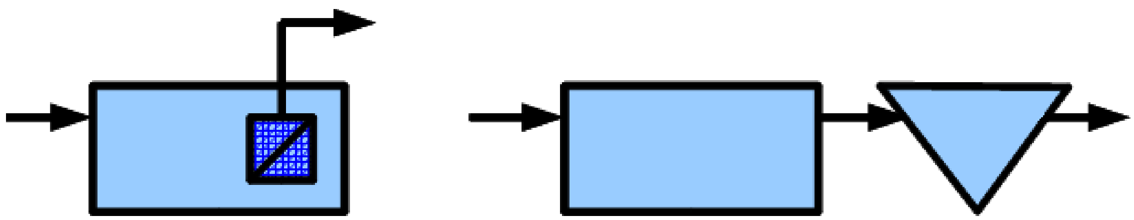


Figure 6. From the left: MBR system consisting of biotreatment (large rectangle) and membranes (small square), and CAS system consisting of biotreatment (large rectangle) and sedimentation (triangle). Arrows represent treated water flow.

The additional step in CAS, or rather the removed need for it in MBR, makes MBR bottom area, generally referred to as footprint, smaller than for that of CAS. As a rule-of-thumb, MBR footprints are one third of that of CAS (Judd 2011).

Another advantage of combining biotreatment with membrane filtration is that the hydraulic retention time (HRT), which is the time it takes for water to pass the reactor, and sludge retention time (or sludge age), which is the duration of stay in the system for an average microorganism, are decoupled (Judd, 2011). The membrane thus sustains microorganisms in the bioreactor until they are removed by discharge, non-dependent of the water flow through the membrane. This allows high sludge age while maintaining low HRT (Judd, 2011).

The membrane barrier also allows the mixed liquor suspended solids (MLSS) concentration in the bioreactor to be kept higher for the MBR than that of CAS, which may reduce the MBR footprint even more (Van Dijk and Roncken, 1997; Melin et.al., 2006).

High concentration of MLSS combined with low HRT hinder flocs to form, and thus offers a larger active surface area of the total microorganisms, which allows high contaminant removal, of nutrients and organic matter, to be achieved (Van Dijk and Roncken, 1997). Maintaining high sludge age combined with high MLSS concentrations have several benefits for effluent quality as it promotes microorganism growth due to high availability of food, growth of influent specialized microorganisms due to high sludge age, and high microbial activity due to increased heat production. MBRs have, as opposed to CAS, shown to be effective when influent concentrations and flow rates fluctuate (Wintgens et. al., 2005; Melin et. al., 2006), and when pathogens are present (Radjenovic et al., 2007). MBR technology in municipal wastewater treatment has shown to be stable under different operating conditions, such as sludge age, volumetric loading rates and temperatures (Mohammed et al., 2008). The high quality effluent produced by MBR systems can be suited for in-process recycling, or in other applications, such as irrigation or groundwater recharge (Le-Clech, 2010).

As high MLSS concentrations are allowed in MBR systems due to the membrane barrier, in theory, HRT can be adjusted to provide exactly the amount of energy needed for repair of microorganisms, and thus keeping an infinitely long sludge age and no sludge production. There are difficulties with keeping sludge production in pilot and full-scale MBRs, why it is not to be expected, however, a lower sludge production for MBR systems than for CAS is usually accomplished.

Many MBR systems are available in expandable packages, where a larger membrane area can be acquired by the adding of one or more pre-packed membrane modules, or one or more complete packages including biotreatment tanks and membrane modules. The flexibility of the wastewater treatment capacity is of advantage for expanding treatment plants or sites where inflow varies greatly. It may also be more feasible to add an MBR package than to build new or expand existing treatment basins.

There are however some disadvantages associated with MBR systems. The membrane modules require frequent maintenance and monitoring, as they are susceptible to clogging and fouling, and have pressure-, temperature- and pH related limitations (Melin et al., 2006). The permeate transport and fouling prevention requires energy, and a higher energy consumption can be expected for MBR systems than for CAS. It is also of great importance to educate staff members, for proper membrane maintenance and monitoring.

5.2 MBR FUNDAMENTAL PRINCIPLES

As mentioned above, MBR systems are composed of a combination of membranes and biotreatment. The most discussed and studied topic with MBR systems is known as fouling. Fouling is therefore, along with membrane technology and biotreatment, further described below.

5.2.1 Membrane technology

Membrane technology has long been used, and is increasingly popular in municipal wastewater treatment, as it has great potential in removing contaminants such as pathogens and SS (Wintgens et al., 2005). Utilization of membrane filtration is very flexible, it is easily adjusted to fluctuating feed concentrations and flows, and it is a stable process that is easily shut down and restarted (Hoyer and Persson, 2007). For pulp and paper mill wastewater, membrane technology has been noted for effectively reducing COD, AOX, SS, color and heavy metals (Pokhrel and Viraraghavan, 2004) and can be considered BAT for reuse of process water. In MBR, membrane technology plays an essential role to retain the microorganisms in the biotreatment tank.

Transmembrane flow

The fundamental principle of membrane filtration is inducing mass transfer through a membrane, the mass transfer being driven by a force (IUPAC, 1996). Membrane processes can occur by diffusion, extraction or rejection. For wastewater treatment, membranes are mainly used for rejection, where small constituents of the feed are allowed to pass through the membrane, including water molecules, while larger ones are rejected (Judd, 2011). The rejected constituents are referred to as retentate, the constituents that pass become permeate and the raw solution is referred to as feed (Figure 7).

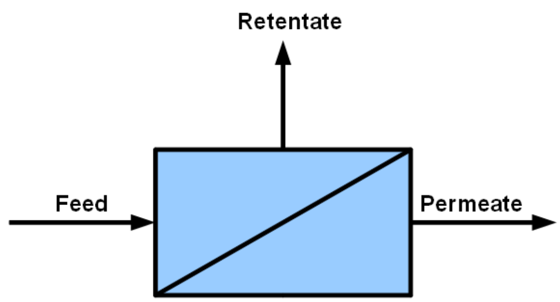


Figure 7. Feed entering a filtration unit, resulting in retentate and permeate.

Where permeate emerges from the membrane is referred to as downstream, while where the inflow occurs is referred to as upstream (IUPAC, 1996). The mass transfer can either occur by dead-end flow, where no retentate is produced (Judd, 2011), or by crossflow, where permeate moves in the direction normal to the membrane surface and a stream of retentate is obtained (IUPAC, 1996) (Figure 8).

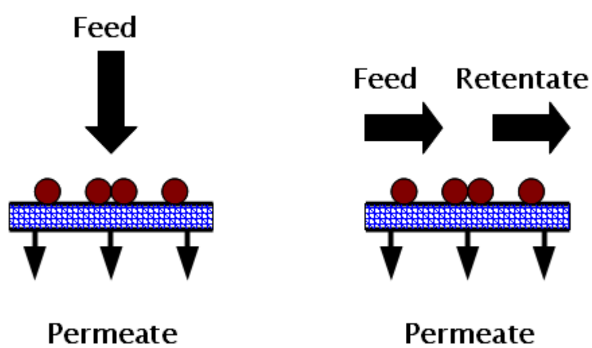


Figure 8. Feed, permeate and retentate directions for dead-end flow and crossflow.

For describing transport across a membrane, the term 'flux' is used. Flux is defined as the amount of a specific constituent that passes through a specific membrane surface area during a unit of time. It is officially expressed in [kmol/(m^2 s)], [m^3/(m^2 s)] or [kg/(m^2 s)] (IUPAC, 1996), but is also commonly expressed as LMH, short for [L/(m^2 h)] at standard temperature (Judd, 2011). There exists a critical membrane flux, where clogging starts to occur at the membrane surface. Flux below the critical membrane flux is referred to as sub-critical flux (Judd, 2011).

Flux over MBR membranes generally ranges between 10 and 150 LMH and is dependent on the applied pressure, the viscosity of wastewater and membrane properties (Judd, 2011).

The applied pressure in MBR systems is most commonly induced by the pumping of water tangential or normal to the membrane, using positive or negative pressure respectively, or by using air scouring. Air scouring is performed by placing aerators underneath a submerged membrane, allowing a mixture of air and liquid to flow over the membrane (Judd, 2011). The flux is thus achieved by the lifting of wastewater by air onto the membrane surface. Air scouring also promotes liquid flow fluctuations and local tangential shear transients, which indirectly increase flux by discouraging particle deposition on the membrane surface. Most efficient air scouring is known to be a so called 'slug flow', where large gas bubbles pass up through tubular membranes. Air scouring is most effective in tubular membranes, where the air slugs have the most contact area (Judd, 2011).

As mentioned above, flux is also dependent on the water viscosity. Water viscosity, in its turn, is inversely related to temperature. An increase in temperature will thus cause a decrease in water viscosity, resulting in an increase of the flux (Judd, 2011).

Along with applied pressure and water viscosity, the membrane properties are of great importance. The type and magnitude of mass transfer to be performed is largely regulated by the membrane properties, such as pore size, charge and texture (Van der Bruggen et al., 2003).

There are four main categories of membrane filtration used for wastewater treatment, each designed for rejection of contaminants in a certain size interval; micro-, ultra- and nanofiltration, and reverse osmosis (Judd, 2011).

Microfiltration (MF) rejects particles larger than 0.1 µm (IUPAC, 1996), and is used for removal of suspended solids, including bacteria (Wintgens et al., 2005). Ultrafiltration (UF) rejects particles of sizes 2 – 100 nm (IUPAC, 1996), including viruses and organic macromolecules (Wintgens et al., 2005). Nanofiltration (NF) removes particles of sizes between 0.2 – 2 nm, such as small organics, color and multivalent ions (IUPAC, 1996). Reverse osmosis (RO) allows rejection of particles smaller than 0.2 nm, such as singly charged ions (Judd, 2011).

Achieving equal flux for MF and UF, assuming otherwise similar membrane properties and equal water viscosity, requires higher applied pressure for UF than MF. The higher pressure applied in UF allows contaminants larger than the pores to pass through the membrane, due to deforming or flexibility. Retained particles are therefore represented by different parameters for MF and UF: pore size of the membrane for MF and molecular weight cut-off (MWCO) for UF. MWCO is a parameter which describes the rejection of 90 % of particles of a certain molecular weight (Van der Bruggen et al., 2003). When using MF, deposition of particles onto the membrane is essential, as it narrows the pores and thus provides cleaner effluent (Le-Clech, 2010). As for UF, a high-quality effluent is produced from the process start-up, and the duration of the deposition is avoided (Le-Clech, 2010). Accordingly, UF might be considered more effective; however, the larger pores of MF membranes facilitate cleaning and thus prolong life time.

Membranes in MBR technology

For MBR technology, mainly MF and UF are utilized (Radjenovic et al., 2007). Both effectively remove suspended matter while not affecting conductivity and dissolved oxygen concentration in the permeate (Wintgens et al., 2005), and are less prone to having pores clogged than NF and RO. NF and RO are generally used for final polishing of water (Melin et al., 2006). The price for membranes have decreased during the recent years, from approximately €150/m^2 in 2005 (EUROMBRA, 2005) to approximately €50/m^2 in 2011 (Judd, 2011).

Membranes are available in a variety of different material, but they are all designed to meet the desired properties of membranes; high surface porosity, narrow pores, mechanical strength and a certain resistance to cleaning processes (Judd, 2011). For usage in MBR systems, there are mainly two types that are of interest; polymeric and ceramic (Judd, 2011). Metallic membranes are also available (Radjenovic et al., 2007), but are so far more expensive than polymeric and ceramic. Polymeric membranes often consist of a thin layer with low permeability, and one or more thicker layers with high permeability to maintain structure and increase the flow over the membrane. Polymeric membranes can be made hydrophobic or hydrophilic, for MF or UF (Van der Bruggen et al., 2003). The most common polymeric materials include cellulose esters, polyamides, polysulphone, polytetrafluoroethylene and polypropylene, and are all hydrophobic (Radjenovic et al., 2007). However, hydrophobic membranes are more apt to fouling, why they are sometimes modified to having a hydrophilic surface by chemical oxidation, organic chemical reaction, plasma treatment or grafting (Radjenovic et al., 2007). Ceramic membranes are more resilient to chemical, thermal and mechanical strains than polymeric membranes, but are less flexible. They are prepared with alumina (Al_2O_3), titania (TiO_2), silica (SiO_2) and zirconia (ZrO_2), and can be made for MF or UF (Van der Bruggen et al., 2003).

5.2.2 Biotreatment

Biotreatment, where microorganisms are used for wastewater purification, is a widely used wastewater treatment as it offers effective reduction of organic matter and nutrients without the use of chemicals (Metcalf and Eddy, 1991). Biotreatment is used for the removal of both suspended and dissolved contaminants, as microorganisms exploit them as a part of their metabolism. Their metabolism results in cellular growth and repair, as well as the release of water and various mineralized compounds, such as carbon dioxide (CO_2) and inorganic nitrogen products (Judd, 2011).

In CAS, the main aim of the biotreatment is the conversion of organic and inorganic matter into cell tissue. Once converted into cell tissue, in wastewater treatment referred to as sludge, it can be physically removed by sedimentation or flotation (Metcalf and Eddy, 1991).

MBR systems are also designed to utilize the benefits of biotreatment, but the main aim is not to produce cell tissue for discharge, but rather limit the amount of cell tissue being produced. The biotreatment is designed to create a cell tissue steady state, where organic and inorganic matter content of the influent is solely used for the upkeep and repair of cells, such that little or no sludge is produced. To accomplish steady state, a high concentration of microorganisms is required, along with short HRT to supply sufficient feed. This allows sludge age to be high. Being able to keep a high sludge age is also advantageous for promoting development of slow-growing specialized microorganisms which are able to degrade low-biodegradable pollutants.

Microorganisms in biotreatment

Most processes in biotreatment are performed by bacteria, but there are also other microorganisms involved, such as fungi, protozoa, rotifers, algae and archaea. All contribute to the reduction of contaminants in wastewater.

Bacteria, which constitute the majority of microorganisms in biotreatment, vary in size, but are generally not larger than 15 µm, and are thus retained by both MF and UF membranes. They are mainly heterotrophic and can be found in aerobic, anoxic and anaerobic environments. Amongst other classifications, bacteria are divided into subgroups regarding what temperature they occur in; psychrophilic (-10 to 30 °C), mesophilic (20 to 50 °C) and thermophilic (35 to 75 °C) (Metcalf and Eddy, 1991), of which only the two latter are used for MBR systems (Judd, 2011). Archaea are similar to bacteria in size and shape, but are in fact from another domain than both eukaryotes and prokaryotes. They are an important part of the anaerobic digestion and are more tolerant to extreme environments than bacteria.

Fungi, require half the nitrogen amount as bacteria for growth, and have the ability to degrade cellulose, which makes them useful in biotreatment. They are more tolerant to extreme pH values (2 to 9) than bacteria (4.0 to 9.3) and are also mainly heterotrophic (Metcalf and Eddy, 1991). Protozoa, nematodes and rotifers are the largest microorganisms involved in biotreatment and feed on bacteria and particulate organic matter. Maintaining a population of protozoa, nematodes and/or rotifers in biotreatment reduces the sludge production, as all are effective consumers of bacteria and large particles of organic matter (Metcalf and Eddy, 1991). Algae are mostly important for their ability to produce oxygen, which contributes to the overall health of aquatic ecosystems. They are above all an important part of wastewater treatment in aerobic and facultative oxidation ponds (Metcalf and Eddy, 1991).

Biological processes in biotreatment

Depending on the reduction-oxidation (redox) state of the environment, different processes are conducted by microorganisms. The degradation of organic matter occurs under aerobic conditions, where oxygen (O_2) is used as oxidant; under anoxic conditions, where O_2 is found in compounds such as nitrate (NO_3^-); or under anaerobic conditions, where an endogenous oxidant is used (Metcalf and Eddy, 1991).

The aerobic degradation of organic matter results in production of new cells, CO_2, ammonia (NH_4^+) and byproducts such as extracellular polymeric substances (EPS) (Metcalf and Eddy, 1991).

$$OM + O_2 + \ Nutrients \ \rightarrow CO_2 + \ NH_4^+ + New\ cells + Byproducts \qquad (1)$$

In addition to production of new cells, available O_2 is used for endogenous respiration, which results in release of further CO_2 and NH_4^+, and also generates water and energy (Metcalf and Eddy, 1991).

$$Cells + \ O_2 \rightarrow \ CO_2 + \ H_2O + \ NH_4^+ + \ Energy \qquad (2)$$

The anoxic degradation of organic matter is similar to that of the aerobic degradation, but differs in used oxidant; in the absence of dissolved O_2, primarily NO_3^- is used as oxidant, which leads to the production of nitrogenous gas (N_2). The degradation from NO_3^- to N_2, referred to as denitrification, is performed by heterotrophic bacteria (Kemira Kemwater, 2003).

$$OM + \ 2NO_3^- + \ H^+ \rightarrow \ N_2 + \ HCO_3 \qquad (3)$$

Anaerobic degradation of organic matter occurs when no oxygen is available. Organic matter is then degraded into methane (CH_3), CO_2 and water by methanogens (Kemira Kemwater, 2003).

$$OM \rightarrow \ CH_3 + \ CO_2 + \ H_2O \qquad (4)$$

Anaerobic treatment, also referred to as fermentation, is usually applied for treatment of sludge or heavily polluted wastewaters (Kemira Kemwater, 2003). In a review of pulp and paper mill wastewater treatment, Pokhrel et al. (2004) found anaerobic treatment of bleaching kraft effluent to be less suitable than aerobic, due to the low resistance of methanogens to toxic compounds regularly found in the bleaching effluent.

Production of biomass for aerobic and anoxic oxidation is estimated at approximately 0.5 kg per kg COD. Anaerobic digestion is less effective, and produces only 0.1 kg biomass from 1 kg COD (Kemira Kemwater, 2003).

If nitrogen removal is required, nitrifying bacteria can be utilized in the aerated basin to convert NH_4^+ into NO_3^-. The process, referred to as nitrification, is carried out in two steps, preformed by three different species of bacteria; nitrosomonas, nitrobacter and nitrospira. Nitrosomonas oxidize NH_4^+ to nitrite (NO_2^-), while nitrobacter oxidize NO_2^- to NO_3^-. Nitrospira is involved in both processes (Metcalf and Eddy, 1991).

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 2H^+ + 2H_2O \quad (5)$$

$$2NO_2^- + 2O_2 \rightarrow 2NO_3^- \quad (6)$$

Biotreatment in MBR technology

In MBR technology, as feed is introduced into the bioreactor, new biomass is continuously generated, while some is decayed by endogenous respiration, as explained in section 5.2.1. Endogenous respiration, when referred to, includes biomass loss and energy requirements for processes other than growth; maintenance, decay, endogenous respiration, lyses, predation and death are commonly included.

Endogenous respiration can be encouraged by high sludge age, which increases biomass concentration (Radjenovic et al., 2007; Pollice et al., 2008) showed that for treating municipal wastewater, the MBR could be operated at high sludge age without having a negative impact on biodegrading activities.

By combining high access to food (using low HRT) and long sludge age, the sludge concentration can be kept high enough for all energy to be used for cell repair, thus maintaining a somewhat constant level of MLSS (Judd, 2011).

By maintaining a sludge age that induces equal endogenous respiration as provided energy, it is theoretically possible to reach a steady state of little or no excess sludge production. If the provided energy is limited, restoration of cells is prioritized over production of new cells. High biomass concentration, in biotreatment referred to as mixed liquor suspended solids (MLSS), is thus favorable for achieving little or no excess sludge, keeping sludge loading low. Optimal biomass and sludge age for low excess sludge production depend on feed properties and microorganism population, but can be found by observing the sludge yield. If a too high sludge age is kept, the viability of the microorganism population can be negatively affected, thus reducing the endogenous respiration and resulting in a higher sludge yield (Radjenovic et al., 2007). The reduced viability of high biomass concentration liquids can be explained by the limited transfer of oxygen and substrate caused by high viscosity

(Radjenovic et al., 2007). Typical MLSS concentrations in MBR are in the range of 10 – 25 g MLSS/L (Radjenovic et al., 2007).

If no excess sludge is withdrawn, there is a risk of non-biodegradable compound accumulation, which could be toxic to the microorganisms. Non-biodegradable compounds can however, in some cases be degraded by hydrolysis and/or enzymatic solubilization (Pollice et al., 2008).

For a more effective MBR biotreatment, sludge decay rate can be increased in a number of ways; accelerating lysis by physical or chemical treatment, inducing cell death and lyses by thermal treatment on a fraction of the sludge, ultrasound disintegration, ozone-induced biodegradation, alkaline treatment and growth of controllable predators (Radjenovic et al., 2007).

As MBR systems utilize the same biological processes for reduction of organic matter and nutrients as the commonly used CAS process, a similar composition of microorganisms can be expected. However, the decoupling of sludge age from HRT in MBR systems affects the concentration of the higher microorganisms, including rotifers and protozoa, depending on parameter design. Generally, compared to CAS, lower concentrations of higher organisms are found in MBR systems (Judd, 2011). On the other hand, when sludge age is the same for both systems, and HRT is kept high, the higher organisms appear in higher concentrations in MBRs (Judd, 2011). This indicates that the usually low HRT of MBR systems is responsible for the observed scarcity of higher organisms. The low presence of higher organisms directly affects predation in the bioreactor, which makes limitation of sludge production solely dependent on endogenous cell decay and availability of energy (Judd, 2011). Endogenous decay is therefore higher in MBR (0.05 – 0.32 /day) than in CAS (0.04-0.075 /day) (Judd, 2011). Typical endogenous decay rate value for MBR is 0.12 /day (Judd, 2011).

MBR systems have been proven to be effective for nitrogen and phosphorus removal, using external compartments or intermittent aeration (Radjenovic et al., 2007). Nitrogen and phosphorus removal in MBR systems is enhanced by the retention of nitrifying bacteria and phosphate accumulating organisms in the bioreactor, caused by the membrane barrier (Radjenovic et al., 2007). Floc sizes in MBR biotreatment tend to be smaller than in CAS biotreatment, allowing an increased oxygen transfer to individual microorganisms, which may be one of the reasons for more efficient nitrogen reduction in the former (Judd, 2011).

5.2.3 Fouling

The MBR technology has, as mentioned, some disadvantages. There is however one problem that, due to its complexity, has gained more attention than others: fouling. Fouling is described as the reduction of flux due to deposition on the membrane surface (Judd, 2011). The deposition of particles, referred to as foulants, is affected by a variety of factors, relating to both biotreatment and membranes. The key issue in the operation of an MBR system is to prevent and control fouling.

Fouling mechanisms

For any filtering process, there is the issue of reduced transmembrane flow over time, due to deposition of particles on the membrane. In crossflow systems, deposition occurs until the adhesive forces of the membrane, are equal to the scouring forces of the passing flow, whether created by the pumping of water or air scouring (Radjenovic et al., 2007).

The relationship between flux (J), viscosity (η), transmembrane pressure (ΔP) and resistance (R) can be seen in equation 1 (Judd, 2011). The reduction of flux due to deposition on the membrane surface accordingly leads to an increase in resistance, which will lead to a decrease in efficiency for the MBR system.

$$R = \frac{\Delta P}{\eta J} \qquad (7)$$

The total resistance (R) is commonly divided into three subcategories; resistance of membrane, resistance of fouling layer and resistance of surface-solution interaction. Resistance of membrane is determined by membrane properties, such as charge and pore size and is usually represented as the permeability. Resistance of the fouling layer is dependent on both membrane properties and feed properties, and resistance of surface-solution interaction is the result of concentration polarization, which occurs in the boundary liquid layer where liquid velocity is close to zero. It causes reduced flow over the membrane and can be prevented with increased turbulence (Radjenovic et al., 2007). MBR membrane fouling is mostly dependant on the interactions between the biotreatment suspension and membrane surface (Judd, 2011); thus the most crucial resistance is that of the fouling layer.

The fouling layer of the membrane, contributing to the total resistance, can occur in four ways; complete blocking, intermediate blocking, standard blocking and cake filtration (Figure

9). Complete and intermediate blocking occurs by the occlusion of pores by particles without and with superimposition, respectively. Standard blocking occurs when particles smaller than the pores deposit onto the pore walls, resulting in reduction of membrane pore size. Cake filtration occurs when particles larger than the pores deposits onto the membrane (Radjenovic et al., 2007).

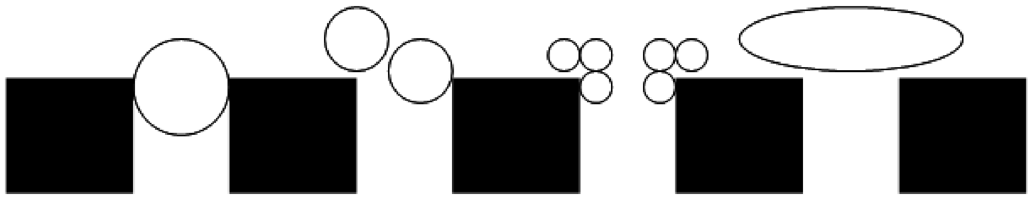


Figure 9. Pore clogging from the left: complete blocking, intermediate blocking standard blocking and cake layer.

The three former are considered one type of fouling, causing ‘fouling resistance’, while cake filtration is considered another, causing ‘cake layer resistance’ (Radjenovic et al., 2007). It is generally assumed that colloid and soluble materials are the cause of pore blocking, while suspended solids cause cake layer resistance (Radjenovic et al., 2007). Thus the primary indicator of fouling propensity and resistance of wastewater in MBR systems is the amount of colloid and soluble materials, as well as suspended solids (Judd, 2011), all generally referred to as foulants. The cake layer can also be referred to as biofilm or biocake (Le-Clech, 2010).

While some of the foulants enter the bioreactor with the influent, most are generated by the microorganisms in the bioreactor (Judd, 2011). One specific type of foulant has been singled out as the most fouling-causing; extracellular polymeric substances (EPS) (Radjenovic et al., 2007). EPS is mainly produced by microorganisms during the biological treatment, but can also enter the system via the inflow water. EPS are macromolecules, such as carbohydrates, proteins, lipids, and nuclein acids that help the aggregate bacterial cells to form flocs and biofilms (Judd, 2011). When EPS deposits on the membrane surface it, due to its heterogeneous nature, forms a hydrated gel, which presents a significant barrier to permeate flow. The most significant factors for EPS concentration are sludge age, substrate composition and organic loading (Judd, 2011).

Factors that affect foulant membrane deposition are; liquid temperature, dissolved oxygen content, foaming, floc characteristics and membrane hydrophobicity and surface charge (Judd, 2011).

Foaming can be caused by high sludge age, high liquid temperature, low F:M ratio or high MLSS content. Foaming is an indicator of fouling propensity, as the foam has hydrophobic properties, and is likely to adhere at the membrane surface to avoid water, thus reducing membrane permeability.

Floc characteristics largely determine the type of pore clogging (Judd, 2011), and differ between CAS and MBR. Mean particle size for CAS is 160 um, while MBR have two mean particle sizes; around 10 um and 240 um (Judd, 2011). The particles of sizes around 10 um are mainly small colloids, particles and free bacteria, which causes complete, intermediate and standard blocking. The larger particles are flocs, which do not deposit onto the membrane due to size, however contribute to increased EPS levels and subsequent fouling (Judd, 2011). Membrane surface hydrophobicity and charge attracts hydrophobic flocs, increasing fouling (Judd, 2011).

Fouling can also be caused by clogging of aerators, leading to uneven aeration of the membranes and subsequent fouling (Le-Clech, 2010).

Pumping of the feed makes fouling more pronounced than for using vacuum pressure or air scouring, due to the higher permeate flux achieved and subsequent higher organic loading. Pumping of activated sludge also induces shear stress to microbial flocs, causing them to break-up, which leads to a decrease in particle size and releasing of foulant material from flocs (Radjenovic et al., 2007)

Fouling prevention

As permeate flow through the membrane is essential for the MBR system and its performance, it is of great importance to prevent and, if possible, amend fouling. Radjenovic et al. (2007) summarized the most common actions to take in the following five categories: pretreatment, physical or chemical cleaning, reducing flux, increase aeration and chemical or biochemical modification of the mixed liquor.

A method of preventing fouling is to keep high shear forces on the membrane surface. Typically, crossflow velocities of 2 – 3 m/s are sufficient to avoid formation of reversible fouling in pumped MBR systems (Lin et al., 2012). The parameter determining air scouring shear forces is the superficial gas velocity, which in a study for treatment of dyeing and printing paper showed to increase flux linearly between 0.011 – 0.067 m/s (Lin et al., 2012). Typical gas/water ratio for MBR application in industrial wastewater ranges between 10:1 to 50:1 (Lin et al., 2012).

Altering the process is another solution to the fouling problem. Reducing flux over the membrane, thus decreasing loading, prevents fouling but causes an increased demand of membrane area. The cost of a larger membrane area might not be more economic than fewer membranes with shorter life time (Radjenovic et al., 2007). The two alternatives are thus either to reduce flux by using a larger membrane area or using a smaller membrane area, which requires a high cleaning frequency, referred to as intermittent operation (Radjenovic et al., 2007). Most MBR systems treating municipal wastewaters are operated intermittently, with relaxation every ten minutes and chemical cleaning every few months (Radjenovic et al., 2007).

Further process changes can be made by altering the biological properties of the mixed liquor. If sludge age is changed, the release of EPS is affected, as it, as described above, depends on biomass properties. Addition of chemicals is the most common method to alter the mixed liquor properties (Radjenovic et al., 2007), usually preformed using flocculants or coagulants, such as powdered activated carbon, to encourage polymerization and thus reducing the amount of small foulants in the biotreatment tank (Radjenovic et al., 2007).

Regarding cleaning, fouling is classified into three practical categories depending on cleaning method; reversible, irreversible and irrecoverable. Reversible fouling is removed by physical cleaning (Radjenovic et al., 2007), such as back-flushing or relaxation. The permeate flow is reversed in back-flushing, and is shut off and replaced by air scouring in relaxation. Most full-scale MBR plants use relaxation rather than back-flushing (Radjenovic et al., 2007). Irreversible fouling is either removed by physical or chemical cleaning (Radjenovic et al., 2007) and is directed towards the strongly adsorbed foulants. Chemical cleaning is conducted using sodium hypochlorite and sodium hydroxide for organic foulants and with acidic solutions for removal of lime or other inorganic foulants (Radjenovic et al., 2007). Sodium hypochlorite at concentration 0.3% is the main chemical agent for organic foulants, and citric acid for the removal of inorganic foulants (Le-Clech, 2010). In chemical cleaning, the membrane is either soaked in the cleaning solution or back-flushed with it. Most MBRs are chemically maintenance cleaned once a week and recovery cleaned two times a year (Radjenovic et al., 2007). Irrecoverable fouling refers to fouling that cannot be undone, neither physical nor chemical, and is the type of fouling responsible for membrane life time. Some irrecoverable fouling always occurs. However, (Radjenovic et al., 2007) found that irrecoverable fouling occurs even under the critical membrane flux, in the sub-critical flux. Fouling at sub-critical flux starts with initial conditioning fouling, where foulants deposition occurs until the adhesive forces of the membrane, are equal to the scouring forces of the passing flow (Judd, 2011). Slow fouling follows, were irrecoverable fouling slowly increases the TMP over the membrane, and finally, when the fouling layer is thick enough, a sudden jump in TMP occurs, and the membrane permeability drastically decreases (Radjenovic et al., 2007). The flux where fouling occurs at an acceptable rate and no chemical cleaning is necessary is commonly referred to as sustainable flux (Le-Clech, 2010).

Results and type of cleaning is largely decided by choice of membranes; ceramic and cylindrical polymeric membranes are back-flushable, while flat sheet membranes are rather cleaned by relaxation (Judd, 2011). MBR systems equipped with HF membranes usually require the membrane tank to be drained before recovery cleaning, while MBR systems with FS membranes are commonly cleaned directly in the MLSS (Judd, 2011). General recommendations for cleaning can be seen in Table 4.

Table 4. Cleaning recommendations for HF, FS and MT membranes (EUROMBRA, 2005).

Cleaning	**Unit**	**HF**	**FS**	**MT**
Physical cleaning interval	*minutes*	10	10	N/A
Physical cleaning duration	*minutes*	1	1	N/A
Backflush flux	*LMH*	17	0	N/A
Chemical cleaning interval	*months*	6	6	6
Chemical cleaning duration	*hours*	2	2	2

As far as pretreatment, screening is necessary for most membranes. If there is high risk of debris entering the biotreatment basin after the pretreatment, the basin should be covered (Melin et al., 2006).

5.3 MBR DESIGN

The performance of any MBR system is dependent on the design of the two included technologies; membrane filtration and biotreatment, and how they are combined. The design, in its turn, is chosen based on the wastewater properties and desired contaminant removal. Membrane properties can be designed by choice of pore size, material, pretreatment and configuration. Biological treatment can be designed for removal of organic matter, nutrients and other contaminants by choice of redox environment and abiotic parameters.

For treatment of municipal wastewater, with comparable properties and target values for contaminant removal, there are a few standard operating parameter values for the design. For industrial use however, there is a lack of standard configurations and design parameters (Lin et al., 2012). Absolute operating parameter values can only be determined heuristically, for both municipal and industrial MBR systems (Judd, 2011), and pilot testing is always recommended for optimal design, considering removal rates and cost considerations (Lin et al., 2012). MBR configurations along with membrane and biotreatment design alternatives are presented below.

5.3.1 MBR configuration

The most common MBR systems are roughly divided into two main types, based on placement of the membranes (Judd, 2011). The first type consists of a bioreactor connected to an external membrane module, through which water is pumped. These MBR types are known as side-stream or recirculated MBR systems (rMBR) (Figure 10) and employ high crossflow velocities to achieve membrane flux (Lin et al., 2012). Crossflow velocities for rMBR systems are usually around 2 - 4 m/s (Le-Clech, 2010). The second type consists of a bioreactor with a membrane placed internally, from which permeate is either drawn by vacuum, or by air scouring (Lin et al., 2012). The bioreactor can also be pressurized to achieve permeate flow (Lin et al., 2012). MBR systems with internal membrane placement are referred to as immersed or submerged MBR systems (sMBR) (Figure 10). Other, less common MBR configurations include the air-lift rMBR, where air scouring is used for inducing permeate flow in a separate membrane tube (Judd, 2011).

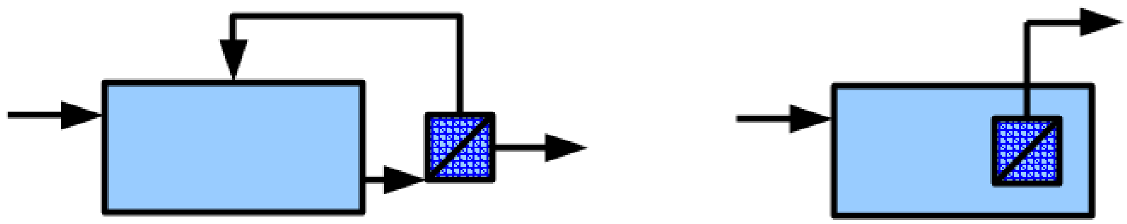


Figure 10. rMBR configuration with membrane unit placed externally, and sMBR configuration with membrane unit placed internally.

The sMBR can be designed with or without a separate compartment for the membranes, depending on aeration needs (Lin et al., 2012). Both rMBR and sMBR systems are designed for continuous flows of wastewater (Judd, 2011). For both types, the MLSS concentration is regulated by an outlet, preferably placed at the bottom of the bioreactor.

The membrane modules are generally placed in the aerated compartment, but can also be placed in the anaerobic or anoxic compartments (Judd, 2011). An advantage of membrane module placement in the aerated compartment is that the aeration can be jointly used for oxygen transport to microorganisms and air scouring.

The sMBR, when no extra compartment is used, requires the least space of the three and can be used in already existing biotreatment. The rMBR, being located externally, has the advantage of being easily accessible for maintenance, and can also be applied to already existing treatment plants.

Removal of excess sludge, and thus controlling the MLSS level in the biotank, is performed by the opening of an outlet in the bottom of the biotank.

Steps preceding the membrane bioreactor, regardless of choice of biotreatment, may include mechanical separation, chemical treatment and/or filtration depending on the wastewater properties and desired removal efficiency.

5.3.2 Membrane design

When applied in MBR systems, membranes are assembled into what is generally referred to as membrane modules, which include aeration ports, permeate flow connections and, if used in sMBR systems; supporting frames. Membrane modules are designed to have high water purification abilities, be cost-efficient and not be too space consuming. There are three main types of membranes, assembled into modules, which are used in MBR systems; hollow fiber (HF), (multi)tubular (MT) and flat sheet (FS) (Judd, 2011).

As the membrane types listed above have different properties that affect flux and limit transmembrane pressure, they can be considered less or more suitable for sMBR and rMBR configurations. Membrane modules operated under low pressure are appropriate for sMBR configuration, while those operated under high pressure are best suitable for rMBR (Table 5).

Table 5. Membrane types and main application (Melin et al., 2006; Radjenovic et al., 2007)

Membrane type	**sMBR**	**rMBR**
Hollow fiber	X	X
(Multi)Tubular	-	X
Flat sheet	X	-

HF membranes are cylindrical and usually assembled into frame-type modules (Figure 11), connected to a permeate outlet in one or both ends. Permeate is driven inwards through the membrane using vacuum, air scouring or using a pressurized bioreactor (Radjenovic et al., 2007). HF membranes are generally cheaper than MT and FS membranes, but are more prone to clogging (Le-Clech, 2010).

Figure 11. Left to right: Outside to inside permeate flow of HF membranes, PURON® single-headed HF membranes and PURON® HF modules.

MT membranes are assembled and contained in cylindrical pressure vessels (Figure 12), where permeate flows outward through the tubular membranes and into an outlet (Radjenovic et al., 2007). Both HF and MT membranes are mainly made of polymeric material (Judd, 2011).

Figure 12. Left to right: Inside to outside permeate flow of MT membranes, Wehrle MT membranes and Wehrle MT membrane modules at site.

FS membranes are put together into plate and frame-modules (Figure 13) and can be of either polymeric or ceramic material (Judd, 2011). Permeate is derived using inward transportation, and is driven by vacuum, air scouring or using a pressurized bioreactor (Radjenovic et al., 2007)

Figure 13. Left to right: Outside to inside permeate flow of FS membranes, KUBOTA® FS membrane and the KUBOTA Submerged Membrane Unit®.

There are numerous membrane manufacturers, and as the market for MBR technology expands, many more are expected to appear. A list of manufacturers producing membranes for industrial wastewater treatment, and who are active in Europe, is presented in Table 6.

Table 6. Membrane manufacturers active in Europe (MBR Network, 2012).

	Manufacturer	Name	Material	Filtration	Country	Web page
HF	Koch	Puron[1]	Polymeric	UF	US	www.kochmembrane.com
	Martin Systems	siClaro[1]	Polymeric	UF	DE	www.martin-systems.de
	GE water	ZeeWeed[1]	PVDF	UF	US	www.gewater.com
	Polymem	-	PES	MF/UF	FR	www.polymem.fr
	Mitsubishi	Sterapore	PVDF	UF	JP	www.mrc.co.jp
	Siemens	Memcor	PVDF	UF	DE	www.water.siemens.com
MT	Wehrle	Biomembrat[1]	PES	MF/UF	UK	www.wehrle-env.co.uk
	Tami industries	InsideCéram	Ceramic	MF/UF	FR	www.tami-industries.com
	Likuidnanotek	Likuid[1]	Ceramic	MF/UF	ES	www.likuidnanotek.com
	Triqua	SubTriq[1]	PVDF		NL	www.triqua.eu
FS	Kubota	Kubota[1]	Polyethene	MF	JP	www.kubota-mbr.com
	Eflo	EfloMBR[1]	PVDF	UF	UK	www.eflo.com
	Triqua	MaxFlow[1]	PDVF/PES	MF/UF	NL	www.triqua.eu
	Microdyn-Nadir	BIO-CEL	PES	UF	DE	www.microdyn-nadir.de
Others	Alfa Laval	Hollow Sheet	PVDF	UF	SE	www.alfalaval.com
	Martin Systems	siClaroDM[1]	Polymeric	MF	DE	www.martin-systems.de
	Grundfos	BioBooster[1]	Ceramic	UF	DK	www.grundfos-biobooster.com

1 = Complete MBR system available.

The expected lifetime of membranes is affected by loss of membrane integrity, which can occur due to chemical oxidation by cleaning chemicals, faulty installation, and presence of abrasive or sharp-edged materials in the feed and faulty membrane structure (Le-Clech, 2010). Le-Clech et al. (2010) found the MBR technology not to be mature enough to predict membrane lifetimes; however membrane suppliers offered specific lifetime guarantees between 3 – 8 years. Modeling membrane ageing is currently not possible, as physical and chemical characterizations are not yet complete (Le-Clech, 2010).

To calculate required membrane area, sustainable flux and peak flux through the membranes are used. Knowing the required membrane area gives an indication of minimum tank volume. Manufacturer guidelines on necessary air scouring of the membranes are used for dimensioning of aeration system, which can be combined with aeration for biotreatment. The tank volumes of the MBR system should always be dimensioned according to the biotreatment, as it is the most time consuming process (Van Dijk and Roncken, 1997).

5.3.3 Biotreatment design

The design of biotreatment is, as for membrane design, dependent on wastewater quality and required contaminant removal. The biotreatment process can be designed to be solely aerobic or anaerobic, and if nitrogen and/or phosphorus content are to be reduced, additional basins can be added. If space is limited, both aerobic and anoxic environments can be created in one basin by intermittent aeration, where aeration is preformed periodically.

Lin et al. (2012) found no difference in biotreatment efficiency between HF and FS sMBR systems, which implies that membrane type is not to be considered during biotreatment design. Biotreatment processes are however, affected by variations of feed properties, loading rates and abiotic properties such as temperature and pH.

A general rule for determining tank volumes for biotreatment is that the most slow-growing biological process determines the tank volume. The microorganisms that perform the slowest process must thus at least remain in the tank the time the process takes, which is why one of the most important design parameters of biotreatment systems is the mean cell-residence time, also referred to as sludge retention time or sludge age. It describes the duration of stay of an average cell in the biotreatment tank.

In anaerobic systems, microorganisms reproduce slower than in aerobic systems, why the sludge age is required to be higher than for aerobic systems. Using membrane filtration in MBR technology however, allows microorganisms to be retained in the biotreatment compartment for a long period of time, and thus eliminates sludge age as a critical parameter. Sludge age in MBR systems ranges between 5 days to infinity, but is commonly set to around 25 days (Melin et al., 2006; Le-Clech, 2010; Judd, 2011; Lin et al., 2012).

The biotreatment tank volume can also be calculated to achieve a desired organic loading rate (OLR), being the amount of organic matter introduced to the biotreatment over a specific period of time. For MBR systems, an OLR of 2 $kgCOD/m^3d$ is generally recommended (Ujang, 2003). Accordingly, the biotreatment tank volume can be determined by

$$V = \frac{QCOD_{in}}{OLR} \qquad (9)$$

where V is the tank volume, Q is the wastewater flow, COD_{in} is the COD concentration of the influent wastewater and OLR the organic loading rate.

To ensure that the biotreatment functions properly, addition of nutrients might be required. A rule-of-thumb is to set the nutrient ratio for BOD:N:P at 100:5:1 (Teixeira et al., 2005). The nutrient ratio can also be expressed as COD:N:P, and is commonly set to 100:2.5:1 (Judd, 2011). Variations on nutrient ratios are for example COD:N:P ratios of 100:2.6:1 (Lin et al., 2012) and 280:5:1 (Hall et al., 1995).

Another aid in designing MBR biotreatment is to use computer models. The activated sludge model No. 1 (ASM1) is adapted for CAS, but can be modified to fit MBR biotreatment by taking into account biomass kinetics and the build-up of resistance to describe membrane fouling (Lee et al., 2002). Other possibilities for modeling MBR systems have been studied, such as the usage of the program Urban Water Research (URWARE), using 84 parameters to simulate mass and energy flows (Hessel, 2005). The existing models however, require validation and further development (Ng and Kim, 2007).

5.3.4 Pretreatment

Screening is always advisable for MBR systems. Especially double-headed HF modules are prone to aggregate fibers and debris in the top (Radjenovic et al., 2007). It is however always advisable to remove large debris, objects and particles before MBR treatment (Judd, 2011). A woven mesh type siege was proven to be more efficient than wedge wire sieves (1 mm) in a German municipal MBR (Melin et al., 2006), and a Swedish distributor of MBRs consistently recommends a drum screen (3 mm) as pretreatment for municipal MBR systems with HF membranes (Hotz, 2012). In a pilot scale MBR using FS membranes, a drum screen with 0.4 mm pores provided satisfactory removal of particles and debris (Bengtsson, 2012).

5.4 MBR PERFORMANCE

Since MBR technology first appeared on the market, much research has been made, and many full-scale and pilot-scale MBR systems have been installed. Since the 90’s, MBR technology has been used for municipal wastewater treatment, consistently showing excellent contaminant removal (Holler and Trösch, 2001). With the ability to successfully treat industrial wastewater, which generally is of higher organic matter concentration, MBR technology for industrial use gained speed in the early 00’s (Lin et al., 2012). Recently, a growing interest for MBR implementation in the pulp and paper industry can be seen, and several studies, pilot and full-scale plants show feasibility (Lin et al., 2012). The performance of MBR technology is presented for municipal, industrial and pulp and paper application respectively.

5.4.1 Municipal application

The increased awareness of water scarcity in the world has contributed to the implementation of MBR systems for the treatment of municipal wastewater. In addition to high removal efficiency of contaminants (Table 7), the membrane filtration also forms a barrier for bacteria and viruses, which contributes to the disinfection of the wastewater (Melin et al., 2006).

Table 7. MBR removal efficiencies and outlet effluent quality for treatment of municipal wastewater, as compiled by (Melin et al., 2006)

Parameter	**Removal efficiency (%)**	**Effluent quality (mg/L)**
TSS	>99	<2
COD	89-98	10-30
BOD	>97	<5
N-tot	36-80	<27
P-tot[1]	62-97	0.3-2.8

[1] = With a dosage of ferric

Mohammed et al. (2008) investigated the performance of an anoxic-aerobic sMBR under different operating conditions, including sludge age (30 – 35 days), OLR (606, 1440 and 2500 mg/L), MLSS (9980 and 26720 mg/L), and found that it was stable and thus recommended it for municipal wastewater with varying contaminant concentrations. Varying sludge age was further investigated by Pollice et al. (2008), who found that the COD removal in municipal wastewater, using a sMBR, increased at sludge ages 20 through 80 (92 – 94 %) to, but decreased at complete retention (86 %).

In an attempt to further improve COD removal efficiency in MBR treatment on municipal wastewater by the adding of 0.5 g/L powdered activated carbon, it was increased from 96.5 % to 98.9 – 99.9 % (Cao et al., 2005).

MBR technology for municipal wastewater treatment is thus advantageous compared to CAS in terms of effluent quality but, as for all applications of MBR, requires frequent monitoring and maintenance (Melin et al., 2006).

5.4.2 Industrial application

The water quality parameter that differs the most between industrial and municipal wastewaters is the organic matter content, usually ranging between 250 – 800 mg/L for municipal wastewater and >1000 mg/L for industrial wastewater (Lin et al., 2012). In principle, high COD values can be treated with high enough HRTs. Typical HRT values for treatment of industrial wastewater using MBRs are 0.5 – 3 and 2 – 10 days for aerobic and anaerobic treatment, respectively (Lin et al., 2012).

MBR treatment of industrial wastewater shows similar COD removal efficiencies to those of municipal wastewater. Artiga et al. (2005) studied treatment of winery wastewater with high organic matter content and tannery wastewater with low organic matter content in a sMBR, which proved high efficiency; COD removal above 97 % and 86 %, respectively.

Several studies have shown MBR technology to be well suitable for wastewaters with high organic matter content. Holler and Trösch (2001) showed a COD reduction above 95% in a ceramic rMBR system with MLSS concentration of 10000 – 22000 mg/L and 1.5 hour HRT, even as organic loading rate varied between 6 – 13 kgCOD/m^3day. A similar result was presented by Mohammed et al. (2008), where organic matter and nitrogen was removed using a sMBR with 8 hours HRT and a sludge age of 30 – 35 days; COD removal varied from 97.8 – 99.9 %, BOD removal between 98.9 – 99.9 % and NH3-N removal between 91.0 - 99.9 % at MLSS levels between 9980 – 26720 mg/L. Another study showed that high COD removal (above 95 %) was achieved with COD/N ratios varying between 5.3 – 9.3, thus indicating that COD removal is irrespective of COD/N ratio (Zhimin et al., 2009). Full-scale MBR systems show similar results, and COD removal efficiencies are consistently high (Table 8).

Table 8. Full-scale MBR performance in various industrial wastewaters (Lin et al., 2012).

Wastewater origin	**MBR type**	**OLR** *kgCOD/m^3d*	**Volume** *m^3*	**MLSS** *g/L*	**HRT** *d*	**Feed** *kgCOD/m^3*	**Removal** *% COD*
Wheat starch waste	An rMBR MT	2.1	2000	10	-	-	78
Maize-processing	An rMBR MT	2.9	2610	21	5.2	15	97
Sugar manufacturing	Ae sMBR FS	-	5000	9.3-15.7	-	0.05-6	>90
Winery	Ae sMBR FS	-	300	-	-	5-77	high
Tannery	Ae rMBR MT	-	680	10-20	1.5	2.99	95
Landfill leachate	Ae rMBR MT	-	-	25-35	-	1.5-3.5	-
Automotive oily	Ae rMBR MT	-	1100	8	2-5	3-4	>92
Laundry	Ae sMBR FS	-	-	3-9	0.83-1.25	0.7	90

1 = Calculated

The biogas produced by anaerobic biotreatment of high organic content wastewaters, was found to cover the energy demand of pumping feed in an rMBR (Fuchs et al., 2003). Three types of high organic content wastewaters (COD concentrations varying between 9700 - 29100 mg/L, 5800 - 20150 mg/L and 40700 - 64600 mg/L) treated in an anaerobic rMBR showed excellent COD removal rates while producing high methane yields (Fuchs et al., 2003).

5.4.3 Pulp and paper application

Wastewater from the pulp and paper industry can be challenging to treat, as it often contains high levels of organic matter and suspended solids, and usually is of high temperature, as described in chapter 4.2.1. The performance of MBR technology for different applications in the pulp and paper processes have been studied, and overall, reviews indicate that it is, in most cases, feasible (Pokhrel and Viraraghavan, 2004; Lin et al., 2012). High quality effluent and the possibility of internal reuse are identified as the primary driving forces for the increasing interest in MBR technology (Lin et al., 2012). Pokhrel and Viraraghavan (2004) stated that both aerobic and anaerobic treatment systems are feasible for treatment of wastewater from all types of pulp and paper mills, with the exception of anaerobic treatment of bleached kraft effluent, as anaerobic microorganisms are more sensitive to toxic substances than aerobic microorganisms. Anaerobic treatment has however shown to be well suited for treatment of pulp and paper wastewater, used in either sMBR or rMBR, where in sMBR the produced biogas can be used for membrane scouring (Lin et al., 2012). Overall, thermophilic biotreatment generated effluent of comparable quality to that of mesophilic biotreatment, but membrane fouling was found to be more frequent for the former (Lin et al., 2012). Economic analyses suggested that thermophilic MBR treatment of foul condensate had lower operational operation costs as compared to a steam stripping system (Lin et al., 2012). Removal efficiencies observed in twelve studies of MBR application for pulp and paper wastewater ranged between 82 - 99 % for COD and almost 100 % for TSS, with HRTs ranging between 0.12 – 2.5 days (Lin et al., 2012).

On the downside, Mahmood and Elliott (2006) found MBR technology for the reduction of sludge production of the pulp and paper industry, although technically feasible, not economically justified. Zhang et al. (2009) found that pulp bleaching effluent treated in a HF sMBR could not be reused in the papermaking process without further treatment of RO (Zhang et al., 2009).

Recent lab-scale and pilot-scale studies on pulp and paper wastewater treatment, and the results obtained can be seen in Table 9. Two studies were performed using ceramic membranes, and the others using polymeric materials.

Table 9. Summary of MBR performance for treatment of pulp and paper industry wastewaters.

Wastewater	**MBR type**	**MLSS** *kg/m³*	**Temp** °C	**Volume** *m³*	**Feed** *kgCOD/m³*	**Removal** *% COD*	**Reference**
Foul kraft cond.	An sMBR FS	10	37-55	0.01	10	97-99	Lin et al., 2009
Synthetic cond.	Ae rMBR MT	10	55-70	0.008	1	>99.5	Berube et al., 2000
Foul kraft cond.	Ae sMBR HF	3	35-55	0.004	5	87-97	Texeira et al., 2005
Paper mill ww	Ae rMBR HF	11.2	-	-	1	86	Galil et al., 2003
Paper mill ww	Ae rMBR	-	-		3	91.7	Gommers et al., 2007
Paper mill ww	Ae sMBR FS	15	-	9	1	89	Lerner et al., 2007
Paper mill ww	Ae sMBR HF	8	25-34	10	0.6	91.7	Zhang et al., 2009

There are a few full-scale MBR systems installed for application in the pulp and paper industry, amongst them is in Papeterie du Rhin, France. The ZeeWeed® MBR system was built in the year of 2000, and is of sMBR configuration equipped with HF membranes from ZENON Membrane Solutions, part of GE Water & Process Technologies. The MBR is installed to have the capacity to treat a wastewater flow of 900 m^3/day, which is pretreated using drum screens and an equalization basin. The permeate flow is driven by vacuum pressure, and 30 – 80 % is recycled in other processes. The MBR is operated at MLSS concentrations between 8 and 16 g/L and achieves 95 % COD reduction and BOD levels under 5 mg/L. The main reason for choosing MBR treatment was on-site space limitations and the recycling possibilities (GE Water & Process Technologies, 2008).

Another reason for installing MBR technology is wastewater reduction. The McKinley Paper Company in USA and Köhler Paper Company in Germany, both installed full-scale MBR systems by Siemens Water Technologies. The McKinley Paper Company uses MBR in combination with RO to achieve almost total recycling of the process water. The paper mill produces 190000 ton recycled linerboard per year and only uses 7 % of the water usually used by plants of its size. Köhler paper mill produces cardboard, 40000 ton/year, and due to challenging effluent quality standards chose to install MBR and RO. The effluent quality was significantly improved, and recirculation of process water was made possible, reducing water usage by 75 % (Wagner, 2010).

The first thermophilic MBR was built for the VHP paper mill in Ugchelen, Netherlands, in the year 2000. The MemTriq® rMBR is designed for a flow of 12 m^3/h and is operated at 55°C with wastewater from the bleaching process, with a COD concentration of 4.5 g/L. No excess sludge is produced, and a COD reduction of over 85 % is commonly achieved. The MBR is preceded by a dissolved air flotation (DAF) step for the reduction of fibers and debris. The treated wastewater is then recycled for reuse in the bleaching process (Triqua, 2002).

6 CASE STUDY

This case study aims to use the knowledge acquired in the literature study on MBR treatment to identify and evaluate three MBR implementations at Korsnäs, as compared to the present treatment as well as one treatment previously calculated by ÅF.

6.1 BACKGROUND

Improvement of the external wastewater treatment at Korsnäs pulp and paper mill (Korsnäs) is currently under investigation by Korsnäs and ÅF, where different options are evaluated based on performance and cost.

6.1.1 Korsnäs pulp and paper mill

Situated in Gävle bay, in the east of Sweden, the Korsnäs mill is one of the largest producers of pulp and paper in Sweden, and has been active since the beginning of the 20^{th} century (Korsnäs, 2008). The Korsnäs mill is currently allowed to produce 700 000 air dry ton of kraft pulp per year (Adt/year). The produced kraft pulp is used for the manufacturing of paper and carton board products onsite, forming an integrated system. Out of the total kraft pulp produced, 57 % is bleached and 43 % unbleached (Sivard, 2008).

The production is distributed onto three fiber lines (FL 1, 2 & 3) and three paper machines (PM 2, 4 & 5). Two of the fiber lines (FL 1 & 2) are used to produce unbleached kraft pulp from pine wood, while the third (FL 3) is used to produce bleached kraft pulp from pine and birch, altered approximately every 24 hours. The three paper machines produce paper and carton boards, depending on the produced pulp.

Bleaching of the pulp is performed using the ECF method, thus generating wastewater containing both AOX and chlorate. Compared to other Swedish kraft pulp mills using ECF bleaching, the Korsnäs mill is one of the largest process water users (Figure 14), and subsequently does not meet the BAT standards of 30 – 50 m^3/Adt.

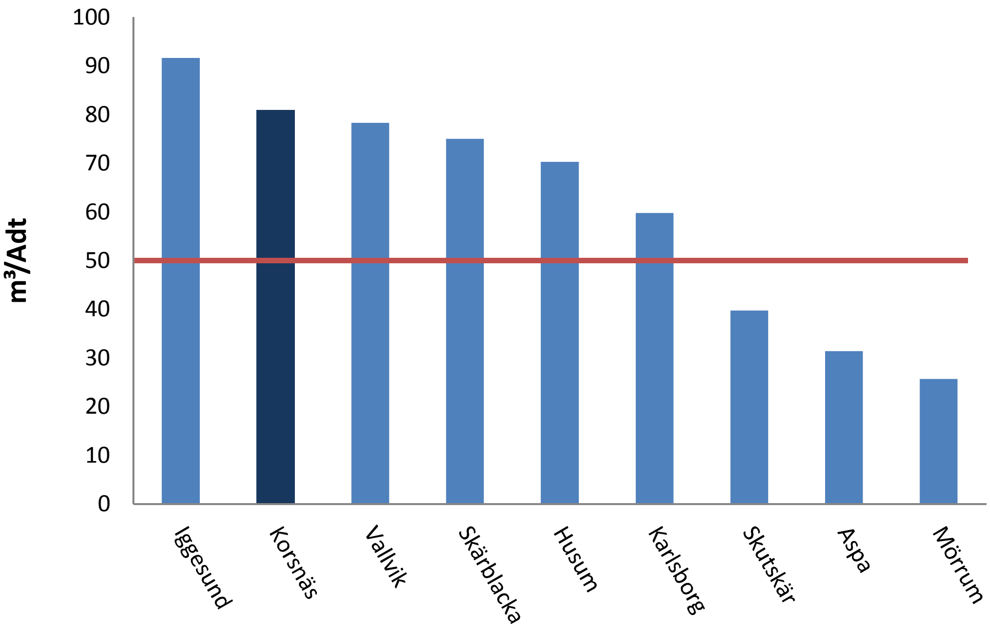


Figure 14. Process water consumption per air dry ton (Adt) in Swedish ECF kraft pulp mills 2010 (Skogsindustrierna, 2011). The red line represents the highest value of the BAT standard interval.

6.1.2 Wastewater effluent quality

While measures for reducing process water quantity are being reviewed by Korsnäs, the main focus of improvement however, is on the quality of the wastewater treatment effluent. The threshold values for effluent quality at Korsnäs were, at the time of writing, under review in The Swedish Environmental Supreme Court, and were to be set in the summer of 2012. The emission levels from 2010 exceeded BAT emission levels (Table 10).

Table 10. Emission levels relative to pulp production. NVV propositions are based on allowed production of 700,000 Adt/year. Emissions 2010 are measured by Korsnäs and reported to Skogsindustrierna.

Parameter	**Unit**	**BAT technology[1]**	**Emissons 2010[2]**
COD	*kg/Adt*	10	20
TSS	*kg/Adt*	1.8	3.7
Tot-N	*g/Adt*	150	333
Tot-P	*g/Adt*	10	26

[1]= Adapted from to BAT regulations. [2]= As presented by Skogsindustrierna (2011).

6.1.3 Present external wastewater treatment

The present external wastewater treatment is located next to the Korsnäs mill and consists of an aerated lagoon (AL) preceded by four primary clarification basins for sedimentation (C1, C2, C3 & C4) and followed by a final clarification basin (FC) (Figure 15).

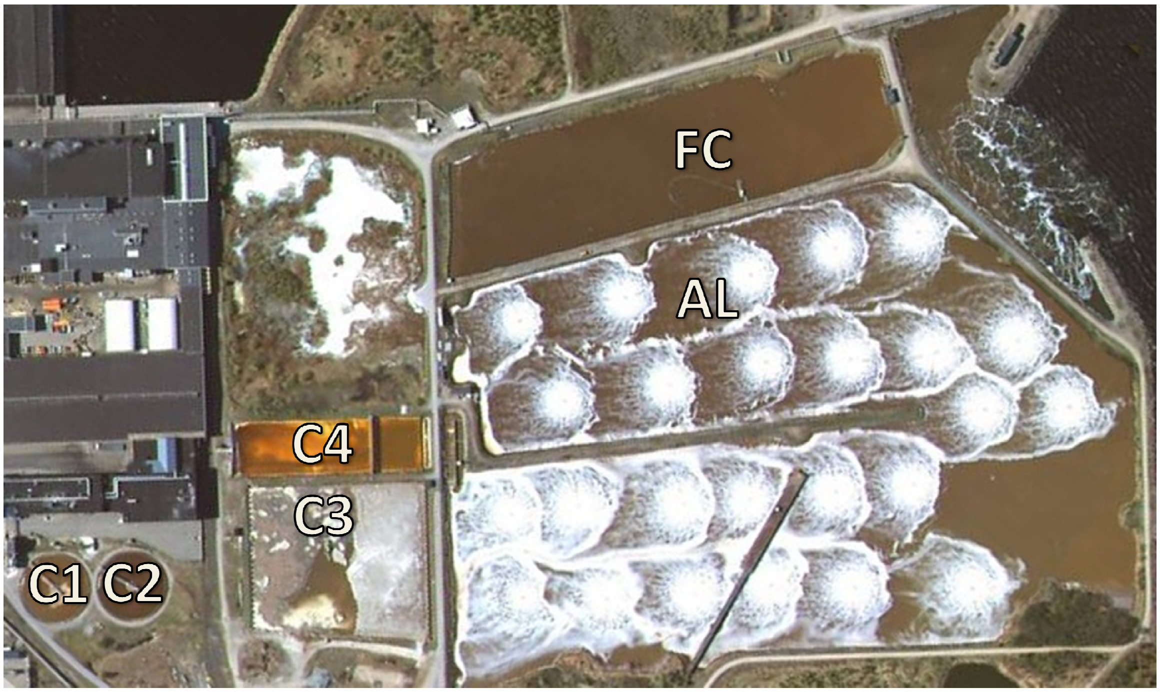


Figure 15. An overview of the external wastewater treatment at Korsnäs. The wastewater treatment includes clarifier 1, 2, 3 and 4 (C1, C2, C3 and C4), the aerated lagoon (AL) and the final clarifier (FC) (© Lantmäteriet, permission I2012/0021, 2012).

The aerated lagoon consists of an anoxic zone for chlorate reduction, followed by an aerobic zone for the reduction of organic matter and nutrients. The chlorate reduction is improved by the adding of urea, and the aerobic zone is oxygenated by the use of 26 surface aerators, all of 55 kW effect. Wastewater entering the aerated lagoon is of temperature around 37 °C, and is reduced to about 20 – 30 °C when exiting, depending on season. The final clarification basin (FC), of volume 30000 m^3, leads to a 120 m wide air curtain, where the treated water is mixed with sea water.

The transport of wastewater into the primary clarification basins and subsequently the aerated lagoon and final clarification basin is divided into three main pipes; the fiber line pipe (FLP), the bleach effluent pipe (BLP) and the miscellaneous pipe (MLP) (Figure 16).

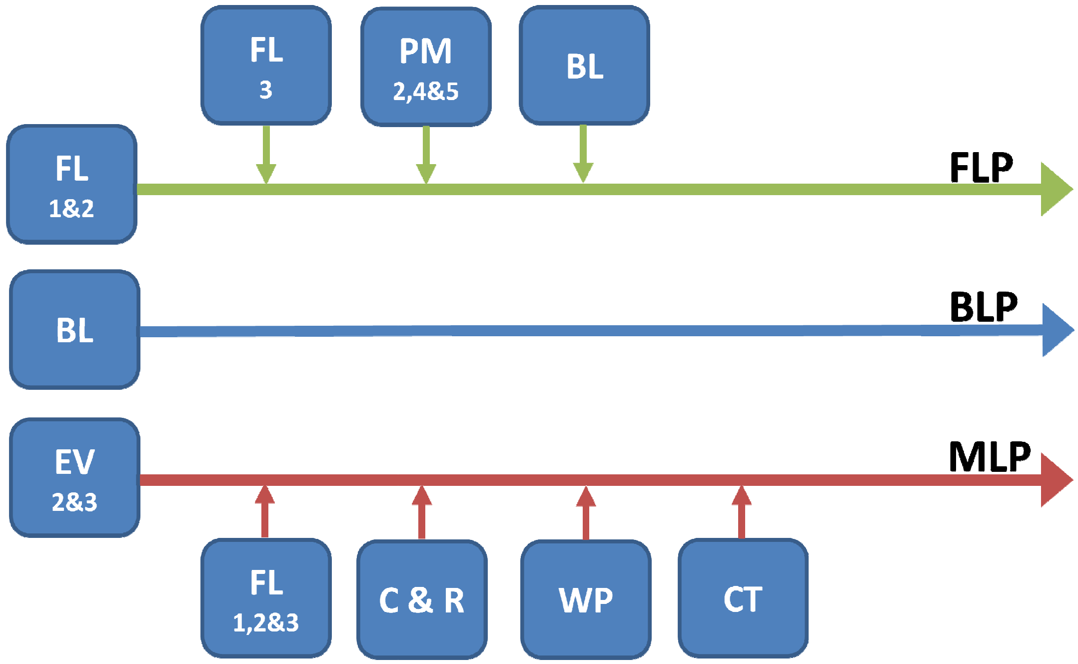


Figure 16. The three main pipes in the process wastewater transport at the Korsnäs pulp and paper mill; the fiber line pipe (FLP) containing wastewater from the fiber lines (FL), paper machines (PM) and bleaching effluent (BL); the bleaching pipe (BLP) containing wastewater from the bleach treatment (BL); miscellaneous pipe (MLP) containing wastewater from the evaporation (EV), the fiber lines (FL), causticizing and resin (C & R), wood preparation (WP) and the collection tank (CT).

FLP carries wastewater from the three fiber lines (FL 1, 2 & 3), the three paper machines (PM 2, 4 & 5) and a minor part of the bleach plant effluent (BL). The FLP wastewater is thus principally characterized by high suspended solids content (Table 11), which is mainly comprised by fibers.

BLP carries the major part of the bleach plant effluent (BL), and thus, along with organic matter, contains AOX and chlorate, and has a low pH value.

MLP carries wastewater from a variety of stages in the production of pulp; two evaporation plants connected to recovery boilers (EV 2 & 3), half the effluent from the three fiber lines (FL 1, 2 & 3), the causticizing and resin treatments (C & R), the wood preparation (WP) and a collection tank mainly containing evaporation effluent (CT).

All three main pipes have high flows, amongst which MLP has the highest (Table 11).

Table 11. Flow and contaminant concentrations in the three main pipes BLP, FLP and MLP (Korsnäs, 2012)

Parameter	**Unit**	**FLP**	**BLP**	**MLP**
BOD	*mg/L*	-	270	150
COD	*mg/L*	390	860	310
TOC	*mg/L*	110	350	90
TSS	*mg/L*	570	40	250
Tot-N	*mg/L*	1.7	2.3	5.0
Tot-P	*mg/L*	0.3	1.7	0.3
Flow	m^3/h	1400	900	2800

Wastewaters from all three main pipes are eventually destined for the aerated lagoon, but are, due to their diverse properties, initially transported to different clarification basins (Figure 17). The fibrous wastewater from FLP is directed into C1 and C2 for reduction of suspended solids by settling. The effluent from C1 and C2 is then transported into C3, where it is mixed with wastewater from MLP and retained for 8 hours before entering the aerated lagoon. The bleaching process effluent carried by BLP has a low pH value and high temperature, why it is directed into the separate basin C4, where it is retained for 12 hours before entering the aerated lagoon. The hydraulic retention time of the aerated lagoon and the final clarification basin is 4 to 5 days and 15 hours, respectively.

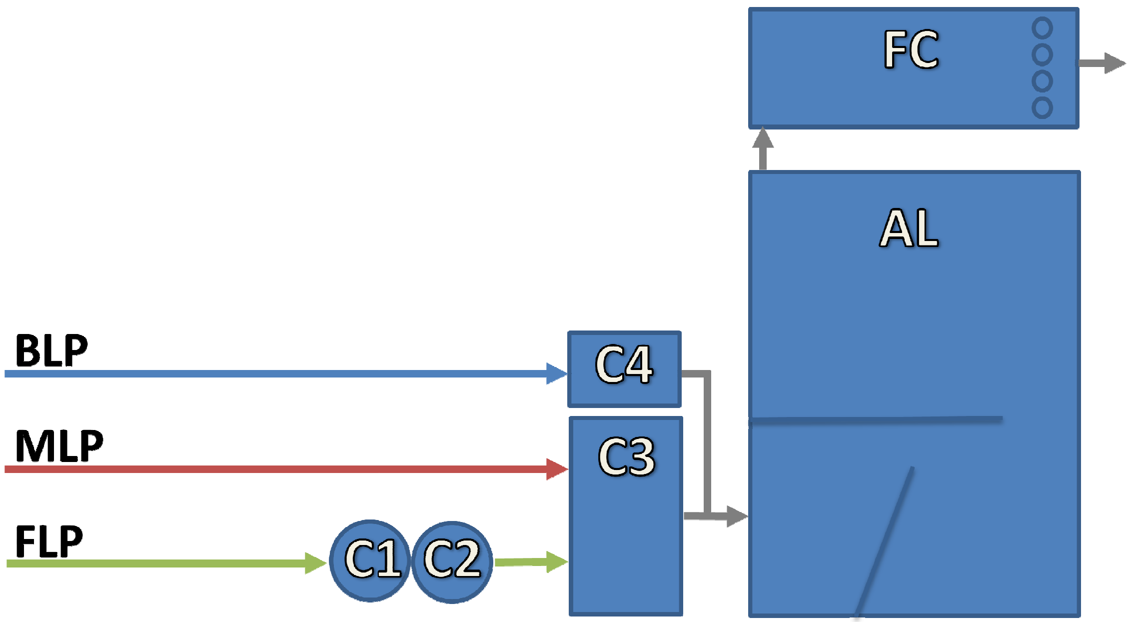


Figure 17. Present wastewater treatment at Korsnäs pulp and paper mill.

Removal of organic matter and suspended solids is achieved in all basins, including the aerated lagoon (Table 12). Nutrient content removal, is because of its dependency on biomass production, only achieved in the aerated lagoon, and is thus coupled with organic matter removal. No measurement data was collected in between C1 and C2, nor AL and FC, why they are presented jointly. Removal of nitrogen in AL is not achieved, but rather occurs in FC.

Table 12. Reduction of suspended solids (TSS). organic matter (COD, TOC & BOD) and nutrients (N & P) in the wastewater treatment basins at Korsnäs.

Parameter	Unit	C1 & C2	C3	C4	AL & FC
TSS	%	85	45	10	-
COD	%	15	15	5	41
TOC	%	15	15	5	42
BOD	%	10	10	5	80
Tot-N	*kg/t CODred*	-	-	-	5
Tot-P	*kg/t CODred*	-	-	-	1.8

Apart from the three main pipes, there is a pipe for transporting clean process water directly into the sea. As no treatment is necessary for the clean water pipe, it will not be further considered.

6.1.4 Identification of sites for further wastewater treatment

For the evaluation of technical and economical feasibility of implementing an MBR in the external wastewater treatment at Korsnäs, three alternatives were identified, along with one alternative previously calculated by ÅF (Figure 18). The new wastewater treatment systems were applied on the following process flows:

1. FL1&2: The effluent from the two fiber lines producing unbleached kraft pulp from pine wood in FLP
2. BL: The effluent from the bleaching of pine and birch kraft pulp in BLP
3. CT: The effluent from condensate from evaporations, collected in the collecting tank in MLP

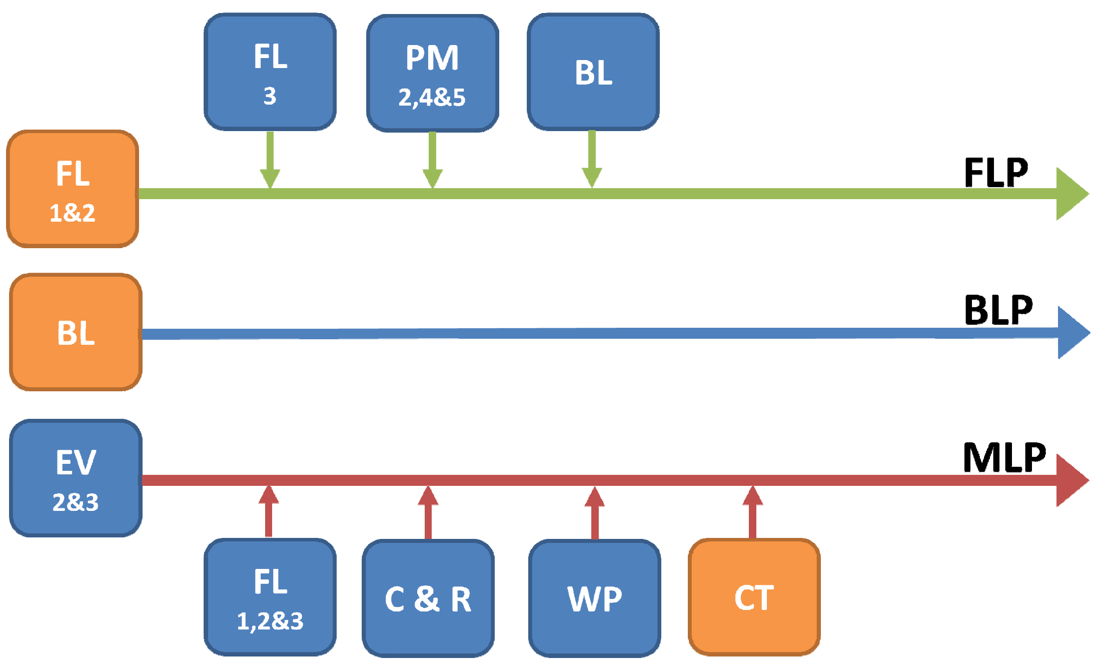


Figure 18. Sites for application of additional wastewater treatments technology (orange colored)

The three identified flows all originate from different processes, and thus have varying properties; the wastewater from the two fiber lines in FLP contain large amounts of fibers, measured as TSS; the pulp bleaching wastewater in BLP is of high pH and temperature, and contains both AOX and chlorate; and the evaporation condensate in the collection tank in MLP contains large amounts of organic matter, measured as COD. All three process flows are of high temperature, estimated to 55, 70 and 75 °C for FL 1 & 2, BL and CT respectively.

6.1.5 Layout of sites for further wastewater treatment

Each alternative implementing an MBR system was calculated for three types of configurations. The MBR configurations chosen for application at Korsnäs are the following three:

- An sMBR system equipped with hollow fiber (HF) membranes
- An sMBR system equipped with flat sheet (FS) membranes
- An rMBR system equipped with microtubular (MT) membranes

The biotreatment for all MBR configurations was chosen to be aerobic, due to the many references available for it, and the process is chosen to be performed under thermophilic (55 °C) conditions, to minimize cooling costs. The three types of membranes, HF, FS and MT, were chosen for calculations, as they are the most commonly used, as described in chapter 5.3.2.

The HF and FS sMBR systems were chosen to be designed with a separate compartment for the membrane module (Figure 19), to allow dimensioning of membrane tank and biotreatment tank, separately. The MT rMBR configuration is recirculated (Figure 19).

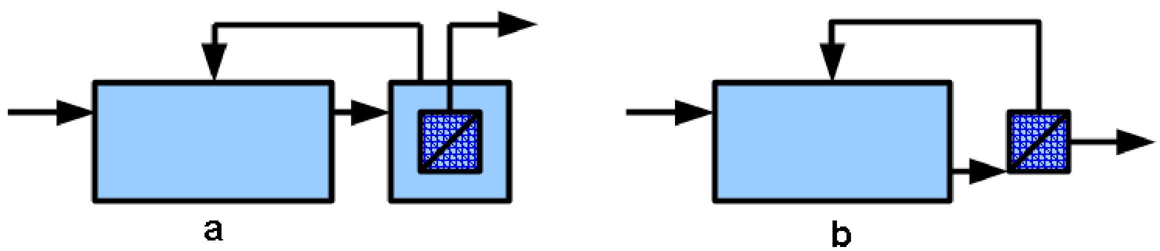


Figure 19. MBR configurations for application at Korsnäs: a) sMBR with separate compartment for membrane modules (HF and FS). b) rMBR (MT).

Each process flow was thus calculated for implementation of three types of MBR systems; HF, FS and MT, of which HF and FS are designed with a separate membrane compartment and MT were designed as an external module.

Alternative 1: FL 1&2

The first alternative was to implement MBR on the wastewater flow from FL 1 & 2 in FLP (Figure 20). In the current wastewater treatment, FLP is firstly directed into C1 & C2, followed by C3, the aerated lagoon and the FC. For implementation of an MBR, the pipes connecting FL 1 & 2 to FLP were removed and redirected to an MBR on site. Removing FL 1 & 2 from the FLP would reduce the organic loading on C3, AL and FC. As FL 1 & 2 has a high concentration of TSS, a drum filter pretreatment will be added. MBR treated water was considered clean, and was thus directed to the sea, where it was mixed with effluent water from the final clarification and sea water.

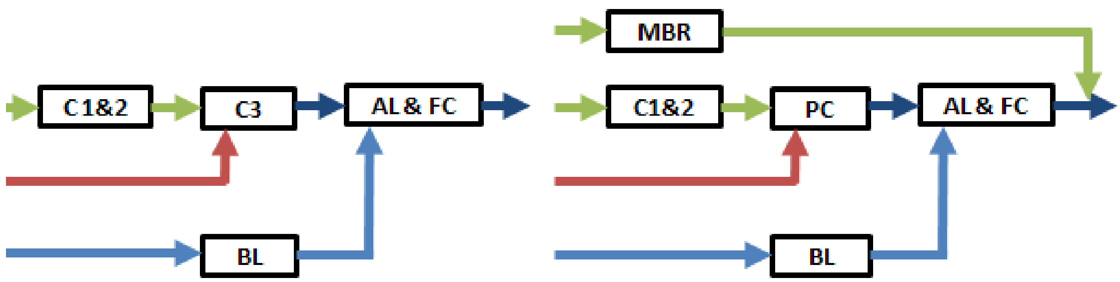


Figure 20. The site for MBR application in FLP.

The effluent is of high COD and TSS concentration, >900 mg/L and >700 mg/L respectively (Table 13). Of the total wastewater flow in FLP, FL 1 & 2 are responsible for 16.5 %, with a joint flow of 234 m^3/h. Average temperature of the water is estimated to 55 °C.

Table 13. Water quality parameters in FLP measured by Korsnäs 20.2- 26.2, 2012.

Parameter	Unit	FL 1&2	FL 3	PM 2,4&5	BL
BOD	*mg/L*	**-**	-	-	-
COD	*mg/L*	**910**	450	140	160
Tot-N	*mg/L*	**12**	2	2	1
Tot-P	*mg/L*	**1.6**	0.1	0.2	0.2
TOC	*mg/L*	**300**	150	44	57
TSS	*mg/L*	**730**	-	420	-
Flow	*m^3/h*	**230**	26	650	160

Alternative 2: BL

The second alternative is implementation of MBR on the wastewater flow from BL in BLP (Figure 21). In the current wastewater treatment, BLP is directed into the bleach effluent clarification basin and transported into the aerated lagoon and the following final clarification basin. The implementation of an MBR would eliminate the need for the bleach water clarification basin and reduce the loading on both AL and FC. The MBR effluent will be treated the same way as for alternative 1.

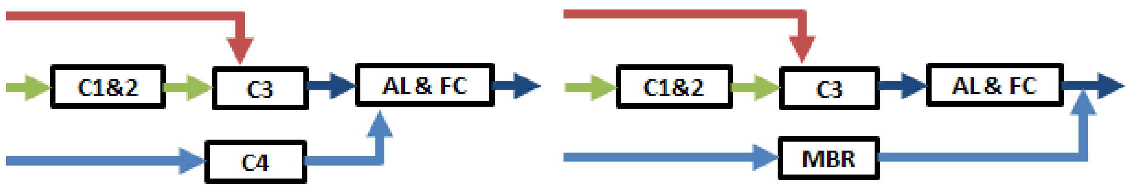


Figure 21. The site for MBR application in BLP.

The effluent flow from the pulp bleaching is high, at 900 m^3/h, and it is the sole contributor to BLP. The wastewater has high COD concentrations (~900 mg/L) and low TSS concentrations (~40 mg/L) (Table 14). The pulp bleaching effluent has a low pH value due to the bleaching process. Average temperature of the water is estimated to 70°C.

Table 14. Water quality parameters in BLP measured by Korsnäs 20.2- 26.2, 2012.

Parameter	Unit	BL
BOD	*mg/L*	**270**
COD	*mg/L*	**860**
Tot-N	*mg/L*	**2.3**
Tot-P	*mg/L*	**1.7**
TOC	*mg/L*	**350**
TSS	*mg/L*	**42**
Flow	*m^3/h*	**900**

In addition to the content listed in Table 13, the bleach effluent contains AOX. However, AOX has not been measured directly in BLP, but rather in the pipe that precedes the aerated lagoon (AL), where water from FLP, BLP and MLP is mixed. The pipe preceding the aerated lagoon will be referred to as the mixed pipe (MIXP). To allow calculations on AOX reduction, the AOX concentration in MIXP is estimated to originate exclusively from BLP, which results in an AOX concentration of approximately 17 mg/L.

Alternative 3: CT

The third alternative is implementation of MBR is on the wastewater flow from CT in MLP (Figure 22). In the current wastewater treatment, MLP firstly enters clarification basin 3, and is then transported into the aerated lagoon and the final clarification basin. For implementation of an MBR in MLP, the water flow from the collection tank will be separated from the other process flows and treated by an MBR. When treated, the water will be directed to the outlet of the final clarification basin, such as in alternative 1 and 2. The loading on C3, AL and FC will be reduced.

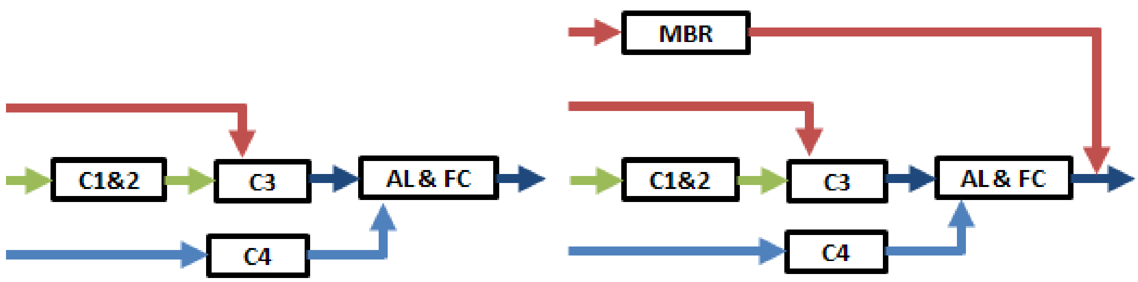


Figure 22. The site for MBR application in MLP.

The evaporator condensate has, similar to the wastewaters of MLP and BLP, high COD concentrations (~1000 mg/l) (Table 15). The effluent flow from the collection tank represents 17.5 % of the total flow in MLP, at approximately 485 m^3/h. Average temperature of the water is estimated to 75 °C.

Table 15. Water quality parameters in MLP measured by Korsnäs 20.2- 26.2, 2012.

Parameter	Unit	EV 2&3	FL 1,2&3	C & R	WP	CT
BOD	*mg/L*	17	-	150	340	**580**
COD	*mg/L*	66	66	290	900	**1000**
Tot-N	*mg/L*	20	1.3	15	5.9	**13**
Tot-P	*mg/L*	0.1	0.1	0.3	1.2	**0.1**
TOC	*mg/L*	26	28	78	290	**260**
TSS	*mg/L*	-	-	-	-	**-**
Flow	*m^3/h*	200	370	63	72	**480**

Alternative 4: CAS BL

The fourth alternative is the application of a conventional activated sludge system on the bleach effluent flow (Figure 23), also treated in alternative 2. The implementation of CAS would, similar to that of an MBR, eliminate the need for the bleach water clarification basin and reduce the loading on both AL and FC. The CAS effluent will be considered clean and thus be directed to the outlet of the final clarification step.

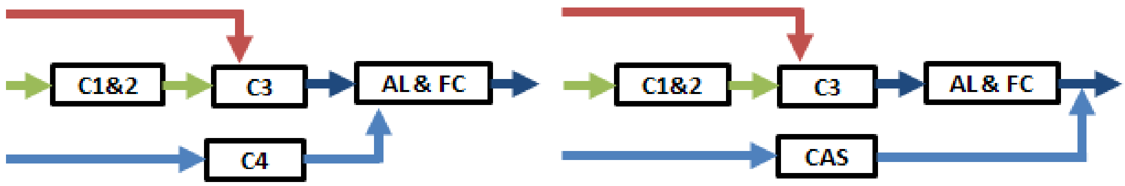


Figure 23. The site for CAS implementation in BLP.

Water quality parameters are equal to that described in alternative 2 (Table 14).

6.2 METHODS

Data on magnitude of flows and contaminant concentrations in each process flow was provided by Korsnäs and controlled by ÅF. The data had a degree of uncertainty, originating only from one week measurements. The calculations performed by ÅF are for overview purposes only, and the following results are to be considered as approximates.

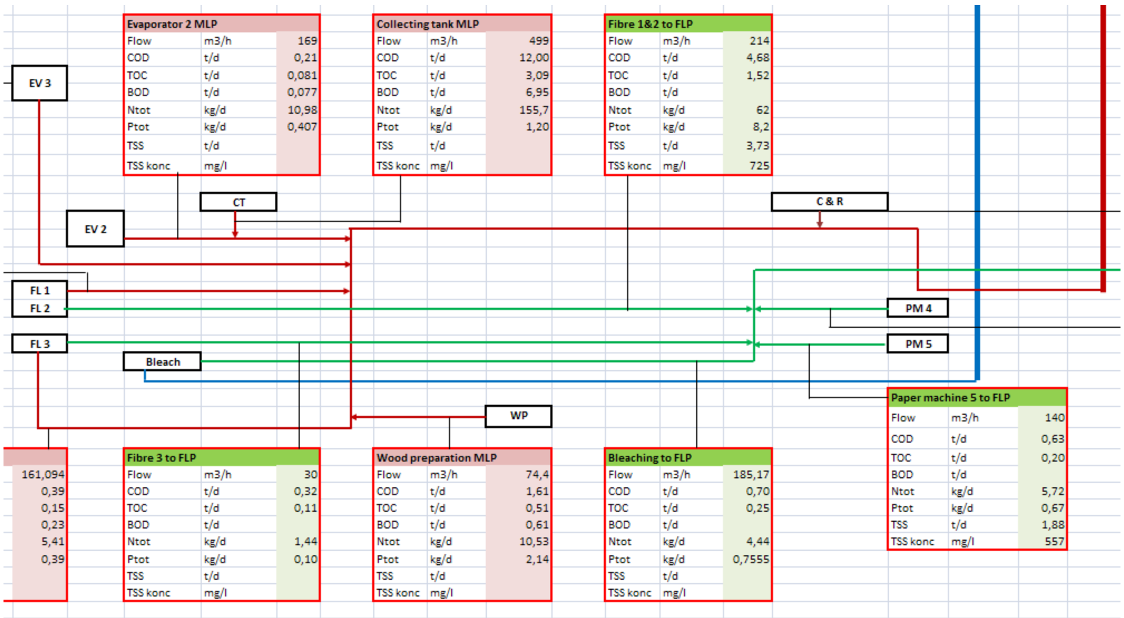
All emission data was adjusted to represent the present allowed production of pulp; 700 000 Adt/year. The mass flows are thus expressed as mass per time, i.e. kg/d. For calculations of yearly values, 365 days of operation was assumed.

6.2.1 Model

To calculate the achieved wastewater contaminant reduction for each MBR or CAS treated process flow, a model over water flows and mass flows was used (

Figure 24).

Figure 24. Screen dump of excel spread sheet used for emission calculations.



The model was set up in Microsoft Excel, and included all process flows described in chapter 6.1.3. Each process flow was attached to one or more of the three main flows, and mass transport was calculated. All basins of the current wastewater treatment system were integrated in the model, and the mass flows were reduced when passing through them. The reduced mass was further used to calculate nutrient requirements, oxygen demands, sludge production and subsequent costs.

For each proposed alternative for improvement of the current wastewater treatment system, the model was altered. When MBR or CAS was introduced into the model, the process flow of concern was removed from the present main pipe, and redirected into an MBR box, where mass flow was reduced. The remaining process flows remained unchanged, while the main pipe of concern, due to the removal of a process flow, had a reduced flow. To facilitate calculations, the changed loading on the original wastewater treatment basins were assumed to not have effect on their mass reduction.

6.2.2 Design data

Design flow

For each process flow, a design flow was calculated according for the design of the wastewater treatment. Design flows for alternative 1, 2 and 3 were calculated using empirical flow data from Korsnäs, and a safety factor.

$$Design\ flow = Average\ flow\ \times\ Safety\ factor \qquad (10)$$

The safety factor was based on the fluctuations of the total outflow from the current wastewater treatment system, thus reflecting the fluctuations of the total outflow from the current wastewater treatment system (Figure 25).

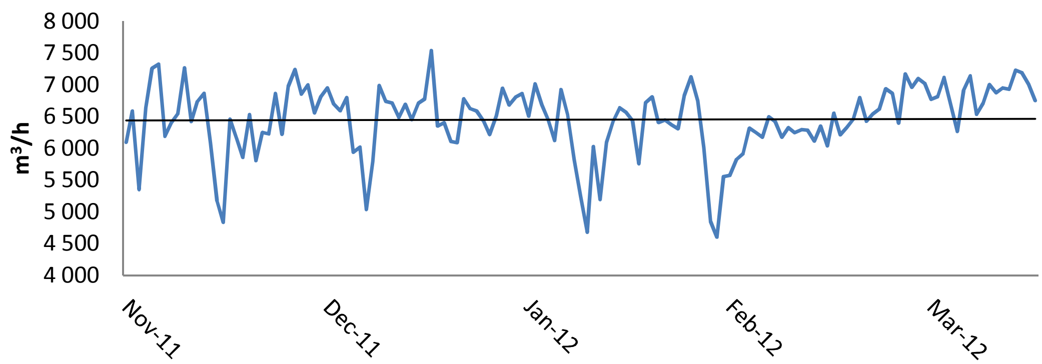


Figure 25. Flow fluctuations at the outlet of Korsnäs wastewater treatment.

The peak flows were approximately 20 % above average, why a safety factor of 1.3 was chosen.

Design COD values

For each process flow, a design value for COD was calculated for the design of the wastewater treatment. COD design values for alternative 1, 2 and 3 were calculated using empirical COD data from Korsnäs, and a safety factor.

$$Design\ COD\ = Average\ COD\ \times Safety\ factor \qquad (11)$$

The safety factor was based on the fluctuations of the total amount of COD transported from FLP, BLP and MLP to the aerated lagoon, per day during a five month period (Figure 26).

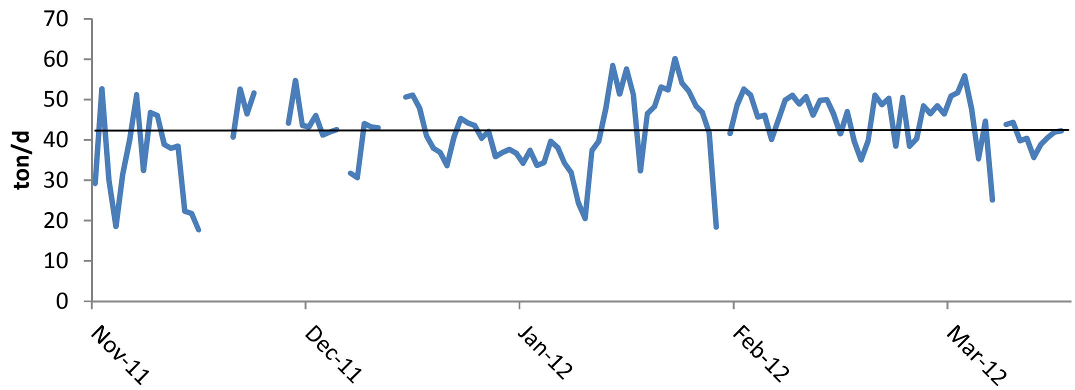


Figure 26. COD transport fluctuations at the inlet of the aerated lagoon at Korsnäs wastewater treatment.

The peak flows were approximately 40 % above average, why a design factor of 1.4 was chosen.

6.2.3 Membrane design

Membrane module design was performed using mainly manufacturer information. Representing HF membranes was the PURON® single-headed membrane produced by Koch Membrane Systems (Figure 11). It is available pre-packed into a variety of modules, of which, the least space-consuming is chosen, the PSH1800. Representing FS membranes was the KUBOTA® membrane produced by KUBOTA Corporation (Figure 13). It is provided in the KUBOTA Submerged Membrane unit®, which includes air diffusers. A rule-of-thumb mean design net flux for both HF and FS is 20 LMH (Judd, 2011). MT membranes intended for treatment of industrial wastewaters are generally custom made due to the varying wastewater properties, however, when data was required, the BIOMEMBRAT® process design (Figure 12) by Wehrle Technologies was used as reference. MT design fluxes vary, such as for the BIOMEMBRAT®, where 70 - 180 LMH is recommended. A flux of 150 LMH was used for calculations on wastewater treatment design using MT rMBR. The large membrane flux of MT is a result of the large applied pressure of rMBR systems, as described in chapter 5.3.10. The required membrane area for each type of membrane and flows was thus calculated using design flows and membrane flux.

$$Required\ membrane\ area = \frac{Design\ flow}{Membrane\ flux} \tag{12}$$

The membrane tank volume for the three MBR alternatives was then calculated using manufacturer data on packing density in the above mentioned membrane modules and the calculated required membrane area.

$$Membrane\ tank\ volume = \frac{Required\ membrane\ area}{Packing\ density\ of\ membrane\ modules} \quad (13)$$

The module design parameters used can be seen in Table 16.

Table 16. Parameters for membrane area and tank design.

Parameter	Unit	HF	FS	MT
Design flow	*m^3*	300	12000	650
Membrane flux	*LMH*	20	20	150
Packing density in membrane module	*m^2/m^3*	181	80	N/A

As membrane unit standard sizes were not available for the MT option, and no actual tank was needed for the rMBR, it was not calculated.

6.2.4 Biotreatment design

Dimensioning of the biotreatment tanks for each process flow was performed using information on process flow properties and the recommended COD loading for MBR, which is approximately 2 kg/m^{3}d (Ujang, 2003).

$$Biotreatment\ tank\ volume = \frac{Average\ flow \times Design\ COD}{Recommended\ COD\ loading\ for\ MBR} \quad (14)$$

The biotreatment design parameters used can be seen in Table 17.

Table 17. Design parameters for biotreatment tank volume calculations (Appendix C).

Parameter	Unit	Alt 1	Alt 2	Alt 3
Design COD	*mg/L*	900	900	1000
Average flow	*m^3/d*	5500	21600	12000
MBR COD loading	*kg/m^3d*	2	2	2

The hydraulic retention time (HRT) for each biotreatment tank was calculated using biotreatment tank volume and flow data.

$$HRT = \frac{Biotreatment\ tank\ volume}{Average\ flow} \quad (15)$$

As sludge age is decoupled from HRT, it is not of concern for the biotreatment tank volume dimensioning, but rather a matter of sludge discharge. The sludge age is preferably kept at approximately 25 days (Melin et al., 2006; Le-Clech, 2010; Judd, 2011; Lin et al., 2012), and was thus set accordingly.

6.2.5 Footprint

MT membrane footprint was assumed to be equal to those of the FS membrane tanks, which consumed the most space. Footprints were calculated based on information on membrane unit proportions, as provided by Koch and Kubota for HF and FS, respectively (Appendix A).

The biotreatment tanks were all designed to be 10 m deep, and footprints were calculated according to calculated tank volumes.

6.2.6 Effluent water quality

The contaminant removal was calculated using the model described in chapter 6.2.1. To facilitate calculations, AOX and chlorate content, as well as pH values were assumed not to influence the performance of the MBR or CAS.

Reduction efficiencies of the MBR treatment were set according to biodegradability of the organic matter in each process flow. The process flows in alternative 1 and 2 were both of high COD/BOD ratios, and were subsequently assumed to have a higher organic matter removal than alternative 3. The COD reduction for MBR treatment was estimated based on previous results from studies and references presented in chapter 5.4 and can be seen Table 18.

Table 18. Biodegradability of the organic matter in alternative 1, 2 & 3, based on average concentrations measured during week 5, 2012.

Parameter	Unit	Alt 1	Alt 2	Alt 3
COD	*mg/L*	910	860	1000
BOD	*mg/L*	N/A	270	580
COD/BOD	-	3.0[1]	3.2	1.7
COD reduction	*%*	80	80	85

1 = Estimated

The contaminant reduction efficiency of each existing treatment basin, including the aerated lagoon, was considered unchanged when the MBR was introduced to the system. The suspended solids concentration after treatment with MBR was assumed to be 1 mg/L. The reduction efficiencies used in the model can be seen in Table 19.

Table 19. Reduction efficiencies per parameter for the wastewater treatments used for calculations on contaminant removal in the used model.

Parameter	Unit	C1 & C2	C3	C4	AL & FC	MBR
TSS	*%*	85	45	10	-	~100
COD	*%*	15	15	5	41	80 - 85
TOC	*%*	15	15	5	42	80 - 85
BOD	*%*	10	10	5	80	95

As for AOX and chlorate removal in the MBR, 60 % and 50 % were assumed respectively. Since AOX and chlorate were assumed to originate solely from BLP, the only alternative affected by MBR implementation is alternative 2: BLP.

The nutrient removal was calculated according to the organic content and suspended solids removal. The biomass produced was estimated to contain 5 % nitrogen and 0.5 % phosphorus, and the nutrient removal was calculated.

The total effluent quality of Korsnäs wastewater treatment was calculated for each alternative, including both the MBR or CAS treated process flows and the remaining flows treated by the original treatments, to allow comparison between the different alternatives. Wastewater treated with MBR or CAS is thus combined with the remaining treated water at the end of the final clarification basin. The total emission levels were calculated by adding the MIXP out with the MBR out (Appendix B).

6.2.7 Nutrient requirement

The concentration of dissolved nutrients in the mixed liquor is required to be 2.5 mg/L and 1 mg/L for nitrogen and phosphorus, respectively, to optimize growth (100:2.5:1 for COD:N:P). The nutrient addition was thus calculated to maintain that level. The requirement of 100:1 COD:P varies between studies, why calculations on phosphorus requirements ranging from 0.15 to 1.5 were performed. The nutrient requirement used for calculation of alternative 4 is set to 100:3:1.1 by ÅF.

Required amount of nutrients for growth was calculated using average flow data and the above stated levels of nutrients.

$$Required\ nutrients\ for\ growth = Average\ flow \times Dissolved\ nutrients \quad (16)$$

The required addition of nutrients was calculated using the known required amount of nutrients for growth and the amount of nutrients in each process flow.

$$Addition\ of\ nutrients = Required\ nutrients - available\ nutrients \quad (17)$$

The amount of suspended nutrients was calculated according to the amount of suspended solids in the effluent water of the MBR and CAS. The suspended solids were estimated to contain 5 % nitrogen and 0.5 % phosphorus.

6.2.8 Oxygen demand

One of the main costs for MBR technology is the energy demand of the membrane air scouring. Air scouring is only performed in the sMBR configurations, where HF and FS membranes are used. As described in chapter 5.3, the rMBR configuration with MT membranes is designed for transmembrane transport by pumping, and is subsequently not included in the following results.

The air flow required for membrane scouring in the two sMBR alternatives, with HF and FS membranes, is calculated using the specific aeration demand (SAD_m) and membrane area for the membranes.

$$Required\ air\ flow = \frac{Specific\ aeration\ demand}{Membrane\ area} \quad (18)$$

The air flow calculation parameters used can be seen in Table 20.

Table 20. Design parameters for air flow demand calculations for hollow fiber (HF) and flat sheet (FS) membranes.

		Alt 1		**Alt 2**		**Alt 3**	
Parameter	**Unit**	**HF**	**FS**	**HF**	**FS**	**HF**	**FS**
Membrane area	m^2	15000	15000	60000	60000	32500	32500
SAD_m	Nm^3/m^2h	0.3	0.3	0.3	0.3	0.3	0.3
Air flow	m^3/h	4500	4500	18000	18000	9800	9800

Oxygen demands for the biotreatment were calculated by the actual oxygen transfer rate (AOR) and standard oxygen transfer rate (SOTR). AOR was calculated as the oxygen required for oxidizing the COD fraction reduced in the wastewater treatments, not including the COD transformed into biomass. SOTR was calculated using AOR and other environmental properties of the water and air interactions (Appendix C).

SOTR was then used to calculate the required airflow (Nm^3/h). The air flow calculation parameters for the biotreatment used can be seen in Table 21.

Table 21. Design parameters for air flow demand of biotreatment.

Parameter	**Unit**	**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
AOR	*ton* O_2/d	5	17	12	8
SOTR	*ton* O_2/d	9	34	23	23

6.2.9 Sludge production

Sludge production is calculated using the spread sheet, where it assumed to be produced as 0.2 kg sludge per kg COD removed, and with a 50 % biodegradability of the total suspended solids.

$$Sludge\ production = Sludge\ from\ COD\ removal + Sludge\ from\ TSS\ removal \quad (19)$$

6.2.10 Costs

For the evaluation of economic feasibility of implementing MBR technology in Korsnäs, capital and operating costs were evaluated separately. The cost of implementing CAS at Korsnäs was previously calculated by ÅF. Economic calculations were based on standard values from ÅF, manufacturer information and recommendations from literature. Calculated costs are approximated, and are to be seen as indications, rather than absolute values.

Investment

The major capital costs of building MBR systems include membranes, tanks and aeration systems. For representative calculations on capital costs however, further costs have also been included. Costs for pumps, blowers, diffusers, pipes, instruments and associated buildings and electrics were calculated, along with the construction of tanks, membranes, screens and control systems. The cost for installation of the various machines was estimated to 100 % for pumps, 30 % for diffusers and 10 % for other machines. Technical contingency, auxiliary equipment and project and administration were calculated using 30, 10 and 10 % of the total capital costs, respectively. Most capital costs are estimated according to similar previous investments.

The cost assumptions for investment costs can be seen in Table 22.

Table 22. Assumed capital costs for calculation of MBR implementation.

Investments	Price	Reference
Pumps	7 kSEK per m^3/h	ÅF
Pump station	250 kSEK	ÅF
Membranes	0.45 kSEK/m^2	Judd
Membrane blower	200 kSEK/unit	ÅF
Fine air diffusers	31 SEK per m^3/h	Eurombra
Coarse air diffusers	5 SEK per m^3/h	Eurombra
Fiber screen	1 MSEK	ÅF
Fine screen	9 kSEK	Eurombra
Membrane and biotreatment tanks	0.8 kSEK/m^3	ÅF
Excavation	1.7 kSEK/m^2	ÅF
Piling	2.2 kSEK/m^2	ÅF
Membrane pumps	3.6 kSEK per 20m^3/h capacity	Eurombra
Biotreatment blower	200 kSEK /unit	ÅF
Biotreatment aerator	440 kSEK	ÅF
Discharge measurement station	1500 kSEK	ÅF
Pipes	7 kSEK/m	ÅF
Electrical	5 kSEK/kW installed	ÅF
Instruments	80 kSEK/circuit installed	ÅF
Control system	2000 kSEK	ÅF
Installation	100% pumps, 30% aerators, 10% other	ÅF
Technical contingency	30% of total capital costs	ÅF
Auxiliary equipment	10% of total capital costs	ÅF
Project and administration	10% of total capital costs	ÅF

Operating costs

Operational costs for MBR systems are mainly electricity demand, sludge handling, personnel cost, maintenance and nutrient addition (Appendix D). For all operating cost calculations, 365 days of operation was assumed. Energy demands for the MT MBR systems were calculated according to manufacturer guidelines. Wehrle external membranes allow a flux rate of 70 through 180 LMH, of which 150 LMH was assumed, and a MLSS concentration of 15 through 35 g/L, of which 30 g/L was chosen. The specific energy consumption of the membrane plant ranges from 1.5 to 4 kWh/m^3, and with the design values chosen, the specific energy consumption was approximated at 3.5 kWh/m^3. The energy demands for the HF and FS membranes were calculated using specific aeration demand data, membrane area data and blower efficiencies.

Nutrient costs were calculated according to requirements, and sludge handling was calculated using sludge production data. Personnel cost was estimated at 25 % more than that estimated for CAS due to probable high educational costs and maintenance and monitoring needs for MBR.

The cost assumptions for operating costs can be seen in Table 23.

Table 23. Assumed operating costs for calculation of MBR implementation.

Operating costs	Price	Reference
Electricity	0.40 SEK/kWh	ÅF
Sludge handling	1500 SEK/ton TSS	ÅF
Personnel	500 kSEK/year	ÅF
Maintenance	2.5% of total investment	ÅF
Nutrients (Urea)	3400 SEK/ton	ÅF
Nutrients (75% Phosphorus acid)	5400 SEK/ton	ÅF

6.3 RESULTS

Results from the technical and economical calculations on alternative 1, 2 and 3 are presented below. When possible, alternative 0 and 4 are also presented.

6.3.1 Design data

Design values for flow and COD-concentrations are presented in Table 24.

Table 24. Design values for wastewater flow and COD concentrations of alternative 1, 2, 3 and 4.

Parameter	Unit	Alt 1	Alt 2	Alt 3	Alt 4
Flow	m^3	300	1200	650	1200
COD	mg/L	1300	1300	1400	1300

6.3.2 Membrane design

The rMBR configurations required the least amount of membrane area, due to the higher flux achieved by pumping than air scouring (Figure 27). Alternative 2, having the largest design flow, required the largest membrane area.

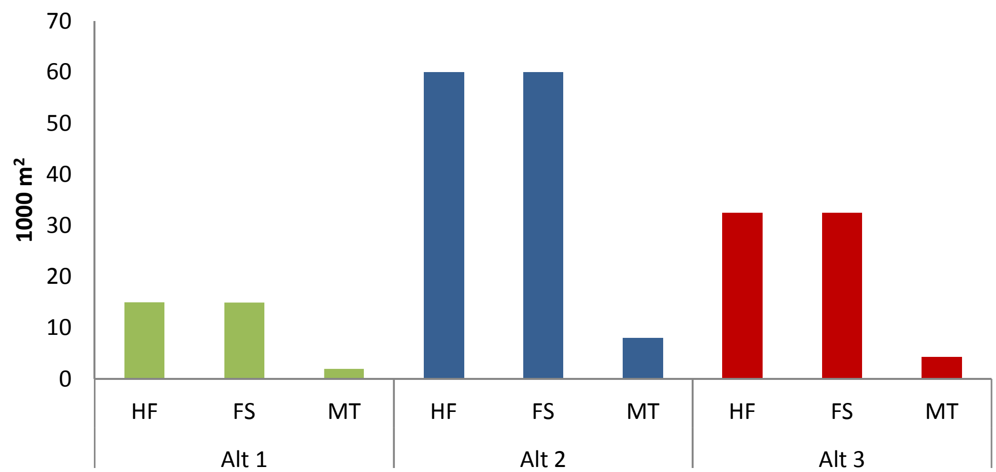


Figure 27. Required membrane area for alternative 1, 2 and 3, using HF, FS or MT membranes.

6.3.3 Biotreatment design

The required biotreatment tank volume is largest for alternative 4, followed by alternative 2 and smallest for alternative 1 (Figure 28).

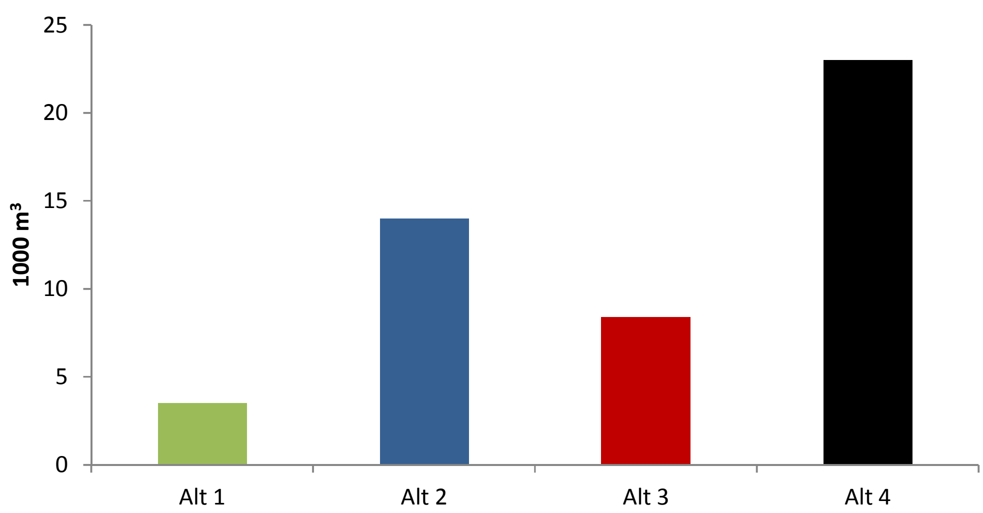


Figure 28. Biotreatment tank volume for alternative 1, 2, 3 and 4.

The biotreatment tank volume for the three alternatives also determines the hydraulic retention time (HRT), which for alternative 1, 2 and 3 are 0.46, 0.43 and 0.50 days respectively, which was within recommended limits of 0.12 – 2.5 days (Lin et al., 2012) and well above the minimum value recommended by Judd (2011) of 0.33 days.

6.3.4 Footprint

The HF module had a higher packing density than the FS module (181 vs. 80 m^2 membrane/m^3 unit) and thus created the smallest footprint of the two (

Table 25). All biotreatment tanks were designed to be of 10 meters depth, and footprints were thus proportional to volumes (

Table 25).

Table 25. Membrane tank volume and footprint for alternative 1, 2 and 3.

		Alt 1			Alt 2			Alt 3		
	Unit	**HF**	**FS**	**MT**	**HF**	**FS**	**MT**	**HF**	**FS**	**MT**
Membrane footprint	m^2	35	45	45	130	170	45	98	128	45
Biotreatment footprint	m^2	350	350	350	1400	1400	1400	840	840	840

The total footprint, including both biotreatment and membrane tanks, for alternative 1, 2 and 3 were all smaller than for alternative 4, including biotreatment and sedimentation tanks, for all membrane types (Figure 29). The higher footprint of alternative 4 is due to lower organic loading for CAS than MBR (0.9 and 2.0 kgCOD/m^3d respectively), and the need for a sedimentation basin.

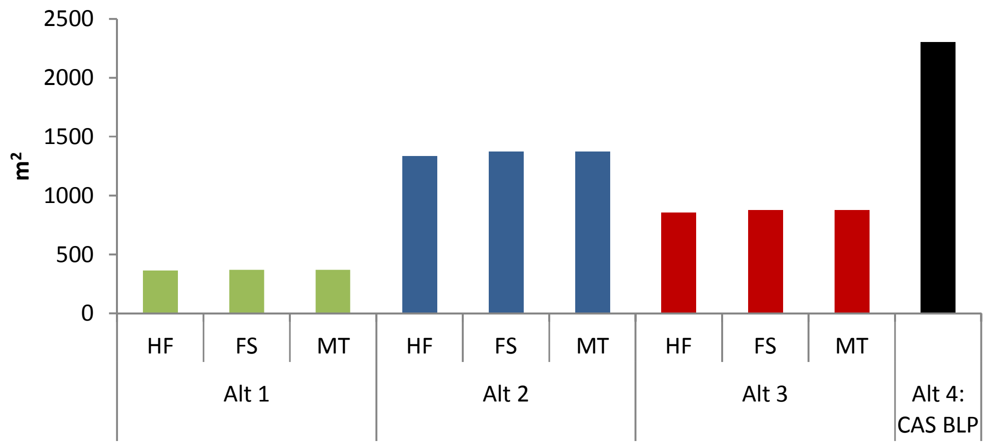


Figure 29. Footprint of alternative 1, 2, 3 & 4, including membrane tanks and biotreatment tanks.

6.3.5 Effluent water quality

Of the five alternatives, the only one to reach the emission target values for COD, TOC and N was alternative 2 (Table 26). It did not, however, reach the target value for P emissions, which alternative 1 and alternative 4 did. All alternatives reached target values for TSS content, while alternative 4 did not reach the TSS concentration target value.

Table 26. Calculated emission levels for the five alternatives (Appendix B). Values highlighted in green are at or below target values.

Parameter	Unit	TARGET	ALT 1: FL1&2	ALT 2: BL	ALT 3: CT	ALT 4: CAS BL
COD	*t/d*	22	28	21	24	22
TOC	*t/d*	7	9	6	9	7
N-tot	*kg/d*	400	520	370	410	470
P-tot	*kg/d*	30	31	48	48	46
TSS	*t/d*	4	3	3	3	4
TSS conc.	*mg/l*	28	25	21	24	30

Both parameters were higher for alternative 2: BLP than for the other alternatives, including the present wastewater treatment, alternative 0 (Figure 30).

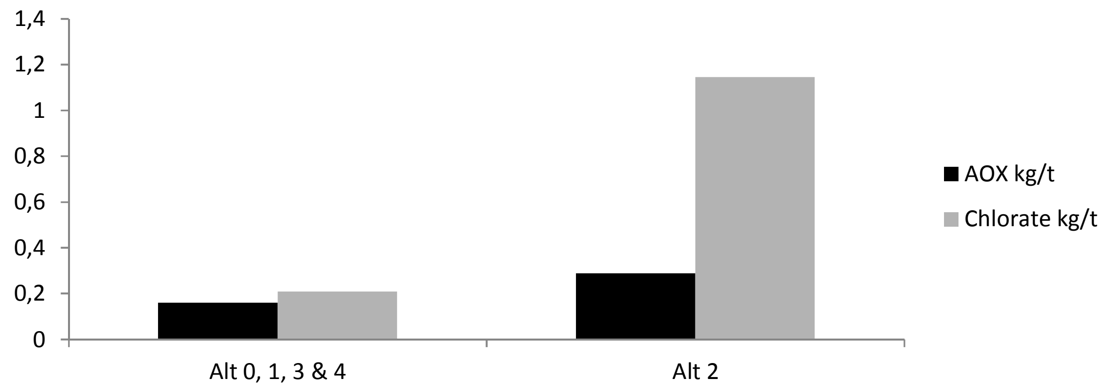


Figure 30. AOX and chlorate emissions from Korsnäs for alternatives of wastewater treatment, alternative 2 being MBR on BLP.

6.3.6 Nutrient requirement

Alternative 4: MLP required the least amount of nitrogen of the three MBR alternatives, while alternative 2: BLP required the most (Figure 31). The difference between alternative 2 and 4 was due to differences in COD removal efficiency, (80 and 50 %, respectively).

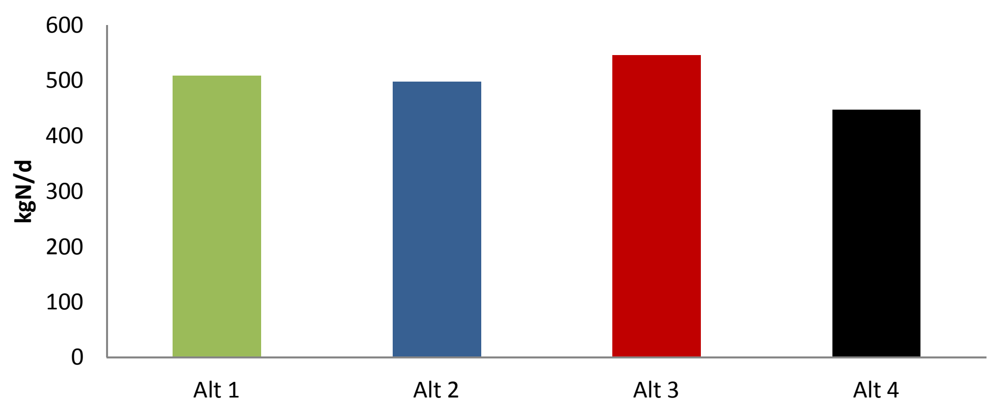


Figure 31. Nitrogen requirements for the MBR and CAS alternatives (Alt 1, 2, 3 & 4).

The amount of phosphorus needed for alternative 1: FLP does not differ much when requirements are changed between 0.15 through 1.5 (Figure 32). Alternative 2: BLP however, changes significantly. Optimization of phosphorus dosage is thus of importance. Alternative 4 does not require phosphorus dosage.

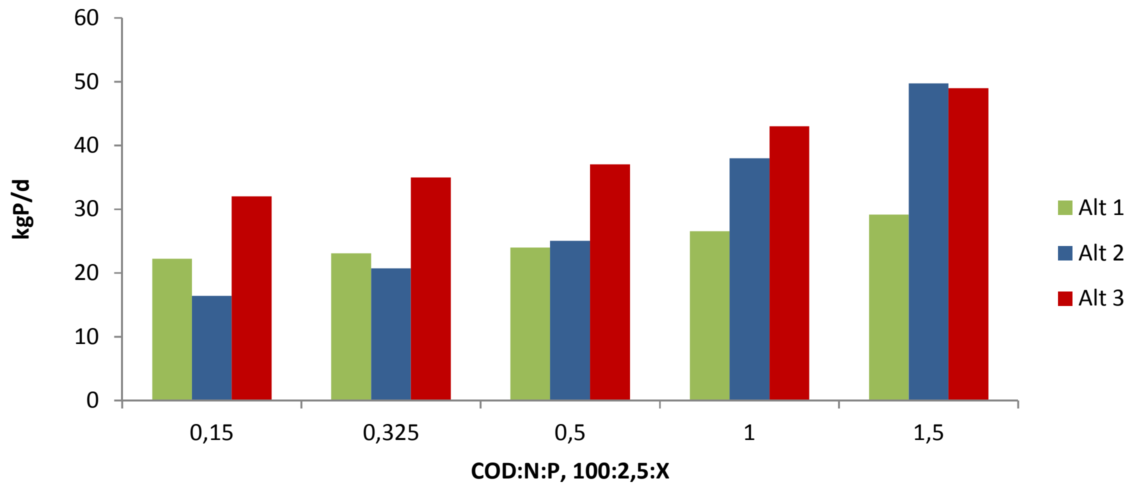


Figure 32. Phosphorus requirements for alternative 1, 2 & 3.

6.3.7 Oxygen demand

As oxygen demand is directly proportional to membrane area, alternative 2 requires the most oxygen of the three alternatives (Figure 33).

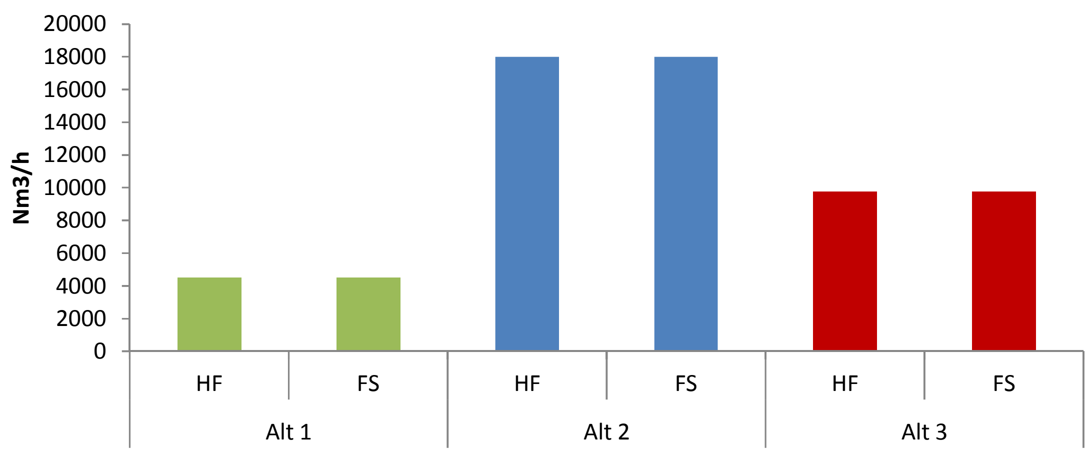


Figure 33. Aeration demand for membrane tanks for alternative 1, 2 & 3, using sMBR configuration.

Aeration of the biotreatment is largest for alternative 2 (Figure 34). Both alternative 2 and 4 are applied to the BLP flow, treating the same wastewater. The higher air flow required for alternative 2 is mainly caused by a higher COD removal efficiency than alternative 4 (80 and 50 %, respectively).

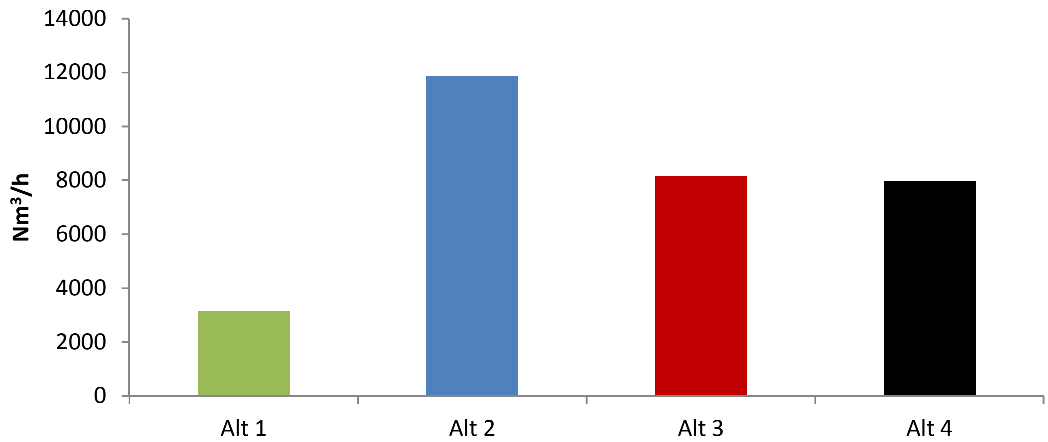


Figure 34. Aeration demand in biotreatment tanks for alternative 1, 2, 3 & 4.

When air flow requirements for membrane air scouring and biotreatment are summarized, alternative 2 was approximately three times as high as alternative 4 (Figure 35). Alternative 1 had the lowest air flow requirements.

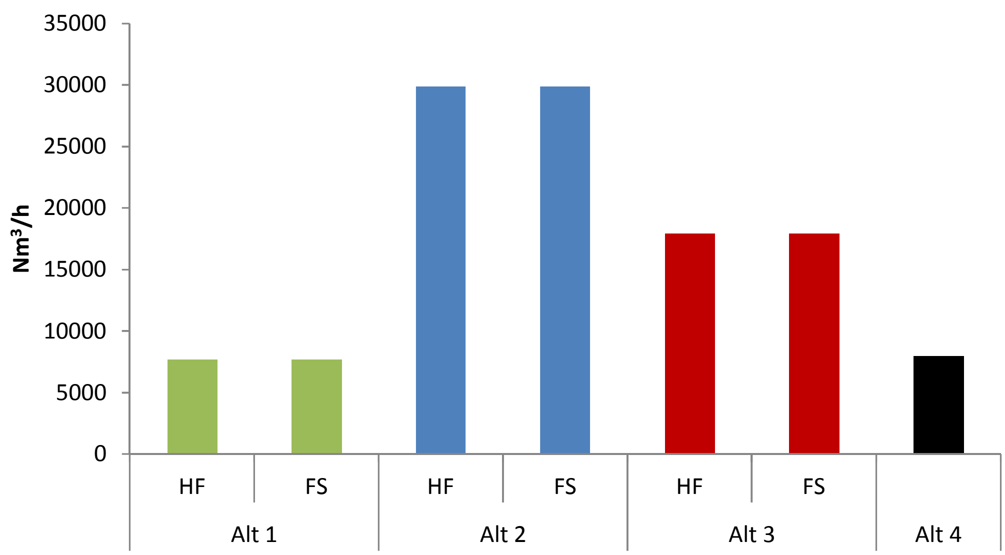


Figure 35. Total aeration demand for membrane and biotreatment tanks for alternative 1, 2, 3 & 4.

6.3.8 Sludge production

Higher sludge production can be seen in all three MBR alternatives (1, 2 & 3) than that for CAS (Figure 36). The higher sludge production of alternative 2 than that of alternative 4 is due to the higher TSS and COD removal of alternative 2 (1 mg/L and 30 mg/L for TSS and 80 and 50 % for COD, respectively).

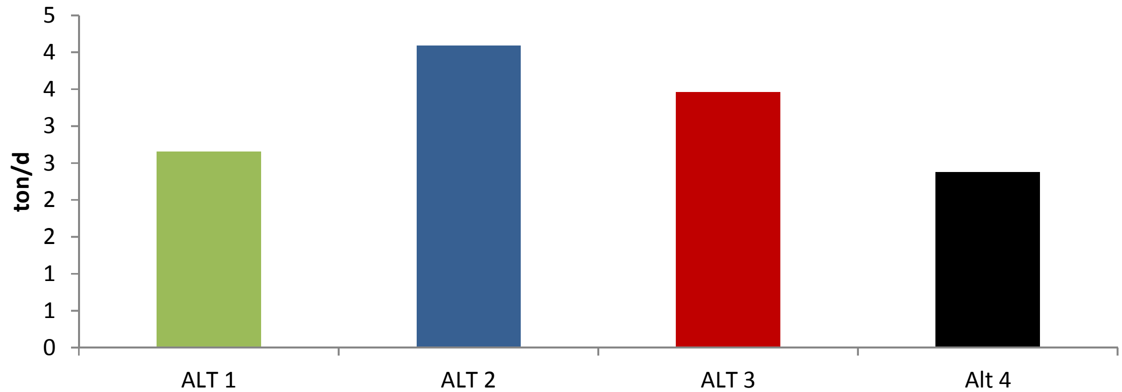


Figure 36. Sludge production for alternative 1, 2, 3 & 4.

6.3.9 Costs

The overall performance of the three MBR alternatives and the CAS alternative are presented in this evaluation. Economic evaluation key results can be seen in Table 27.

Table 27. Key results from the economic evaluation.

		Alt 1			Alt 2			Alt 3			Alt 4
	Unit	HF	FS	MT	HF	FS	MT	HF	FS	MT	
Investment	*MSEK*	114	114	97	194	195	137	152	152	117	128
Operational	*kSEK/year*	11600	11600	13700	17900	17900	28300	13100	13100	15700	10200

Investment

Summarizing the capital costs show that alternative 2 was the most expensive of the three alternatives (Figure 37). Alternative 1 was, for all types of membranes is the least expensive. The sMBR systems were consistently less expensive than rMBR regarding investment costs.

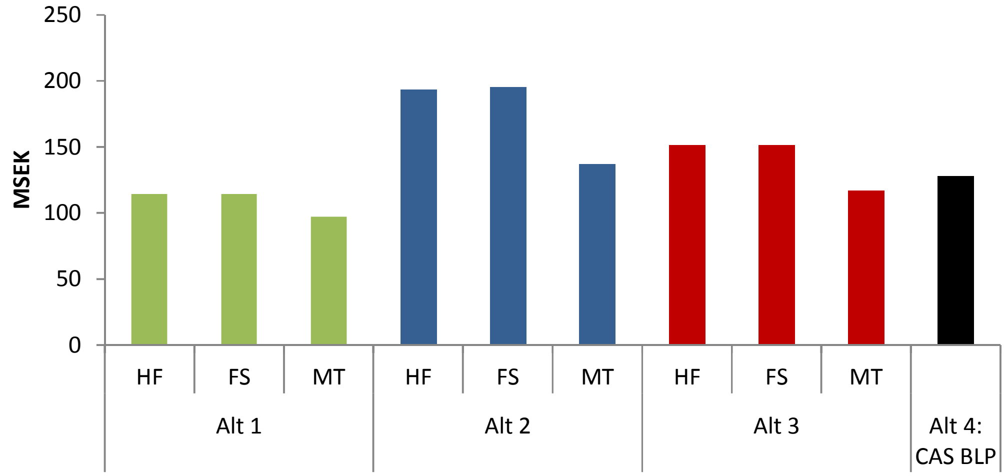


Figure 37. Total capital costs for the three MBR alternatives (Alt 1, 2 & 3) and the CAS alternative (Alt 4).

Detailed investment costs are presented in Appendix E.

Operating cost

Summarizing the operational costs showed similar results as for the capital costs, alternative 2 had the highest costs, while alternative 1 had the lowest of the four (Figure 38). For the operating costs, the rMBR systems were the ones consistently less expensive than sMBR.

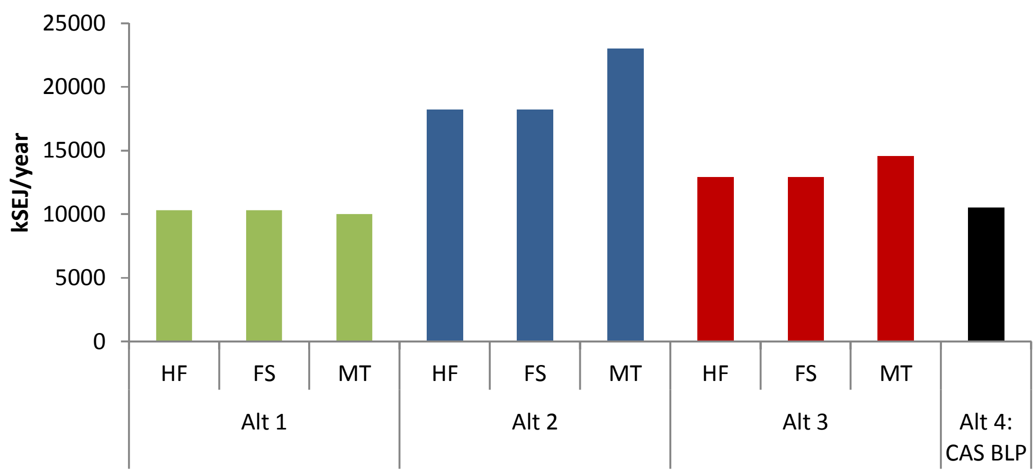


Figure 38. Total operational costs for the three MBR alternatives (1, 2 & 3) and the CAS alternative.

Detailed operating costs are presented in Appendix F.

6.4 TECHNICAL AND ECONOMIC EVALUATION

The membrane design was based on the design flows in Table 23, and was subsequently largest for alternative 2, having the largest flow (Figure 27). The difference between the two sMBR membranes (HF and FS) and the rMBR membrane (MT) was significant. The difference in required membrane area affected all other calculations, such as cost and footprint. The biotreatment design showed that alternative 4, implementing CAS was required to be much larger than that of the MBR alternatives (Figure 28). This result was expected, considering the larger organic loading made possible on the MBR systems.

As expected, all three MBR alternatives were space-efficient and make smaller footprints than the CAS alternative (Figure 29). The small footprints are, as previously described, a result of the smaller required membrane tank volume as compared to sedimentation or flotation tank sizes, and the shorter HRT required for MBR systems than that of CAS. Between the three membrane types, HF, FS and MT within each MBR alternative, the total footprint did not differ much, which indicates that in this case it is rather the biotreatment tank footprint that determines footprint.

Nutrient requirements did not differ much between the four alternatives, even though the process flows were of different characters (Figure 31; Figure 32).

Sludge production is not representative of excess sludge, as sludge age was significantly higher for all three MBR alternatives than that of alternative 4: CAS (Figure 36). The larger sludge production was caused by the more efficient COD and SS removal of MBR. The MBR systems were designed to keep a high sludge age, which would cause part of the produced sludge to be utilized for cell tissue maintenance, thus not becoming excess sludge. Seeing as optimal operational parameters first can be identified on site, the calculated sludge production is not to be considered as excess sludge, but rather a measurement of organic matter removal efficiency.

All three MBR alternatives consistently reached company target values for TSS, which was expected, as solids are to be retained by the membranes.

6.4.1 Alternative 1: FLP

Implementing MBR technology on fiber line 1 and 2 in FLP was the least expensive alternative both for investment (Figure 37) and operation (Figure 38), and created the smallest footprint (Figure 29). The total performance of the wastewater plant however, did not show sufficient contaminant removal to reach the company target values (Table 26). The two parameters that did were P-tot and TSS.

6.4.2 Alternative 2: BLP

Treating the entire BLP with MBR technology was the most efficient alternative for contaminant removal, compared to alternative 1, 3 and 4. It showed parameter values below the company target limits for COD, TOC, N-tot and TSS (Table 26). The AOX and chlorate removal however, suffered from the MBR implementation (Figure 30), as the wastewater was not exposed to any anoxic or anaerobic environment. The BLP, having the largest flow of the three MBR alternatives, subsequently had the largest footprint (Figure 29) and cost, both capital (Figure 37) and operating (Figure 38). The operational cost could possibly be reduced by optimizing phosphorus acid dosage (Figure 32). With a reduction from 1 kgP/day to 0.5 kgP/day, the cost for phosphorus acid was reduced by one third.

6.4.3 Alternative 3: MLP

Implementing an MBR system on the collection tank effluent in MLP did not improve the wastewater treatment significantly (Table 26). The only parameter that reached the company value target was TSS. Both cost and footprint were larger than that for alternative 1, where two parameters reached the company target values.

6.5 RECOMMENDATIONS

Of the three MBR alternatives, the only one that reached acceptable effluent contaminant content was alternative 2: FLP. The costs for alternative 2 however, were higher than that of alternative 4, which provided comparable purification. Neither alternative 1 nor 3 affected the contaminant levels in the wastewater treatment effluent sufficiently to be considered as suitable for application at Korsnäs. Of the two, alternative 1 was considered superior, due to maintaining a lower cost and footprint, while resulting in a better quality effluent. Due to high cost for alternative 2, and insufficient effluent quality for alternative 1 and 3, none of the above described alternatives were considered feasible, and were thus not recommended for implementation of MBR technology at Korsnäs.

7 DISCUSSION

Based on the performed literature study, it is obvious that MBR technology is of increasing importance, above all for its efficient removal of organic matter and suspended solids. Another advantage is the comparatively small footprint compared to other available wastewater treatment technologies. The cost of membranes, having drastically decreased over the recent years, is no longer of hindrance for investing in MBR technology. High energy requirements for aeration and pumping is still a problem, but could be solved using for example biogas from anaerobic biotreatment or intermittent aeration. The fouling issue has been intensely researched, and many solutions have been identified. Even though irrecoverable fouling is inevitable, membranes function for approximately eight years. As new membrane materials are being developed, and existing materials are improved, even longer membrane lives can be expected. The many full-scale references in both municipal and industrial wastewater treatment prove that MBR technology is, in fact a wastewater treatment to rely on.

Using MBR technology in the pulp and paper industry should be feasible. It has previously been used for the treatment of various industrial waters with varying properties, such as high and low organic matter and suspended solids concentrations, mesophilic and thermophilic temperatures. It has proven to be a feasible treatment for industrial wastewaters, including leachate and wastewater from wineries and tanneries. There are also a number of lab- and pilot scale studies that indicate the suitability of MBR technology for treatment of pulp and paper wastewater, in addition to the few full-scale references. The high temperature of some of the pulp and paper wastewater can be used for the upkeep of a thermophilic biotreatment process, and the high temperature will result in high membrane flux. The use of chlorine in the pulp bleaching process may cause problems for the microorganisms in the biotreatment; however, the high MLSS concentration in MBR treatment encourages fast adaption to the influent. The possibility of sludge reduction would be useful for the pulp and paper industry, with its high organic matter and suspended solids content wastewater, as sludge handling is of high cost, and sludge disposal not sustainable.

The case study for MBR implementation in Korsnäs pulp and paper wastewater treatment showed that the higher the flow, the higher the cost for transmembrane transport is, and it seemed to take overhand when sufficient contaminant removal was achieved. The smaller flows treated did not affect the final effluent quality of the total wastewater treatment plant enough to reach target values. The case study rather indicated that MBR treatment is, however contaminant removal efficient on large flows, best applied on small flows due to the high cost of permeate transport. As the smaller flows in the case study did not affect the final effluent quality of the treatment plant, MBR treatment might be best applied where internal recirculation of process water is intended, such as for evaporator condensate.

Low chlorate reduction posed a problem in the case study, as the MBR systems applied were aerobic. Utilizing MBR technology with anaerobic biotreatment or possibly intermittent aeration on ECF bleaching process water might therefore be preferred.

8 CONCLUSIONS

Over all, MBR technology can be considered a reliable and well-functioning wastewater treatment. It offers several advantages to CAS, including excellent effluent quality and low footprint. MBR treatment has shown to be applicable for various types of wastewaters, in both meso- and thermophilic environments, and with various organic strength waters. Several references are available for industrial applications, including pulp and paper.

The case study of MBR application in Korsnäs showed it not to be feasible for the chosen process flows. The result can be seen as an indication that MBR in the pulp and paper industry is best applied in smaller streams, and for the cause of internal recirculation. It may also be implemented when building space is limited. Other types of biotreatment might be of interest for ECF bleaching process water, such as anaerobic treatment.

This study indicates that MBR technology has potential to become an important part of pulp and paper wastewater treatment. Further pilot- and full-scale studies on different types of pulp and paper process waters are needed to launch MBR technology as a reliable and feasible technology in the industry.

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PERSONAL COMMUNICATIONS

Bengtsson, Lars. (2012, March 19). Operations manager, Sjöstadsverket.

Hotz, Roland. (2012, April 2). Commissioning engineer, Björks Rostfria.

APPENDIX A: MEMBRANE DESIGN

Membrane area requirements and footprint were calculated using the information below. Packing density was calculated by dividing unit surface area with unit volume. Information on unit surface area and volume was provided by Koch, Kubota and Wehrle for HF, FS and MT, respectively.

	Unit		Alt 1: FLP			Alt 2: BLP			Alt 3: MLP	
Avg. flow	m^3/h		234			900			678	
Design flow	m^3/h		304			1170			881	
		HF	FS	MT	HF	FS	MT	HF	FS	MT
Net flux	*LMH*	20	20	150	20	20	150	20	20	150
Membrane area	m^2	15210	15210	2028	58500	58500	7800	44070	44070	5876
Unit surface area	m^2	1800	580	N/A	1800	580	N/A	1800	580	N/A
Unit volume	m^3	10	7	N/A	10	7	N/A	10	7	N/A
Packing density	m^2/m^3	181	80	N/A	181	80	N/A	181	80	N/A
Min. tank vol.	m^3	84	190	N/A	324	729	N/A	244	549	N/A
No of modules		9	27	N/A	33	101	N/A	25	76	N/A
Footprint	m^2	35	45	N/A	130	170	N/A	98	128	N/A

APPENDIX B: CONTAMINANT REMOVAL

ALT 1: FL1&2

Parameter	Unit	MIXP in	MIXP out	MBR in	MBR out	TOTAL out
Flow	*m^3/h*	5346	5346	214	214	5560
COD	*t/d*	45	27	5	1	27
TOC	*t/d*	15	9	2	0	9
BOD	*t/d*	18	4	1	0	4
N-tot	*kg/d*	248	502	62	13	515
P-tot	*kg/d*	42	26	8	5	31
TSS	*t/d*	12	3	4	0	3
TSS conc	*mg/L*	90	26	725	1	25

ALT 2: BL

Parameter	Unit	MIXP in	MIXP out	MBR in	MBR out	TOTAL out
Flow	*m^3/h*	4531	4531	1029	1029	5560
COD	*t/d*	28	17	21	4	21
TOC	*t/d*	8	5	9	2	6
BOD	*t/d*	12	2	7	0	3
N-tot	*kg/d*	205	308	57	63	371
P-tot	*kg/d*	28	23	22	25	48
TSS	*t/d*	11	3	1	0	3
TSS conc	*mg/L*	100	26	42	1	21

ALT 3: CT

Parameter	Unit	MIXP in	MIXP out	MBR in	MBR out	TOTAL out
Flow	*m^3/h*	5061	5061	499	499	5560
COD	*t/d*	38	22	12	2	24
TOC	*t/d*	14	9	3	0,5	9
BOD	*t/d*	13	3	7	0,3	3
N-tot	*kg/d*	167	377	156	31	408
P-tot	*kg/d*	48	36	1	12	48
TSS	*t/d*	10	3	3	0	3
TSS conc	*mg/L*	85	26	239	1	24

ALT 4: CAS BL

Parameter	Unit	MIXP in	MIXP out	CAS in	CAS out	TOTAL out
Flow	*m^3/h*	4531	4531	1029	1029	5560
COD	*t/d*	28	14	20	8	22
TOC	*t/d*	8	4	8	3	7
BOD	*t/d*	12	1	6	0	1
N-tot	*kg/d*	205	356	51	111	467
P-tot	*kg/d*	28	15	43	31	46
TSS	*t/d*	11	3	1	1	4
TSS conc	*mg/L*	100	30	38	30	30

APPENDIX C: BIOTREATMENT OXYGEN DEMAND

Oxygen demands for the biotreatments are calculated by the actual oxygen transfer rate (AOR) and standard oxygen transfer rate (SOTR). AOR is calculated as the oxygen required for oxidizing the COD fraction reduced in the wastewater treatments, not including the COD transformed into biomass, here represented as ton 0_2 per day. SOTR is calculated as follows.

$$SOTR = AOR * \left(\frac{C_{10}}{C_T * \beta - C_0} * \frac{1}{\alpha} * Q^{(10-T)} \right)$$

where C_0 = 2 kg O_2/m^3, C_{10} = 11.3 kg O_2/m^3, C_T = 6 kg O_2/m^3, Q = 1.02 m^3 O_2/h, T = 50 °C, α = 0.7, β = 0.95.

APPENDIX D: NUTRIENT REQUIREMENTS

The cost for the addition of nutrients is calculated using the information below.

Parameter	**Unit**	**Alt 1: FLP**	**Alt 2: BLP**	**Alt 3: MLP**
Nitrogen requirement	*kgN/d*	510	500	550
Nitrogen molecular weight	*g/mol*	14	14	14
Urea molecular weight	*g/mol*	60	60	60
Urea requirement	*kgUREA/d*	2200	2100	2300
Urea cost	*kSEK/ton*	3.4	3.4	3.4
Cost	*kSEK/year*	2700	2700	2900

Parameter	**Unit**	**Alt 1: FLP**	**Alt 2: BLP**	**Alt 3: MLP**
Phosphorus requirement	*kgP/d*	27	38	43
Phosphorus molecular weight	*g/mol*	31	31	31
Phosphorus acid molecular weight	*g/mol*	98	98	98
Phosphorus acid requirement	*kgP-ACID/d*	84	120	140
75 % Phosphorus acid requirement	*kg75%P-ACID/d*	110	160	180
75 % P-acid cost	*kSEK/ton*	5.4	5.4	5.4
Cost	*kSEK/year*	220	310	350

APPENDIX E: INVESTMENT COSTS

Investments	**Alt 1**	**Alt 1**	**Alt 1**	**Alt 2**	**Alt 2**	**Alt 2**	**Alt 3**	**Alt 3**	**Alt 3**	**Alt 4**
	HF	**FS**	**MT**	**HF**	**FS**	**MT**	**HF**	**FS**	**MT**	**CAS**
	MSEK	*MSEK*	*MSEK*	*MSEK*	*MSEK*	*MSEK*	*MSEK*	*MSEK*	*MSEK*	*MSEK*
Pump station	1	1	1	2	2	2	2	2	2	2
Cooling	6	6	6	11	11	11	9	9	9	22
Adjustment of pH	1	1	1	1	1	1	1	1	1	1
Nutrient addition	1	1	1	1	1	1	1	1	1	1
Membranes	7	7	1	27	27	4	15	15	2	-
Membr. aerators	4	4	-	12	12	-	8	8	-	-
Biotank	4	4	4	15	15	15	9	9	9	-
Membrane tank	1	1		1	2		1	1	-	-
Membrane pumps	1	1	1	2	2	2	1	1	1	-
Biotreat. aerators	3	3	3	7	7	7	6	6	6	-
Biotank	-	-	-	-	-	-	-	-	-	15
Blower & pump house	-	-	-	-	-	-	-	-	-	2
Sedimentation & sludge piping			-	-	-	-	-	-	-	20
Sludge handling	3	3	3	3	3	3	3	3	3	3
Measure station	2	2	2	2	2	2	2	2	2	2
Pipes	11	11	11	11	11	11	11	11	11	10
Electrical	10	10	10	10	10	10	10	10	10	3
Instruments	5	5	5	5	5	5	5	5	5	4
Control system	2	2	2	2	2	2	2	2	2	2
Montage	10	10	10	10	10	10	10	10	10	2
Tech. contingency	22	22	19	38	38	27	29	29	23	18
Auxiliary equipm.	10	10	8	16	16	12	13	13	10	10
Project & adm.	11	11	9	18	18	13	14	14	11	11
Total	**114**	**114**	**97**	**194**	**195**	**137**	**152**	**152**	**117**	**128**

APPENDIX F: OPERATING COSTS

Operating costs	Alt 1	Alt 1	Alt 1	Alt 2	Alt 2	Alt 2	Alt 3	Alt 3	Alt 3	Alt 4
	HF	**FS**	**MT**	**HF**	**FS**	**MT**	**HF**	**FS**	**MT**	**CAS**
kSEK/year										
Chemicals	1600	1600	1600	2400	2400	2400	1200	1200	1200	600
Electricity	2100	2100	4700	4100	4100	16000	3100	3100	9300	3000
Sludge handling	4500	4500	4500	6000	6000	6000	4500	4500	1800	3000
Personell	500	500	500	500	500	500	500	500	500	400
Maintenance	2900	2900	2400	4900	4900	3400	3800	3800	2900	3200
Total	**11600**	**11600**	**13700**	**17900**	**17900**	**28300**	**13100**	**13100**	**15700**	**10200**